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Measuring Spatio-temporal Characteristics of City Expansion and Its Driving Forces in Shanghai from 1990 to 2015

TIAN Li[1], LI Yongfu[2], SHAO Lei[1], ZHANG Yue[1]

(1. *Department of Urban Planning*, *Tsinghua University*, *Beijing* 100084, *China*; 2. *Department of Architecture*, *Shanghai University*, *Shanghai* 200444, *China*)

Abstract: Urbanization has both direct and indirect impacts on land use change, and analyzing spatio-temporal characteristics of land use change is essential for understanding these impacts. By comparing Landsat TM images, this paper examines the changes of land use structure and landscape patterns in Shanghai from 1990 to 2015. It finds that the city doubled in size, with the growth of isolated construction land being most significant among eight land use types. A land use change matrix was established and landscape indices were selected to evaluate the change of spatial structure in Shanghai. In order to identify the main driving forces of city expansion in Shanghai, this research ran partial least square regression models to assess the impact of 10 social-economic factors on land use change of Shanghai from 1990 to 2015. It then conducted bivariate correlation analysis to explore the drivers of change of various land use types: urban settlement, rural settlement and isolated construction land. Besides quantitative analysis, this paper analyzes the influence of policy-dimensional factors in land use change. It concludes with future potential research topics on land use change in a rapidly urbanizing context.

Keywords: urbanization; land use change; partial least squares regression; driving forces; Shanghai

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1 Introduction

One of the many characteristics which accompany rapid urbanization in developing countries is the significant amount of land converted from agricultural to non-agricultural land (Healey, 1991; Heilig, 1996; Guy and Henneberry, 2000; Xu *et al*., 2007). China is no exception to this rule. From 1981 to 2015, the urbanization rate in China increased from 20.12% to 56.10%. During this period, the urban population grew from 1.997×10^8 to 7.7116×10^8, and the city built-up area expanded from 7438 km^2 to 52 100 km^2, with a growth rate much higher than that of the urban population and urbanization (Ministry of Housing and Urban-rural Development of China, 2015; National Bureau of Statistics of China, 2016).

Urbanization has both indirect and direct impacts on land use change. Urban sprawl is one of the most noticeable effects of urbanization (Lin, 2007). At the global scale, industrialization, urbanization, and population growth have been the most common forces contributing to land-use change (Long *et al*., 2007). At the national scale, Ho and Lin (2004) point out that rural-urban migration, urbanization and accelerated development are the most important factors contributing to expansion of construction land in China. According to Cui and Ma (1999), two forms of urbanization coexist in China. One form is top-down urbanization characterized by the spill-over effects of city and population growth, and the second form of urbanization is bottom-up rural

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Corresponding author: LI Yongfu. E-mail: li_yf@126.com

urbanization based on the growth of Township-Village-Enterprises (TVEs) and smaller towns in rural areas.

These two types of urbanization are often spatially intermingled within municipal regions, leading to the complexity and magnitude of land use change. At the sub-national scale, Liu *et al.* (2002) conclude that the land-use changes in Northeast China result from the change of macro social and economic factors and local geographic conditions. Seto and Kaufmann (2003) cites the Pearl River Delta of China (PRD) as an example, and argues that land expansion is associated with foreign direct investment instead of local land users. Long *et al.* (2007) point out that industrialization, urbanization, and population growth contribute to city expansion in Kunshan, a city in the Yangtze River Delta (YRD). Tian and Zhu (2013) argue that bottom-up industrialization has led to land expansion and fragmentation facilitated by the village collective in the PRD.

There has been a wealth of literature documenting the extent of land use change in China through applying remote sensing data and GIS, focusing on the loss of farm land, in other words, the conversion from cultivated land into construction land and the subsequent consequences (Li and Yeh, 2004; Tan *et al.*, 2005; Tan *et al.*, 2006; Xiao *et al.*, 2006; Long *et al.*, 2007; Deng *et al.*, 2010; Tian and Zhu, 2013). While describing the spatio-temporal characteristics of land use change, Li *et al.* (2007) employ urban growth speed，growth intensity, fractal dimension and urban growth patterns to analyze the growth of urban land in the Yangtze River Delta． Guan *et al.* (2012) use the urban expansion index and urban expansion model to analyze the spatial-temporal growth of Wuhan Urban Agglomeration, and examine the influence of the national strategy of ‘Rise of Central China’ on city expansion. Moreover, there has been substantive research examining the driving forces through regression models (Liu *et al.*, 2002; Xiao *et al.*, 2006; Long *et al.*, 2007; Xu *et al.*, 2007). Most of these research works, however, regard non-agricultural land as a whole, and does not differentiate land use types.

This research is an attempt to combine the spatio-temporal change of city expansion and the quantitative analysis of the driving forces, and dig deeper into the driving forces behind the growth of various land use types. Firstly, we utilized the Landsat TM data and examine the spatio-temporal characteristics of land use change in Shanghai from 1990 to 2015 through the application of the land use change matrix and landscape ecology indices. Then，weidentified the major driving forces behind city expansion and examine the impact of these forces on land use change in Shanghai by the adoption of a Partial Least Square Regression (PLSR) analysis. Moreover, we applied bivariate correlation analysis to examine the social-economic drivers of urban settlement, rural settlement, and isolated construction land. Besides the quantitative analysis, we analyzed the policy-dimensional factors of land use change. This paper concludes with potential future research topics on land use in a rapidly urbanizing context.

2 Materials and Methods

2.1 Study area

Shanghai is located at the mouth of the Yangtze River, the longest river in China. It was founded over 700 years ago. Shanghai was once the financial center of the Far East, but its role as a financial center was seriously weakened after the establishment of the People’s Republic of China in 1949. In 1990, the Chinese government announced a national strategy of development, aiming to revive the Shanghai economy and enhance it srole as a leading city in the Yangtze River Delta. As the most important economic, financial, trade and shipping center of China, Shanghai has experienced significant social, economic, environmental and land use changes since the opening of Pudong New District in 1990.

The Pudong opening up strategy has had a dramatic social and economic impact on Shanghai. Due to a constant inflow of foreign investment and people from other parts of the country, the Shanghai GDP grew from 7.817×10^{10} yuan (RMB) in 1990 to 2.497×10^{12} yuan in 2015. During that same time period, its total population increased from 1.343×10^{7} in 1990 to 2.419×10^{7} in 2015 (Shanghai Statistics Bureau, 1991–2016). The Shanghai metropolitan area covers a land area of 6340.5 km^2, including 18 districts and one county①. The entire Shanhai area includes four distinct regions. The region within the outer ring road is named

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① In 2010, the original Nanhui District was merged into Pudong New Distrct. In 2011, Luwan District was merged into Huangpu District. Since this paper focuses on the land use over the period of 1990–2010, we regard Nanhui and Luwan as independent districts.

within the outer ring road is named as the central city, and the area within the inner ring road is identified as the core area of the central city (Fig. 1). The identification of four sub-regions is presented in Table 1.

