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Monitoring urban expansion and land use/land cover changes of Shanghai metropolitan area during the transitional economy (1979–2009) in China

**Jie Yin · Zhane Yin · Haidong Zhong ·
Shiyuan Xu · Xiaomeng Hu · Jun Wang ·
Jianping Wu**

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Abstract This study explored the spatio-temporal dynamics and evolution of land use/cover changes and urban expansion in Shanghai metropolitan area, China, during the transitional economy period (1979–2009) using multi-temporal satellite images and geographic information systems (GIS). A maximum likelihood supervised classification algorithm was employed to extract information from four landsat images, with the post-classification change detection technique and GIS-based spatial analysis methods used to detect land-use and land-cover (LULC) changes. The overall Kappa indices of land use/cover change maps ranged from 0.79 to 0.89. Results indicated that urbanization has accelerated at an unprecedented scale and rate during the study period, leading to a considerable reduction in the area of farmland and green land. Findings further revealed that water bodies and bare land increased, obviously due to large-scale coastal development after 2000. The direction of urban expansion was along a north-south axis from 1979 to 2000, but after 2000 this growth changed to spread from both the existing urban area and along transport routes in all directions. Urban expansion and subsequent LULC changes in Shanghai have largely been driven by policy reform, population growth, and economic development. Rapid urban expansion through clearing of vegetation has led to a wide range of eco-environmental degradation.

Keywords Land use/land cover · Remote sensing · Transitional economy · Urbanization · Shanghai

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J. Yin · H. Zhong · S. Xu · J. Wang · J. Wu
Key Laboratory of Geographic Information Science,
Ministry of Education, East China Normal University,
3663 North Zhongshan Rd., Shanghai 200062,
People's Republic of China

J. Yin
e-mail: rjay9@126.com

H. Zhong
e-mail: zhd_1981@163.com

S. Xu
e-mail: syxu@geo.ecnu.edu.cn

J. Wang
e-mail: jwang@geo.ecnu.edu.cn

J. Wu
e-mail: jpwu@geo.ecnu.edu.cn

Z. Yin (✉) · X. Hu
Department of Geography,
Shanghai Normal University,
100 Guilin Rd., Shanghai 200234,
People's Republic of China
e-mail: zhaneyin@126.com

X. Hu
e-mail: hxm@shnu.edu.cn

Introduction

Land-use and land-cover (LULC) change is one of the most important human-induced disturbances linked to global environmental and climate change, due to its interactions with global carbon cycles, ecosystem processes, biogeochemical cycles, biodiversity, and even more importantly, human activity (Kilic et al. 2006; Xiao et al. 2006; Aguilar et al. 2003). The worldwide trajectory of LULC changes over the last 300 years is characterized by loss of forest and expansion of agricultural lands (Houghton 2003). However, over recent decades, changes in LULC, especially in developing countries, has involved a decrease in the area of rural land use and an increase in the area of urban land use through urbanization (Dewan and Yamaguchi 2009a, b; Jat et al. 2008; Mundia and Aniya 2006). Urban areas currently cover only 3% of the Earth's land surface but over half of the world's population now resides in cities (Herold et al. 2003; Liu and Lathrop 2002; United Nations 2001). Increasing human activity in urban areas has brought about profound changes in land use and landscape pattern at both local and global scales, and is having a marked effect on ecosystem structure, function, and dynamics, making urban areas fragile regions (Deng et al. 2009; Weng 2007). Accurate and timely monitoring information regarding urban LULC change is useful for understanding the various impacts of human activity on the overall ecological condition of the urban environment (Yeh and Li 1999; Dewan and Yamaguchi 2009a, b).

Since 1979, a policy of reform and opening-up has guided China's transition from a planned economy to a market economy (Xu et al. 2007). Chinese cities have experienced radical changes during this economic transition. Shanghai, as the largest economic center of China, is probably the best illustration of urban land use/land cover change and associated environmental change. The urbanization level of Shanghai was 84.5% at the end of 2005, while the national level was only 42.9% (Wang et al. 2008a, b). Shanghai's urban population numbered only 6.5 million in 1978, but this had increased to 16.5 million by 2008 with an average growth rate of 5.1%/year. As a result of rapid urban population growth, large amounts of rural land have become built-up areas, both as part of planned urbanization and, unfortunately, illegal housing. Rapid urban expansion has also resulted in some eco-environmental problems, particularly a loss of cultivated land, land degradation, scarcity of water resources, urban heat and rain island effects, and environmental pollution. Therefore, it is particularly important to examine the state and trend of urban LULC change, so that sustainable land use and eco-environmental restoration planning can be formulated by policy makers.

Geographic information systems (GIS) combined with remote sensing (RS) and global positioning systems (GPS) have been widely applied and recognized as powerful and cost-effective tools for detecting and analyzing the spatio-temporal dynamics of processes and patterns of urban growth and LULC change at local, regional, and global scales (Hathout 2002; Herold et al. 2003; Lambin et al. 2003). Remote sensing offers valuable multispectral data sets that cover study areas with both positional spatial detail and high temporal frequency (Xiao et al. 2006). GPS can be used to collect the positioning information of fieldwork reference points for RS data correction and classification. GIS is useful for preprocessing, analyzing, and mapping the spatio-temporal processes and patterns of LULC change. The integrative use of "3S" technology has proven its effectiveness with respect to the updating of spatial data and particularly to the provision of accurate and timely geospatial information illustrating land use/cover change patterns (Yang 2002). This information can then be utilized by urban planners and decision-makers in the management and planning of urban spaces (Geymen and Baz 2008).

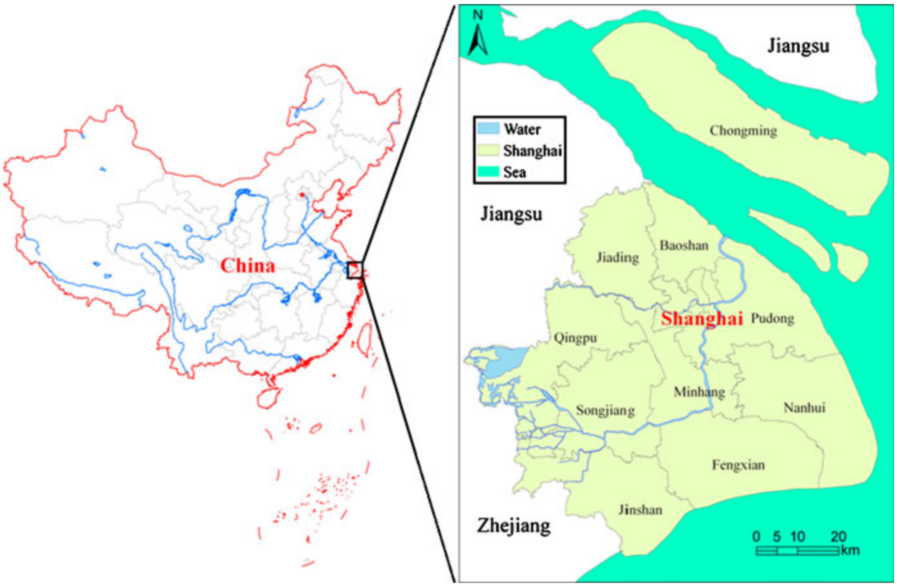
Previous studies have reported on urban growth and consequent land use and land cover change of local areas and most of Shanghai as a whole (Xu et al. 2007; Li et al. 2006). However, less attention has been paid to the spatio-temporal dynamics of the processes and patterns of urban growth and LULC change of the total area of Shanghai during the transitional economy. In this paper, we employed "3S" technology and socio-economic information to identify the specific characteristics of LULC change, characterizing the underlying driving forces in the Greater Shanghai metropolitan area. The main objectives of this study include: (1) to dynamically map and monitor land use/land cover change in Shanghai from 1979 to 2009; (2) to systematically analyze the spatial and temporal characteristics of urban expansion and LULC change in this period; and (3) to understand the effect of the main driving forces on LULC change.