2.2 Data sources and processing

In this study, land use data include the historical land use information of Shanghai in 1990, 1995, 2000, 2005, 2010, and 2015, all from the vector data produced by the Institute of Geographic Science and Natural Resources Research, Chinese Academy of Sciences. Based on the land use classification system issued by the China National Agricultural Committee in 1984, eight land use categories are utilized in this paper: cultivated land, forested land, grass land, water area, urban settlement, rural settlement, isolated construction land (for industry and mining), and unutilized land. Urban settlement includes urban residential land, commercial land, land for public facilities, *etc*. Rural settlement mainly includes two types of land use: land for *Zhaijidi* (free allocated land for farmers to build houses), rural commercial and industrial land. Isolated construction land includes industrial park/clusters and land for mining resources. However, since there have been scarce mining resources in

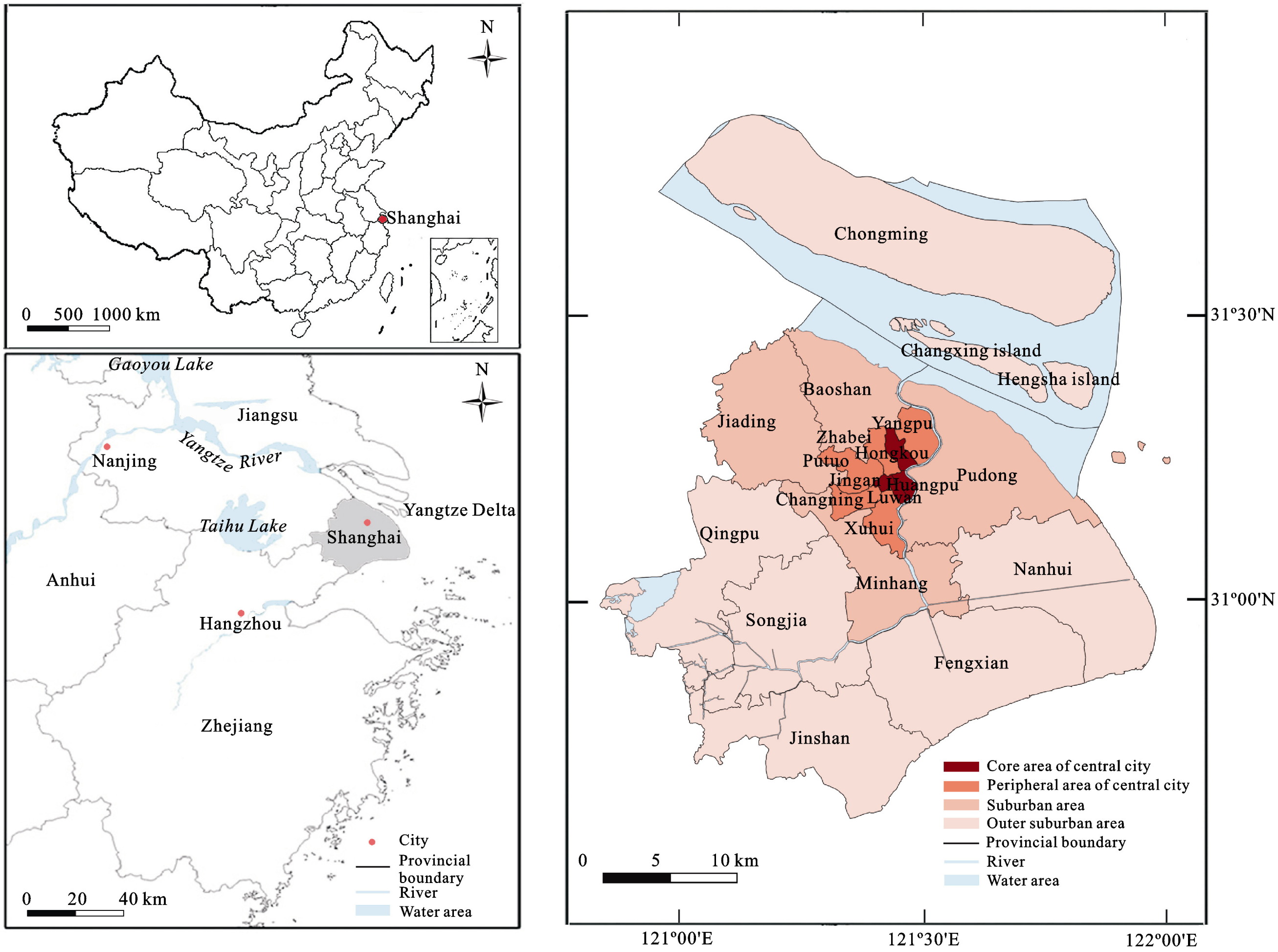

Fig. 1 Location of Shanghai and its sub-regions

Table 1 Identification of sub-regions in Shanghai

Sub-region	District/County
Core area of central city	Jingan, Luwan, Huangpu, Hongkou
Peripheral area of central city	Yangpu, Changning, Xuhui, Putuo, Zhabei
Suburban area	Pudong, Baoshan, Minghang, Jiading
Outer suburban area	Fengxian, Songjiang, Qingpu, Nanhui, Jinshan, Chongming

Shanghai, this type of land mainly refers to industrial land. In general, overall construction land consists of urban and rural settlements and isolated construction land.

2.3 Methods

2.3.1 Land use change matrix and landscape ecology metrics

After processing the land use data, we applied a pixel-to-pixel overlay analysis through overlapping the land use maps of different time periods. In order to quantify and categorize complex land use into identifiable patterns and reveal properties that are not directly observable, land use change matrix and landscape ecology metrics are commonly used. A land use change matrix is applied to measure the mutual conversion among different types of land use. Moreover, landscape ecology metrics have the potential for more detailed analyses of the spatio-temporal patterns of land use change (Antrop and Van Eetvelde, 2000; Turner *et al.*, 2001; Long *et al.*, 2007; Deng *et al.*, 2009). In this research, we select several indices to measure the landscape pattern change of cultivated land, forested land, urban settlement, rural settlement, and isolated construction land by overlapping the land use maps of different time periods.

These landscape indices are explained as follows (Wu, 2007):

(1) Percentage of landscape (PLAND), $PLAND = A_i/A$, where A_i is total area of land-use i; A is total landscape area.

(2) Number of patches (NP).

(3) Patch density (PD), $PD = n_i/A$, where n_i is total number of patches of land-use i; A is total landscape area.

(4) Mean patch area size (MPS), $MPS = A_i/n_i$, where A_i is total area of land-use i; n_i is number of patches.

(5) Landscape shape index (LSI), $LSI = e_i/\mathrm{min}e_i$, where e_i is total length of edge (or perimeter) of class i in terms of number of cell surfaces; $\mathrm{min}e_i$ is minimum total length of edge (or perimeter) of class i. The larger the number is, the more irregular the shape is.

(6) Landscape fragmentation degree (LFD), $LFD = (N_i - 1)/A_i$, where N_i is number of patches, and A_i is total area of land-use i. The larger the number is, the more fragmented the shape is.

2.3.2 Identification of drivers of land use change

The fundamental driving forces of land use change are social and economic factors in nature. In general, the driving forces of land-use are grouped into six categories: population, level of affluence, technology (including transportation), political economy, political structure, and attitudes and values (Turner and Meyer, 1991; Rayner, 1992). Population density and the level of economic and social development affect demands which will be placed on the land, while technology influences the intensity of exploitation that is possible. Political economy, such as property rights and the structures of power from the local to the international level, influence access to or control over land resources, but they are difficult to quantify (Turner *et al.*, 1993). A perfect representation of all socioeconomic drivers, however, is impossible to achieve in a single model (Sohl *et al.*, 2010). Nevertheless, quantifying the impacts of social and economic drivers on land use change can help us better understand the role of these drivers. Based on available time-series data, this research identifies five types of indices, including 10 variables, as drivers of land use change in Shanghai.

(1) Population size and urbanization

Urbanization greatly contributed to the loss of agricultural land in China and has been regarded as one of the most important factors of land-use change (Heilig, 1996; Ho and Lin, 2004). Rapid industrialization and urbanization are often correlated with the increase of population size for the same periods (Fischer *et al.*, 1997; Jenerette and Wu, 2001). In this research, the size of permanent population and the urbanization rate are selected as two key variables of land use change.

(2) Income

Wealth increases per capita consumption and brings about changes in land use through higher resource demands (Turner *et al.*, 1993). This research selects disposable income per capita of urban and rural residents as key variables of income.

(3) Economic strength

Land is a fundamental factor of production, and has been closely linked to economic growth (Richards, 1990). This research identifies GDP and local fiscal revenue as two variables of economic strength.

(4) Investment

In China, economic growth has been strongly characterized by state-led growth (Tian and Ma, 2009), and investment in infrastructure facilities can lead to significant changes in fast-growing cities of developing countries (Tian, 2007). Moreover, foreign direct investment can generate demands for land use, and thus is also a key variable of land expansion.

(5) Transportation

Demands for transport infrastructure have usually been very strong in fast-growing cities of developing countries, and the extension of transport infrastructure such as highways and railways can open up previously inaccessible resources and lead to city expansion (Turner *et al.*, 1993). Therefore, highway mileage and length of rail transit lines are selected as variables of transportation.

2.3.3 PLSR model and bivariate correlation analysis

Realizing the limited observations and multi-correlation problems among variables, traditional multiple stepwise linear regression is difficult to apply in the Shanghai case. Thus, this study adopts a PLSR model (the overall construction land as dependent variables, and 10 types of drivers as independent variables) to analyze the impacts of social-economic factors on the expansion of overall construction land in Shanghai from 1990 to 2015.While exploring the driving forces of urban settlement, rural settlement and isolated construction land, we apply the bivariate correlation to examine the influence of available social-economic factors on land use change.

Furthermore, we find that quantitative analysis is not sufficient to explain the mechanism of city expansion. Thus, we combine qualitative analysis, policy-dimensional impact factor analysis of urban settlement, rural settlement and isolated construction land, with quantitative analysis to illustrate the driving mechanism of land use change.

3 Spatio-temporal Change of Land Use in Shanghai from 1990 to 2015

Shanghai has witnessed significant changes since the opening of Pudong in 1990. Urbanization increased from 66.20% in 1990 to 89.10% in 2015 (Shanghai Statistics Bureau, 1991–2016). From 1990 to 2015, the cultivated land area decreased from 4853.01 km^2 to 3623.73 km^2, and construction land increased from 1202.86 km^2 to 2546.48 km^2, more than doubling in size.

3.1 City expansion of Shanghai

Table 2 City expansion of Shanghai

Period	Area of non-agricultural land (km^2)	Annual growth rate of non-agricultural land within five-year period (%)
1990	1202.86	—
1995	1371.20	2.65
2000	1452.77	1.16
2005	1834.36	4.77
2010	2223.65	3.92
2015	2546.48	1.95

Table 2 and Fig. 2 show the city expansion of Shanghai from 1990 to 2015. We find that construction land grew slowest from 1995 to 2000 due to the influence of the 1997 Asian Financial Crisis and a moratorium by the central government on land supply for commercial developments in 1997. Construction land grew fastest from 2000 to 2010 because of the construction of new towns and industrial parks, and growth slowed from 2010 to 2015 due to the stringent land supply policy, which will be discussed later.

Figure 3 shows the change of the spatial geometric center of construction land in Shanghai. The spatial geometric center was located within the inner ring road region from 1990 to 2005, and it moved to the area between the inner ring road and mid-ring road in 2010 and 2015. Compared with the geometric center of Shanghai's administrative boundary, the direction of construction land expansion was northeast from 1990 to 1995, south from 1995 to 2005, southeast from 2005 to 2010, and northwest from 2010 to 2015. This is consistent with the direction of rapid development in the Pudong New District and southern districts, including Minghang, Fengxian and Jingshan from 1990 to 2010. After 2010, the districts in western Shanghai, including Qingpu and Songjiang, grew faster than other districts.

3.2 Land use structural change of Shanghai from 1990 to 2015

An accelerating urbanization process may increase the structural complexity of land use (Jenerette and Wu, 2001). Table 3 presents the conversion matrix of land use in Shanghai from 1990 to 2000, from 2000 to 2010 and from 2010 to 2015. Cultivated land decreased by 5.17% from 1990 to 2000, 14.45% from 2000 to 2010, and 6.96% from 2010 to 2015, respectively. Forested land decreased by 0.83% from 1990 to 2000, increased by 3.44% from 2000 to 2010, and decreased by 8.75% from 2010 to 2015. Therefore, the growth of construction land was mainly at the cost of cultivated land.