Study area

The Shanghai metropolitan area, with its center located at 31.14°N 121.29°E, is situated at the junction of the Yangtze River and Chinese coastline on the border of the Jiangsu and Zhejiang provinces (Fig. 1). The total area of the Municipality of Shanghai is 7,037.5 km^2, of which 697 km^2 is water. Shanghai's land coastline extends 172 km along the East China Sea coast. Occupying part of the alluvial plain of the Yangtze River Delta, Shanghai lies generally on very flat and low-lying land, with the exception of some hills in its western regions. Altitude is on average about 4 m above Wusong Datum, decreasing from east to west. The city experiences a northern subtropical monsoon climate, with an annual rainfall of 1,122 mm and an annual average temperature of 15.8°C.

Shanghai has historically been one of the most important economic centers in China since the mid to late nineteenth century because of the rapid development of industry and trade. In the 1920s–1930s, Shanghai was well known as the largest financial center in the Far East (Shen 1994). Although urban development slowed due to war, adverse domestic policies and international factors during the 1930s–1970s, the city was still regarded as the largest commercial and industrial city in China (Li 2008). Fortunately, Shanghai has witnessed unprecedented urban development over the past 30 years, initiated by the government's "reform and opening-up policy" in 1978 and "opening Pudong new area to the world" in 1990. With such a fast-growing urban area, Shanghai has consequently experienced a tremendous transformation in land use from a rural to urban area, while the urban fringe has constantly advanced outward into the surrounding agricultural land. At present, the Shanghai metropolitan area consists of 17 districts and one county, with its population reaching 18.9 million and a density of 2,978 people per square kilometer in 2008 (Shanghai Municipal Statistics Bureau 2009).

Fig. 1 Location of the study area



Its annual GDP growth rate has remained consistently greater than 10% over recent decades. Making up 0.1% of the total land area of China, it supplies over 12% of national municipal revenue and handles more than a quarter of total trade passing through China's ports (Walcott and Pannell 2006). Shanghai has become one of the fastest growing economies and most densely populated cities both in China and the world.

Materials and methods

Data acquisition and preparation

Four cloud-free Landsat images were collected and used to evaluate land use/cover change and urban expansion in Shanghai between 1979 and 2009. These were: Landsat MSS of August 4, 1979 (WRS-1 path/row 127–38 and 127–39, downloaded from the Global Land Cover Facility, http://glcf.umiacs.umd.edu/); Landsat-5TM of December 4, 1990; Landsat-7 ETM+ of June 29, 2000; and Landsat-7 ETM+ of May 22, 2009 (WRS-2 path/row 118–38 and 118–39, downloaded from the International Scientific Data Service Platform, http://datamirror.csdb.cn/). Layer stacking and mosaic processing were carried out on the downloaded data using Erdas Imagine 8.7 software, to obtain Multi-band composite images. Rectified Landsat TM images of the same area from 2002 were used as a reference to perform geometric correction on the four images, using Erdas Imagine 8.7 and ArcGIS 9.2 software. Approximately, 65 ground control points (GCPs) were selected in order to register the images to the Universal Transverse Mercator coordinate system using a global positioning system. GCPs were dispersed throughout the images, to make sure the RMS error less than 1 pixel. The images were then resampled to 30 m pixels using the nearest neighbor method, while the first order polynomial fit was also used. Finally, by means of the GIS municipal boundaries layers, the administrative territory of Shanghai was extracted from the images using the 'Extract by Mask' function in the "Spatial Analyst Tools" module of ArcGIS 9.2 software.

Image classification and accuracy assessment

With respect to land cover classification, a system was designed in which areas were considered as belonging to one of five classes: urban/built-up areas (including industrial, residential, commercial and services, roads, transportation, and mixed urban and other urban), water (including rivers, creeks, ponds, and lakes), farmland (including orchard, crop fields, vegetable land, and fallow land), green land (including forest, shrub, lawns, mixed forest lands, and others), and bare land (including land to be built on, exposed soils, unused land, tidal flats, rock, sand, and beaches). According to the pre-determined classification scheme of the study area and image characteristics, four false true color images were produced by combining bands 5, 4, and 3 of the landsat TM/ETM+ images with a 321-band combination of the landsat MSS image. Thirty to fifty training sites, ranging in size from 342 to 6,210 pixels, were selected and used as areas of interest to train the images. The supervised classification was then employed to detect land cover types using a conventional maximum likelihood classification algorithm. Finally, a 4 × 4 majority filter was applied to the classified land covers to reduce the salt-and-pepper effect (Lillesand and Kiefer 1999).