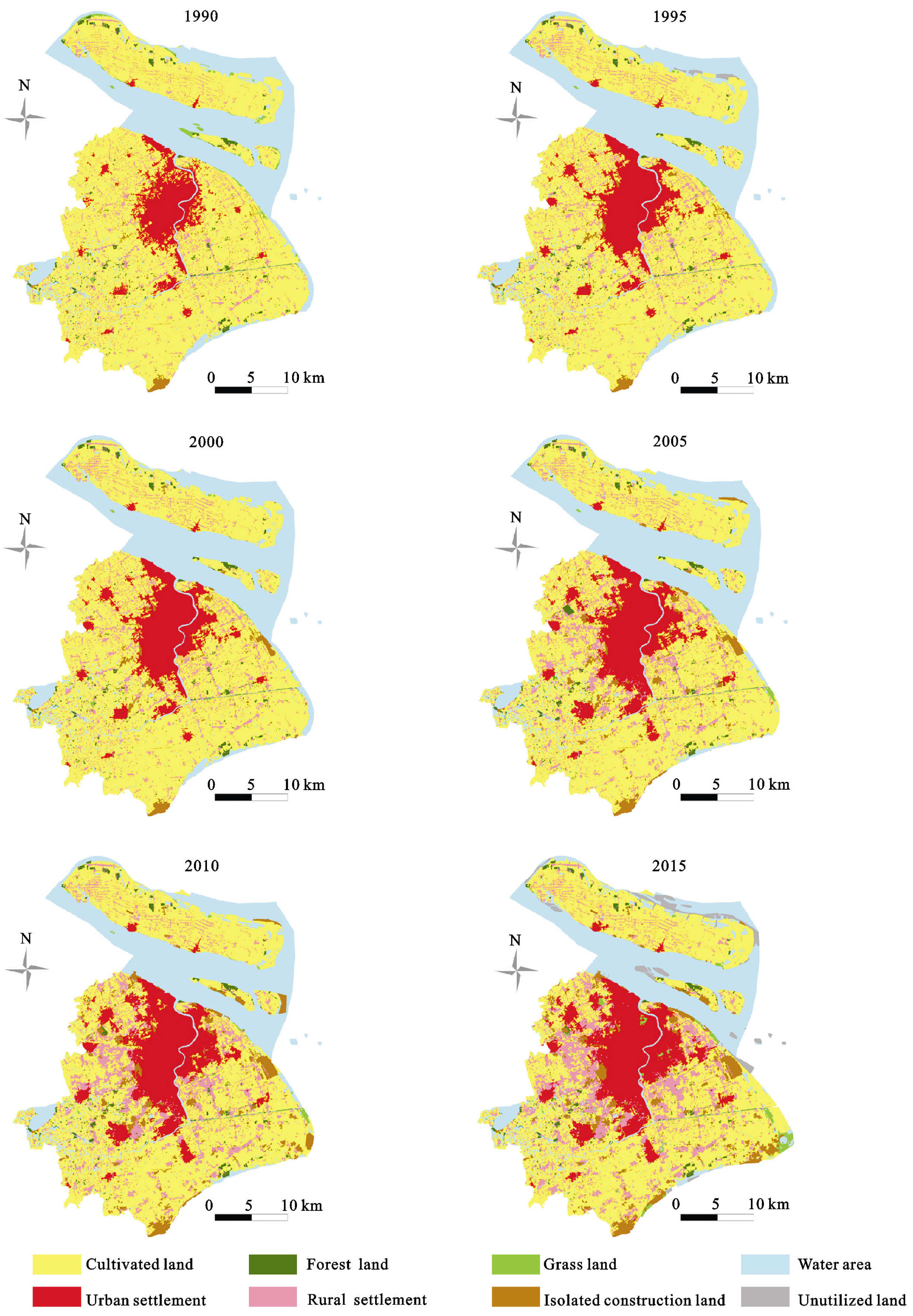

Fig. 2 Landsat TM images of Shanghai in 1990, 1995, 2000, 2005, 2010 and 2015

Meanwhile, urban settlement, rural settlement, isolated construction land, water area and grassland increased by 27.10%, 7.08%, 88.11%, 0.91% and 0.33% from 1990 to 2000. From 2000 to 2010, urban settlement, rural settlement, isolated construction land, and grassland increased by 27.62%, 58.10%, 248.04%, and 75.00%, respectively, but water area decreased by 6.51%. From 1990 to 2010, isolated construction land

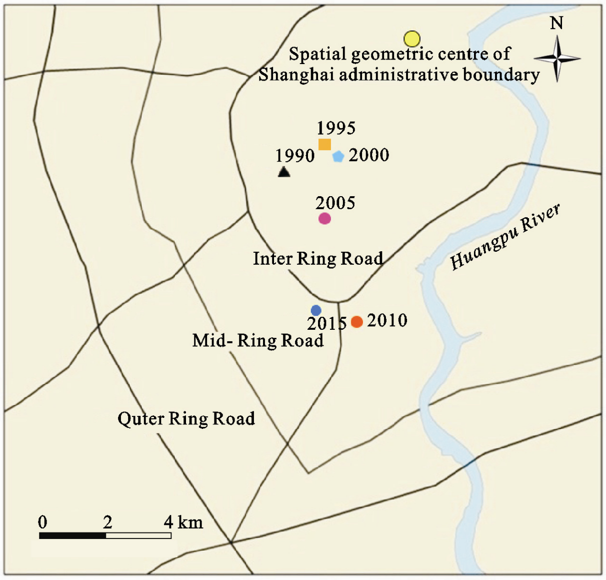

Fig. 3 Change of spatial geometric center of non-agricultural land in Shanghai from 1990 to 2015

grew fastest due to the expansion of industrial parks. From 2010 to 2015, urban settlement, rural settlement, isolated construction land, and grassland continued growing, reaching a growth rate of 8.01%, 21.85%, 8.35%, and 136.80%, and water area decreased by 2.68%.The expansion of industrial park land slowed dramatically during this period.

Figure 4 shows that during the time period studied, the dominant role of agricultural land was gradually weakened, and the non-agricultural landscape expanded significantly. From 1990 to 2015, the percentage of construction land as part of total land increased from 15.01% to 28.86%. Meanwhile, the percentage of agricultural land in total land decreased from 61.23% to 47.34%. The unutilized land took a share of 0.22% in total land in 1990 and 1995, but it disappeared in and after 2000. With the city expansion, all land was fully utilized.

Table 3 Change matrix of each land use type in Shanghai from 1990 to 2015

2000	1990							
	CL (km^2)	FL (km^2)	GL (km^2)	WA (km^2)	US (km^2)	RS (km^2)	IC (km^2)	Total (2000) (km^2)
CL	4537.91	0.20	0.00	10.92	0.90	1.82	1.17	4552.92
FL	1.60	101.39	0.00	0.09	0.00	0.02	0.00	103.10
GL	0.00	0.00	8.47	0.77	0.00	0.00	0.00	9.25
WA	11.81	0.18	0.74	1864.63	0.02	0.08	0.04	1895.20
US	169.99	0.20	0.00	0.24	628.53	0.00	1.08	800.05
RS	38.03	0.99	0.00	0.14	0.01	523.67	0.00	562.84
IC	42.04	0.99	0.00	1.35	0.01	0.01	45.48	89.88
Total (1990)	4801.38	103.96	9.22	1878.14	629.47	525.61	47.78	8013.23
Change in 1990–2000 (%)	–5.17	–0.83	0.33	0.91	27.10	7.08	88.11	

2010	2000							
	CL (km^2)	FL (km^2)	GL (km^2)	WA (km^2)	US (km^2)	RS (km^2)	IC (km^2)	Total (2010) (km^2)
CL	3827.87	0.00	0.62	66.32	0.00	0.05	0.00	3894.87
FL	6.14	97.52	1.96	0.81	0.00	0.22	0.00	106.65
GL	0.00	0.00	6.26	9.92	0.00	0.00	0.00	16.18
WA	16.52	0.24	0.34	1754.76	0.00	0.00	0.00	1771.88
US	209.58	1.10	0.00	1.54	800.05	8.72	0.00	1020.99
RS	331.52	2.76	0.06	5.49	0.00	550.00	0.00	889.83
IC	161.28	1.48	0.00	56.34	0.00	3.85	89.87	312.82
Total (2000)	4552.91	103.10	9.25	1895.19	800.05	562.84	89.88	8013.22
Change in 2000–2010 (%)	–14.45	3.44	75.00	–6.51	27.62	58.10	248.04	

Continue Table

2015	2010							
	CL (km^2)	FL (km^2)	GL (km^2)	WA (km^2)	US (km^2)	RS (km^2)	IC (km^2)	Total (2015) (km^2)
CL	3546.81	0.01	0.00	51.75	2.33	7.87	14.97	3623.73
FL	0.00	97.30	0.00	0.00	0.00	0.00	0.01	97.32
GL	5.77	0.00	14.26	6.46	8.40	1.28	2.16	38.32
WA	3.75	0.06	0.82	1576.65	0.14	0.02	17.15	1598.58
US	84.15	0.53	0.00	0.08	1004.41	6.99	6.60	1102.77
RS	203.05	7.10	0.04	2.26	0.02	871.61	0.15	1084.23
IC	51.33	1.65	1.07	5.36	5.69	2.06	271.79	338.95
Total (2010)	3894.87	106.65	16.18	1642.54	1020.99	889.83	312.82	7883.89
Change in 2010–2015 (%)	–6.96	–8.75	136.80	–2.68	8.01	21.85	8.35	

Notes: CL, cultivated land; FL, forested land; GL, grass land; WA, water area; US, urban settlement; RS, rural settlement; IC, isolated construction land for manufacturing and mining

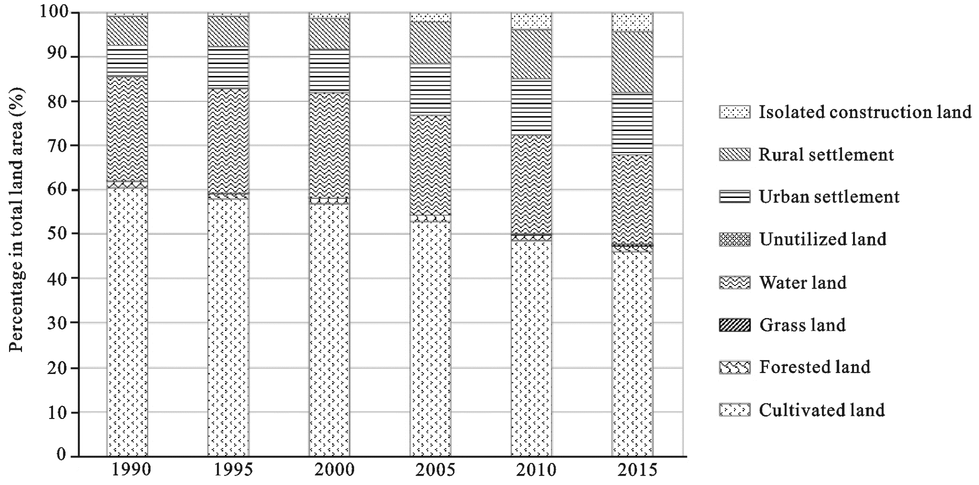

Fig. 4 Land use structural change of Shanghai from 1990 to 2015

3.3 Landscape pattern change of Shanghai

Table 4 shows that in terms of PLAND, the growth of isolated construction land was most significant, at 7.33 times from 1990 to 2015, and the second was rural settlement, 2.02 times. Urban settlement increased by 72.00%, and forested land declined by 7.75%. Meanwhile, the reduction of cultivated land was substantial, from 59.94% in 1990 to 45.26% in 2015. The NP of isolated construction land and cultivated land increased substantially, and that of urban settlement and rural settlement decreased slightly. At the same time, the MPS of urban settlement rose by 95.20% and 130.00%, but the MPS of cultivated land declined dramatically, and the MPS in 2015 was only 14.30% of that in 1990, and the change of LSI and LFD also meant that isolated construction land became more irregular and cultivated land became more fragmented. Different from cultivated land and isolated construction land, urban and rural settlement presented a more consolidated trend. Their NP, PD and LFD decreased, but MPS increased, mostly caused by city expansion which absorbed the original rural communities.

To summarize, the city expansion of Shanghai presents the following characteristics from 1990 to 2015.

(1) The expansion of Shanghai was significant from 1990 to 2010, and growth from 2000 to 2010 was fastest, partly driven by the entry of China into the WTO in 2001 and subsequent foreign direct investment in Shanghai. The growth rate of construction land dramatically

Table 4 Landscape pattern change of main land use types in Shanghai from 1990 to 2015

Landscape pattern	Urban settlement				Rural settlement				Isolated construction land			
	1990	2000	2010	2015	1990	2000	2010	2015	1990	2000	2010	2015
PLAND (%)	7.85	9.98	12.74	13.51	6.56	7.01	11.10	13.28	0.60	1.11	3.90	4.40
NP	78	68	46	70	2576	2881	2505	2379	118	166	319	394
PD (/km^2)	0.123	0.085	0.01	0.01	5.24	5.12	0.31	0.29	2.47	1.85	0.04	0.05
MPS (km^2)	8.07	11.76	22.2	15.75	0.2	0.2	0.36	0.46	0.4	0.54	0.98	0.91
LSI	22.11	14.37	15.1	16.44	69.94	71.99	76.24	73.75	13.83	16.14	27.9	29.88
LFD	0.122	0.084	0.04	0.06	4.9	5.12	2.81	2.19	2.45	1.84	1.02	1.09

Landscape pattern	Cultivated land				Forested land			
	1990	2000	2010	2015	1990	2000	2010	2015
PLAND(%)	59.94	56.80	48.61	45.26	1.29	1.29	1.33	1.19
NP	64	110	212	344	361	356	349	324
PD (/km^2)	0.013	0.024	0.03	0.04	3.47	3.45	0.04	0.04
MPS (km^2)	75.02	41.39	18.37	10.74	0.29	0.29	0.31	0.3
LSI	54.99	40.21	52.35	53.58	23.89	22.35	26.35	25.42
LFD	0.013	0.024	0.05	0.09	3.46	3.44	3.26	3.32

Notes: PLAND is percentage of landscape, PD is patch density, MPS is mean patch area size, LSI is landscape shape index, LFD is landscape fragmentation degree

slowed after 2010 due to the more stringent national land supply policy. Moreover, with the decreased share of secondary industry in total GDP, the growth of industrial land was substantially restrained.