A total of 256 stratified random samples were selected to check the accuracy of each classified map. Accuracy assessment of the LULC maps was then performed using aerial photographs and field data with the help of a global positioning system. The resulting overall classification accuracy was 87.11%, 89.45%, 93.36%, and 91.02% with Kappa values of 0.79, 0.83, 0.89, and 0.87, for the images from 1979, 1990, 2000, and 2009, respectively. These accuracy levels meet the standards recommended by Lucas et al. (1994).

Urban expansion and LULC change detection

In order to evaluate the spatial distribution of urban expansion intensity, an annual urban expansion intensity index (AUEII) was used as an indicator of the 'urbanization speed' of the study area. AUEII can be expressed as follows (Liu et al. 2000):

$$\text{AUEII} = \frac{U_{n+i} - U_i}{nT_{n+i}} \times 100\% \quad (1)$$

where T_{n+i} is the total area of the target unit at time $n + i$; U_{n+i} and U_i the urbanized or built-up area within the target unit at time $n + i$ and i, respectively, and n the interval of the calculating period (in years).

The post-classification change detection technique and spatial analysis methods (concentric circle and sector analysis) were used to analyze the spatio-temporal dynamics of the processes and patterns in urban growth and LULC. The post-classification method was employed to identify conversions from a particular land cover class to other land use categories and their corresponding areas at different times. Although this method has some limitations (Singh 1989; Coppin et al. 2004), it is still one of most commonly used approaches (Fan et al. 2008; Mundia and Aniya 2006) with which to compare data of different sources and dates (Dewan and Yamaguchi 2009a, b). The process involved carrying out an overlay procedure using the GIS in order to measure spatial changes in LULC, with a series of "from-to" matrices produced by comparing layers on a pixel by pixel basis.

The concentric circle and sector analysis methods are effective for characterizing the quantity and spatial distribution of various types of land use in terms of distance and orientation with respect to a pre-determined urban center (Xu et al. 2007)—in this case The People's Square, the origin of Shanghai's regional coordinate systems. A total of 37 concentric zones (i.e., circular buffers) with a width of 2 km and 16 sectors (i.e., fan-shaped areas) with an angle of 22.5° were created to measure distance and orientation, respectively. Using the GIS to overlay these concentric zones and fan-shaped sectors with land use data, a superposition was acquired, making it possible to calculate the total area of each category of land use within each concentric zone and sector. These calculated values can then be displayed on corresponding growth curves and radar-graphs to show the distance/orientation characteristics of different categories of land use in the city.

Results and discussion

The land use and land cover maps of Shanghai metropolitan area for 1979, 1990, 2000, and 2009 are shown in Fig. 2. The total area of every land use category and percentage of each class in the total study region area between 1979 and 2009 were calculated and are presented in Table 1. According to the results obtained from the four classified images, the total area of Shanghai has increased slowly due to shoreline change caused by various coastal processes (i.e., sediment accumulation, erosion) and human intervention (Li et al. 2009; Yu et al. 2000). In terms of land use classes, over the past 30 years urban areas have increased by approximately 2,713 km^2 at an average rate of 90.43 km^2/year, water bodies have increased by 358 km^2 at an average rate of 11.93 km^2/year, bare land has increased by 248 km^2 at an average rate of 8.27 km^2/year, while farmland has decreased by 2,535 km^2 at an average rate of 84.5 km^2/year and green land has declined by 206 km^2 at an average rate of 6.87 km^2/year. The results of this study therefore resemble observations made by Li et al. (2003) and Zhang (2006).