Among the non-agricultural land, the growth of isolated industrial and mining land played a dominant role from 1990 to 2010, and city expansion was largely driven by industrialization during this period. The growth of urban settlement was fairly stable, and the growth of rural settlement was slow from 1990 to 2000, but was much faster from 2000 to 2015. In terms of landscape pattern, urban settlement and rural settlement became more consolidated, but isolated construction land became more fragmented.

Among the non-agricultural lands, the change of forested land, grass land, and water areas fluctuated, but cultivated land kept declining. Moreover, cultivated land became more fragmented, indicating that city expansion was mainly at the cost of cultivated land.

4 Driving Forces of Land Use Change in Shanghai

As mentioned above, construction land in Shanghai more than doubled from 1990 to 2015. Moreover, the change of overall construction land, urban settlement, rural settlement and isolated construction land has been driven by different mechanisms. Therefore, we adopt different models to explore the impact of drivers on the change of various types of land use.

4.1 Driving force analysis of construction land

While adopting the PLSR model, we regard the overall construction land as dependent variables. As discussed earlier, 10 types of drivers are regarded as independent variables to examine their relationships through regression (Table 5 and Table 6). Hampered by a lack of annual land use data, we have only six observations, with those coming in 1990, 1995, 2000, 2005, 2010 and 2015. Under this circumstance, traditional ordinary least square regression is impossible to apply due to the multi-correlation problem among variables (the correlation analysis shows that the correlation coefficients are more than 0.8 among X_1–X_{10}), and this can result in the failure of significance test.

Realizing the existence of multicollinearity among variables, we adopt PLSR to examine the impact of different drivers on the expansion of construction land. PLSR is particularly suitable when the matrix of predictors has more variables than observations, and when there is multicollinearity among X values (http://en.wikipedia.org/wiki/Partial_least_squares, accessed on 12/10/2014). PLSR is used to find the fundamental relations between two matrices (X and Y), i.e.a latent variable approach to modeling the covariance structures in these two spaces. PLSR goes beyond traditional regression

Table 5 Drivers identification of land use change of Shanghai

Type of driver	Independent variable	Variable symbol
Population size and urbanization	Permanent population	X_1
	Urbanization rate (%)	X_2
Income	Disposable income per capita of urban residents	X_3
	Disposable income per capita of rural residents	X_4
Economic strength	GDP	X_5
	local fiscal revenue	X_6
Investment	Actual foreign investment	X_7
	Total investment in infrastructure facilities	X_8
Transportation	Highway mileage in operation	X_9
	Length of rail transit line in operation	X_{10}

in that it also models the structure of X and Y. PLSR is particularly useful due to its ability to analyze data with strong collinear, and even incomplete variables in both X and Y (Wold *et al*., 2001).

Then the following function can be estimated based on PLSR:

$$Y_i=\beta_0+\beta_1(X_1)+\beta_2(X_2)+\ldots+\beta_i(X_i) \quad (1)$$

where Y_i is the area of overall construction land; the meaning of X_i is explained in Table 5; β_i is the standard regression coefficient of X_i.

Based on the above analysis, the function can be established as follows:

$$Y=776.0795-0.0024X_1+6.0372X_2+0.0032X_3+0.0075X_4+0.0641X_5+0.2792X_6+9.0193X_7+0.9730X_8+0.0142X_9+0.2310X_{10} \quad (2)$$

The results show that $R^2 = 0.9974$ of function 2. Then, Bootstrap parameter tests are applied in the function, and variables from X_1 to X_{10} pass the test in the function (Sig. *test*=0.01, *B*=100). Through comparing the regression coefficients and VIP scores of independent variables (Table 7), we find that X_2 to X_{10} are significant in explaining the expansion of construction land, while X_1 is less significant①. Ranking highest to lowest, the five most influential drivers are GDP (X_5) >highway mileage in operation (X_9)>disposable income per capita of urban residents(X_3)>length of rail transit line in operation (X_{10}) >disposable income per capita of rural residents (X_4). According to the regression results, economic growth and investment in transportation greatly contributed to city expansion.

4.2 Driving force analysis of urban settlement, rural settlement and isolated construction land

4.2.1 Driving force of urban settlement expansion

It is obvious that the growth of urban settlement has been influenced by population size and income of urban residents. The GDP of the tertiary industry and real estate investment in an urban area can be selected as indicators of economic strength and investment. Moreover, housing price has been regarded as a key factor of land supply (Wu *et al*., 2009), and we selected average urban commodity housing price as another independent variable. The results of bivariate correlation analysis show that there are strong positive relationships between the five variables and expansion of urban settlement, and all of them pass the significance test (Fig. 5 and Table 8). Through comparing the coefficients of the five variables, we find that average price of commodity houses has the strongest relationship with the expansion of urban settlement, followed by urban population size, the income of urban residents, investment in real estate industry, and GDP of the tertiary industry. Therefore, the growth of real estate, urban population and income of urban residents required large amounts of land to provide

Table 6 Data of variables

Year	X_1 (10^3)	X_2 (%)	X_3 (yuan)	X_4 (yuan)	X_5 (10^9 yuan)	X_6 (10^9 yuan)	X_7 (10^9 USD)	X_8 (10^9 yuan)	X_9 (km)	X_{10} (km)	Y (km^2)
1990	13340	67.4	2183	1665	78.17	16.7	0.18	4.72	3050	0	1202.86
1995	14140	70.8	7172	4246	249.94	22.73	5.3	27.38	3787	15.2	1371.2
2000	16086	74.6	11718	5565	477.12	49.8	3.16	44.99	5970	62.9	1452.8
2005	18903	84.5	18645	8342	924.77	143.39	6.85	88.57	8110	147.8	1834.4
2010	23026	89.4	31838	13746	1716.60	287.36	11.21	149.75	11974	452.27	2223.64
2015	24153	89.1	52962	23205	2496.5	551.95	18.46	142.51	13246	617.53	2546.48

Notse: Data of X_1–X_{10} were from *Shanghai Statistics Yearbook* (1991–2016) (Shanghai Statistics Bureau, 1991–2016); Y is the area of construction land. Data of Y in 1990, 1995, 2000, 2005, 2010 and 2015 were collected from Landstat TM images

Table 7 VIP score of variables

Independent variable	VIP
X_1	0.2898
X_2	1.0276
X_3	1.0558
X_4	1.0491
X_5	1.0701
X_6	1.0365
X_7	1.0395
X_8	1.0466
X_9	1.0659
X_{10}	1.0550