Analysis of LULC change reveals that urban areas have increased by about 1,064% from 1979 to 2009, while the respective increase in bare land was around 126%. The area occupied by water bodies has increased by 243% due to the development of aquaculture from 1979 to 2000 and the construction of large reservoirs and other artificial water conservancy projects in coastal areas between 2000 and 2009. Conversely, farmland and green land exhibit a significant decline with respective rates of decrease of 47.7% and 48.7% over the same period. Figure 3 illustrates the trends of land use/cover change in Shanghai during the transitional economy. Urban areas experienced the largest changes in land use/cover from 1979 to 2000, while farmland experienced most change in 2009.

AUEII values were calculated as 0.80% for 1979–1990, 1.03% for 1990–2000, and 2.27% for

Fig. 2 Land use and land cover maps of Shanghai metropolitan area for 1979, 1990, 2000, and 2009

Table 1 Land use/cover classification statistics from 1979 to 2009 (area in km^2)

Land use types	1979		1990		2000		2009	
	Area	%	Area	%	Area	%	Area	%
Bare land	197.47	3.06	244.49	3.74	250.70	3.72	445.42	6.34
Water bodies	147.21	2.28	221.73	3.39	247.62	3.67	505.35	7.19
Green land	422.99	6.56	255.59	3.91	243.65	3.61	217.18	3.09
Urban areas	254.92	3.95	832.46	12.73	1,529.43	22.69	2,968.01	42.22
Farmland	5,429.47	84.15	4,984.03	76.23	4,469.03	66.30	2,894.47	41.17
Total area	6,452.06	100	6,538.30	100	6,740.44	100	7,030.43	100

2000–2009, suggesting that acceleration of urbanization is mainly attributable to policy changes. During the initial growth stage (1979–1990), "the reform and opening-up policy" removed restrictions on urban development (especially the development of megacities) and restarted the process of rapid urbanization in Shanghai. The second stage (1990–2000) was influenced by the strategy of "opening Pudong new area to the world" and land policy reform, in particular the adoption of the land-leasing system in 1988. At the same time, the first round of large-scale urban renewal began as a result of a policy shift from developing "production cities", to one based an ideology of developing liveable cities that provided residents with a high quality of life (Xu et al. 2007). Most factories have since been relocated to the suburbs. Since 2000, in order to achieve the development goal of building an international economic, financial, trade, and shipping center, the process of urban–rural integration (the second round of large-scale urban renewal) was accelerated with the large-scale construction of satellite towns, industrial zones, and functional areas around the city center and along coastal areas. The entire Shanghai metropolitan area was also unified via perfect traffic systems (such as highways and bridges). Population growth was another important cause of rapid urbanization. The population of Shanghai was 11.4 million in 1979, but had increased to 18.9 million by 2008 due to a combination of large-scale rural–urban migration and natural increase. To accommodate this increasing population and effectively provide the necessary services and management facilities, large areas of land were taken over for public infrastructure, housing, industrial, and commercial uses. Additionally, industrial upgrading and foreign investment were other underlying driving forces of LULC change and urban expansion in Shanghai.

The change matrix based on the post-classification method for the periods of 1979 to 1990, 1990 to 2000, and 2000 to 2009 were obtained, with a summary of the major LULC