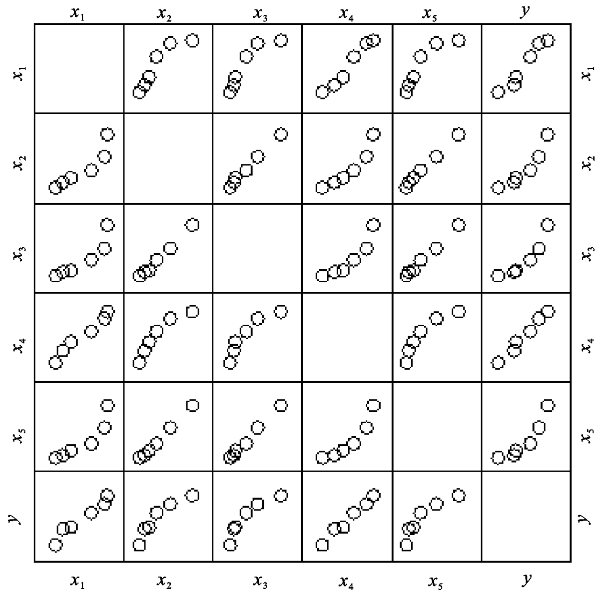

Fig. 5 Bivariate plot matrix of variables and land for urban settlement. x_1 is urban population; x_2 is income of urban residents; x_3 is investment in real estate; x_4 is average price of commodity houses; x_5 is GDP of tertiary industry; y is land for urban settlement

Table 8 Correlation results between different variables of urban settlement

	x_1	x_2	x_3	x_4	x_5	y
x_1	1	0.915*	0.904*	0.985**	0.905*	0.977**
x_2		1	0.997**	0.939**	0.998**	0.934**
x_3			1	0.920**	0.997**	0.921**
x_4				1	0.923**	0.992**
x_5					1	0.916*
y						1

Notes: x_1 is urban population; x_2 is income of urban residents; x_3 is investment in real estate; x_4 is average price of commodity houses; x_5 is GDP of tertiary industry; y is land for urban settlement. * Correlation is significant at the 0.05 level (2-tailed).** Correlation is significant at the 0.01 level (2-tailed)

space, and generated huge demand for the expansion of urban settlement.

4.2.2 Driving force of rural settlement and isolated construction land expansion

In China, rural houses are not allowed to be sold in the open market, and the data of investment in rural areas is not available. We select rural population size and the income of rural residents as two variables to conduct the bivariate correlation analysis. Figure 6 and Table 9 reveal that rural population and income of rural residents are not significantly correlated with rural settlement change, and both of them do not pass the significance test. The rural population decreased from 4.189×10^6 in 1990 to 1.560×10^6 in 2015 (Shanghai Statistics Bureau, 1991–2016), but the land area for rural settlement increased from 525.61 km^2 in 1990 to 1084.69 km^2 in 2015. The decrease of rural population did not lead to the reduction of rural settlement, and the reason lies in the growth of industrial land in the rural area, which will be discussed later.

Figure 7 shows the correlation analysis results between isolated construction land and manufacturing and industrial output value. The coefficient is 0.991, and it is significant at the 0.01 level (2-tailed). Isolated construction land increased from 47.78 km^2 in 1990 to 350.39 km^2 in 2015, 7.33 times from 1990 to 2015, and industrial output value grew at a much higher rate, 22.22 times, due to the dramatic improvement of land use efficiency.

4.3 Policy dimensional influence on expansion of construction land

China has adopted a state-led growth model (Tian, 2014). Besides the individual behavior of land users, the policies established by central/local governments have a huge influence on land use change. In China, local governments are major players in translating the land policy established by the Chinese Central Government into local patterns of land use (Long *et al.*, 2007). Therefore, it is essential to explore the relevant planning policies in order to understand the mechanism of land use change.

4.3.1 Expansion of urban settlement: state-led construction of new towns and function zones

In 2001, the Shanghai municipal government released the 'One Central City, Nine New Towns' plan to promote

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① The variable whose VIP score is bigger than 1 is more significant than that whose score is smaller than 1

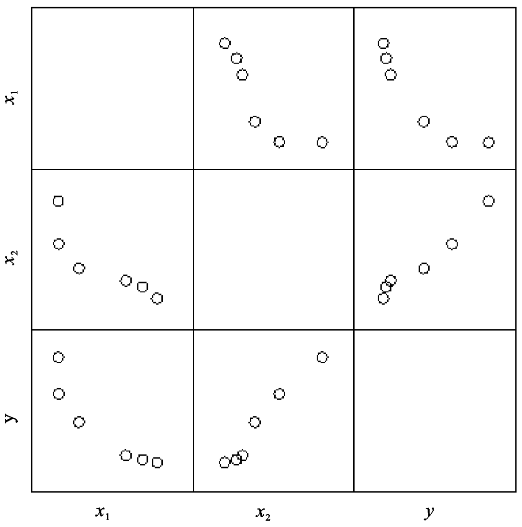

Fig. 6 Bivariate plot matrix of variables and land for rural settlement. x_1 is rural population, x_2 is income of rural residents, y is land for rural settlement

Table 9 Correlation results between different variables of rural settlement

	x_1	x_2	x_3
x_1	1	-0.867^{*}	-0.919^{**}
x_2		1	0.982^{**}
x_3			1

Notes: x_1 is rural population; x_2 is income of rural residents; $x_3$is land for rural settlement.* Correlation is significant at the 0.05 level (2-tailed), ** Correlation is significant at the 0.01 level (2-tailed)

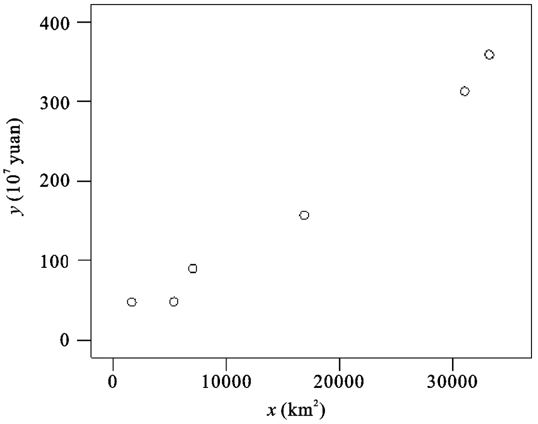

Fig. 7 Bivariate correlation analysis of industrial output (x) and isolated construction land (y)

the development of the suburban areas (Fig. 8), Under the plan, Shanghai would shift from a central city model to a poly-centric model (Hartog and Jun, 2009). The nine new towns include three medium-sized towns with a projected population of 8×10^5 to 1×10^6 (Songjiang new town, Jiading new town, and Lingang new town) and six other new towns with a projected population of 3×10^5 by the end of 2020 (Shanghai City Master Plan, 1999–2020). In order to realize the 'One Central City, Nine New Towns' plan, the Shanghai municipal government has invested substantially in the infrastructure construction of the nine new towns.

The expansion of construction land has also been driven by state-initiated large scale function zones, including nine university towns and 31 large affordable housing areas (Fig. 7). Among the nine university towns, five are located in the suburban areas to accommodate the new campuses of several universities which could not find additional space in the central city. These five towns cover a land area of 21.3 km^2. Thirty-one large affordable housing areas were designated in 2003 to alleviate housing problems caused by sky-rocketing housing prices, and each of these new housing areas are located in the Shanghai suburbs. The land area of these housing projects reached a total of 131.23 km^2 (Shanghai Urban Planning and Research Institute, 2014. Report on functions zones in Shanghai, unpublished report).

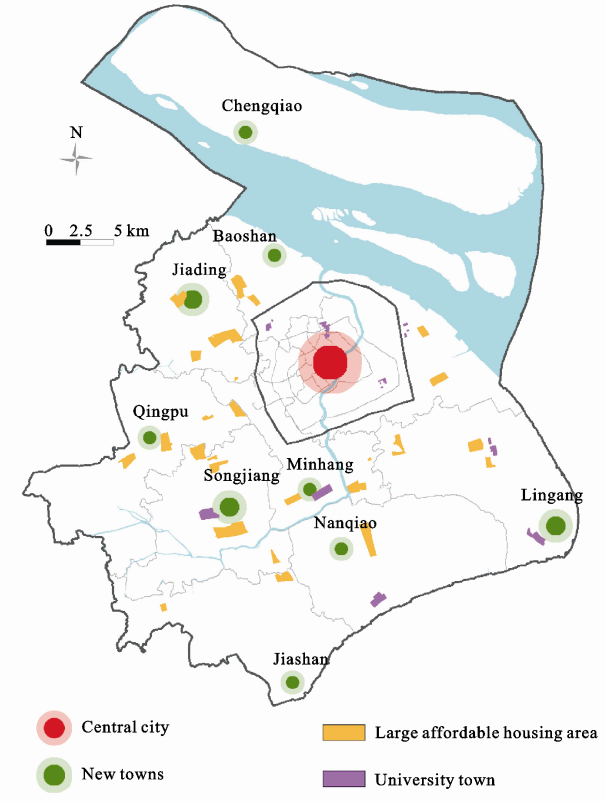

Fig. 8 New towns, university towns and large affordable housing areas in Shanghai (2012). Source: edited based on Shanghai Urban Planning and Research Institute, 2014a

4.3.2 Expansion of rural settlement: bottom-up rural industrialization and suspension of rural Zhaijidi land leasing

Bottom-up rural industrialization has been playing an important role in the land use change of rural areas. Since the reform opening, in order to promote local economic growth, towns and villages were allowed to set up their own industrial zones to attract foreign investment, and every town could own at least one industrial park. By the end of 1995, there were a total of 18 000 township enterprises in the Shanghai suburbs. In 1999, the total number of township enterprises reached 36 000, accounting for 72.00% of the total enterprises in Shanghai (Zhang, 2001). According to the Report on 104 Industrial Clusters in Shanghai (unpublished report) (Shanghai Urban Planning and Research Institute, 2014), there were several hundred industrial patches with a total land area of 188.00 km^2 in the suburbs of Shanghai, which were small township industrial zones in 2012. This can help explain how the land area for rural settlement increased from 525.60 km^2 in 1990 to 1046.98 km^2 in 2015.

4.3.3 Expansion of isolated construction land: government-initiated industrial park construction

Industrialization has long been regarded as one of the main engines driving economic growth in China (Lin, 2007; Long *et al.*, 2007). Since the middle 1980s, the Shanghai municipal government started to upgrade its industrial structure, and relocated manufacturing industries to the suburbs. As a consequence, many industrial parks were established in suburban Shanghai. Until 2012, the Shanghai municipal government and local government had established 9 state-level development zones and 31 municipal-level development zones (http://www.sidp.gov.cn/park/, accessed on 08/01/2015). According to the Report on 104 Industrial Clusters in Shanghai (unpublished report) (Shanghai Urban Planning and Research Institute, 2014), Shanghai had 104 industrial clusters, including state-level, city-level, district-level and township-level industrial parks (Fig. 9), whose land area reached 801.00 km^2 in 2012, accounting for 26.80% of overall construction land①. Among the 104 industrial clusters, 101 clusters are located in suburban Shanghai, and the other 3 clusters are located in the central city. Moreover, there are many other industrial patches scattered throughout the suburban area. Therefore, industrialization and the establishment of industrial parks has been one of major driving forces of urban sprawl in Shanghai.

As the trends of urbanization and industrialization show no signs of abating, the pressure on farmland coming from both urban sprawl and uncontrolled expansion of rural construction land has raised great concerns about food security (Huang *et al.*, 2011). In order to curb the urban sprawl, the Chinese Central Government has introduced a strict farmland protection policy through the land quota system. In 2010, the Shanghai municipal government designated its urban growth boundary, and the land supply outside of the growth boundary has been strictly prohibited. Under this stringent land control policy, city expansion has slowed since 2010.

Fig. 9 Industrial land use in Shanghai (2012). Source: Shanghai Urban Planning and Research Institute, 2014b

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① The 801 km^2 land also includes the land which has been leased out, but currently was not used as the construction land. Therefore, this figure is larger than that detected according to the Landsat TM images. Similarly, the area of total construction land in 2012, 2997 km^2, includes the land leased out but currently vacant.

5 Conclusions

Land-centered development is often regarded as the most significant feature of China's urbanization (Heikkila, 2007; Lin, 2007). Similarly, 'Land-centered urban politics' has been considered as one of the most important driving forces behind the spectacular expansion of Chinese cites and urbanization of China since the 1990s (Deng *et al*., 2010; Ye and Wu, 2014). Since the reform and opening of Pudong New District, tremendous land-use change has occurred in Shanghai. These accelerated industrialization, urbanization, and population increases have significantly affected land-use change through the increase of built-up areas and urban sprawl (Wu *et al*., 2004).

Untangling the relationship between socio-economic status and city expansion is complex. This paper integrated TM image and landscape ecology indices to analyze the spatio-temporal characteristics of land use change in Shanghai from 1990 to 2015. The results show that construction land in Shanghai increased from 1202.86 km^2 in 1990 to 2546.48 km^2 in 2015, more than doubling in size within 25 years. While examining the driving forces of construction land expansion through PLSR, we find that GDP has been the most significant driving force of city expansion. We then analyze the drivers of different land use types: urban settlement, rural settlement and isolated construction land through bivariate correlation analysis, and find they have been driven by different factors, with local government playing a dominant role in land expansion through the establishment of various industrial clusters, new towns and other function zones. Although bottom-up rural industrialization also contributed to sprawl, its influence has been fairly weak. Therefore, the expansion of construction land in Shanghai is largely the result of 'planned sprawl' (Tian *et al*., 2016), and land-centered development has been adopted as a key tool to promote economic growth in Shanghai from 1990 to 2015.

While our research shows that the growth of construction land is much higher than that of population or economic growth, this fact reveals that Shanghai has not been expanding in an efficient or effective way. While population and economic growth inevitably generates demand for city expansion, planning and policy can play essential roles in promoting sustainable city growth. The evaluation of planning and policy in city expansion requires more in-depth research, which should be encouraged for long-term sustainable urban and rural development.

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