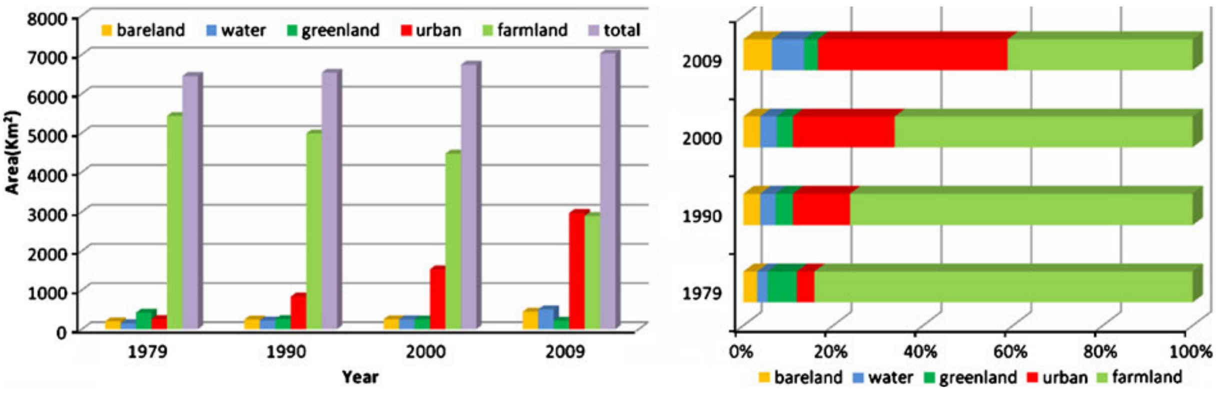


Fig. 3 Total area and percentages of every land use category between 1979 and 2009

Table 2 Major land use/cover conversions from 1979 to 2009 (area in km^2)

'From class'	'To class'	1979–1990		1990–2000		2000–2009	
		Area	%	Area	%	Area	%
Water bodies	Farmland	12.30	8.36	32.34	14.59	35.85	14.48
	Urban areas	13.87	9.42	38.58	17.40	32.82	13.25
Farmland	Green land	167.01	3.08	165.99	3.33	119.34	2.67
	Urban areas	494.88	9.11	738.44	14.82	1,513.20	33.86
	Bare land	185.19	3.41	98.05	1.97	289.79	6.48
Green land	Farmland	324.91	76.81	92.16	36.06	116.29	47.73
	Urban areas	30.62	7.24	79.20	30.99	75.41	30.95
Bare land	Farmland	78.27	39.64	152.93	62.55	81.98	32.70
	Urban areas	69.91	35.40	44.80	18.32	94.89	37.85

conversions shown in Table 2. This calculation indicated that the majority of urban land was acquired by converting areas that were previously farmland, green land, water bodies, or bare land. Transitions also took place from farmland to bare land due to rapid development. In addition, large areas of green land were used for farmland, especially from 1979–1990 in order to meet the growing needs of agricultural development and food supply. However, because of the transforming effect of urban greening and the construction of large-scale artificial forests, a significant positive change was also observed, with some farmland transformed back to green land.

GIS-based spatial analysis also revealed patterns of LULC change in different periods. The distance characteristics of land use classes are presented in Fig. 4. As can be seen from this figure, there is no obvious change in area of water from 1979 to 2000. However, two peak values are visible, with rapid areal expansion in regions approximately 26 to 34 km and 46 to 62 km away from the center from 2000 to 2009 representing the construction of coastal engineering projects. Green land increased rapidly from 1979 to 1990 in areas located 6–16 km from the center, representing rapid development of greening in suburban areas. In contrast, a decline in green land area was observed between 18 and 52 km from the center after 1979. The bare land curve of 1979 was much higher than for other years in terms of the initial 12 km from the center. Bare land in areas 36–60 km from the center increased rapidly from 1979 to 2009, indicating that whereas only a small proportion of bare land growth occurred in the periphery of urban areas, most was present along the coast and in remote islands. It can be clearly seen that the area of farmland within 50 km of the center decreased gradually from 1979 to 2000. The pace of this decline rose quickly between 2000 and 2009, now including areas within 62 km of the center. In contrast, the curves of urban/built-up areas rose dramatically for all years, with outward moving peak values indicating a rapid urban expansion over the past 30 years. Moreover, the magnitude of this increase was amplified between 2000 and 2009, especially in zones located 12 to 62 km from the center, reflecting the simultaneous acceleration of urbanization and suburbanization during this period.

As discussed earlier, results obtained via the sector analysis method can be used to draw radar-graphs illustrating the spatial orientation of LULC change (Fig. 5). The earlier direction of urban/built-up area expansion from 1979 to 1990 was largely on a north–south axis.

However, from 1990 to 2009, the trend shows expansion in all directions along major traffic routes between the city center and the surrounding towns, specifically to the east, southeast, and southwest after 2000. Historically, the direction of urban sprawl in Shanghai has been greatly governed by city planning, with the urbanized area indeed expanding along the east–west axis defined in the General Plan of Shanghai metroregion (1986). Furthermore, on the basis of the 'multi-core and multi-axis' development strategy suggested by the 'Shanghai Master Plan 1999–2020', both the central urban area and the surrounding towns have increased in extent dramatically. In terms of farmland, there is a slight decrease in all directions between 1979 and 2000,

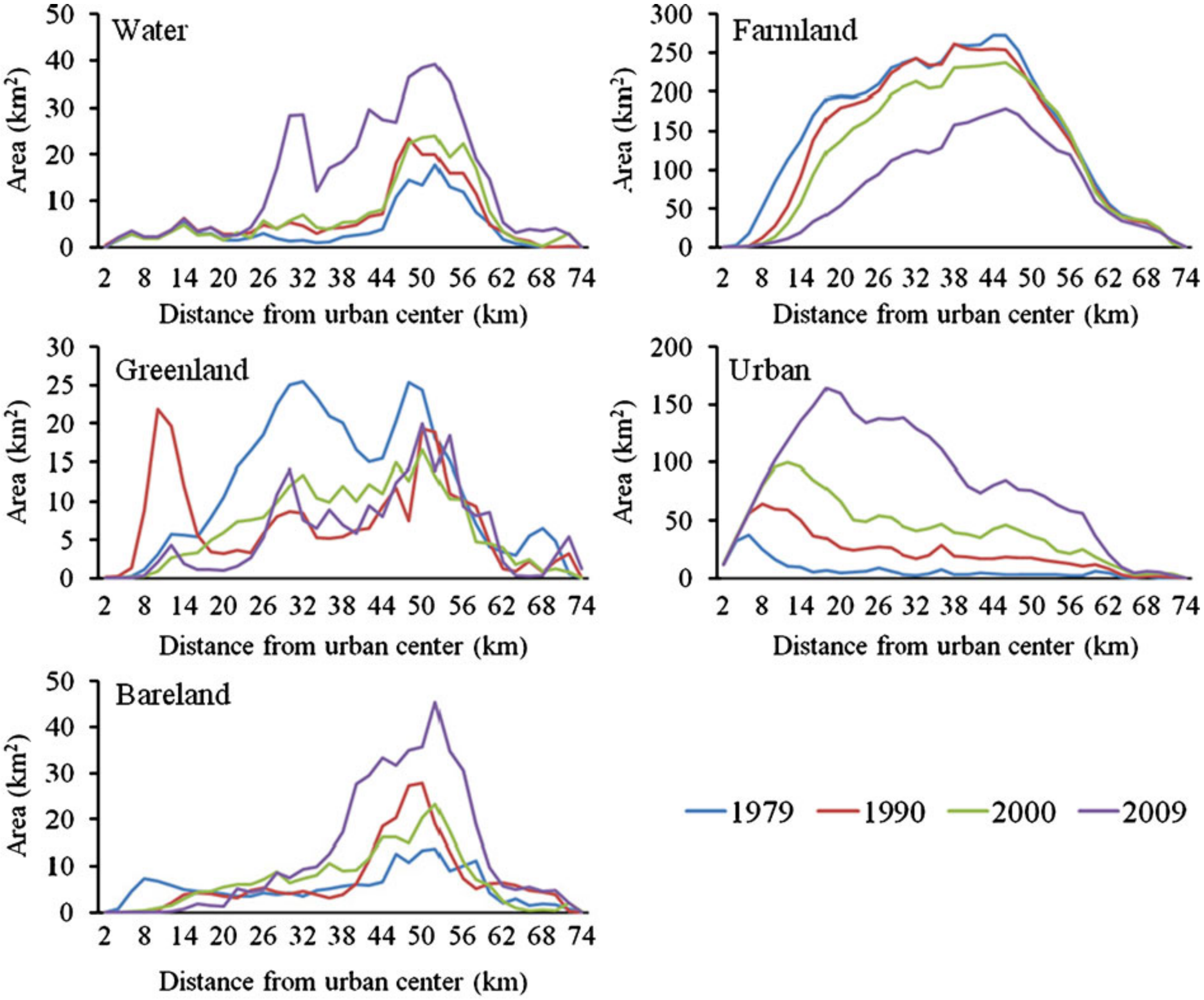
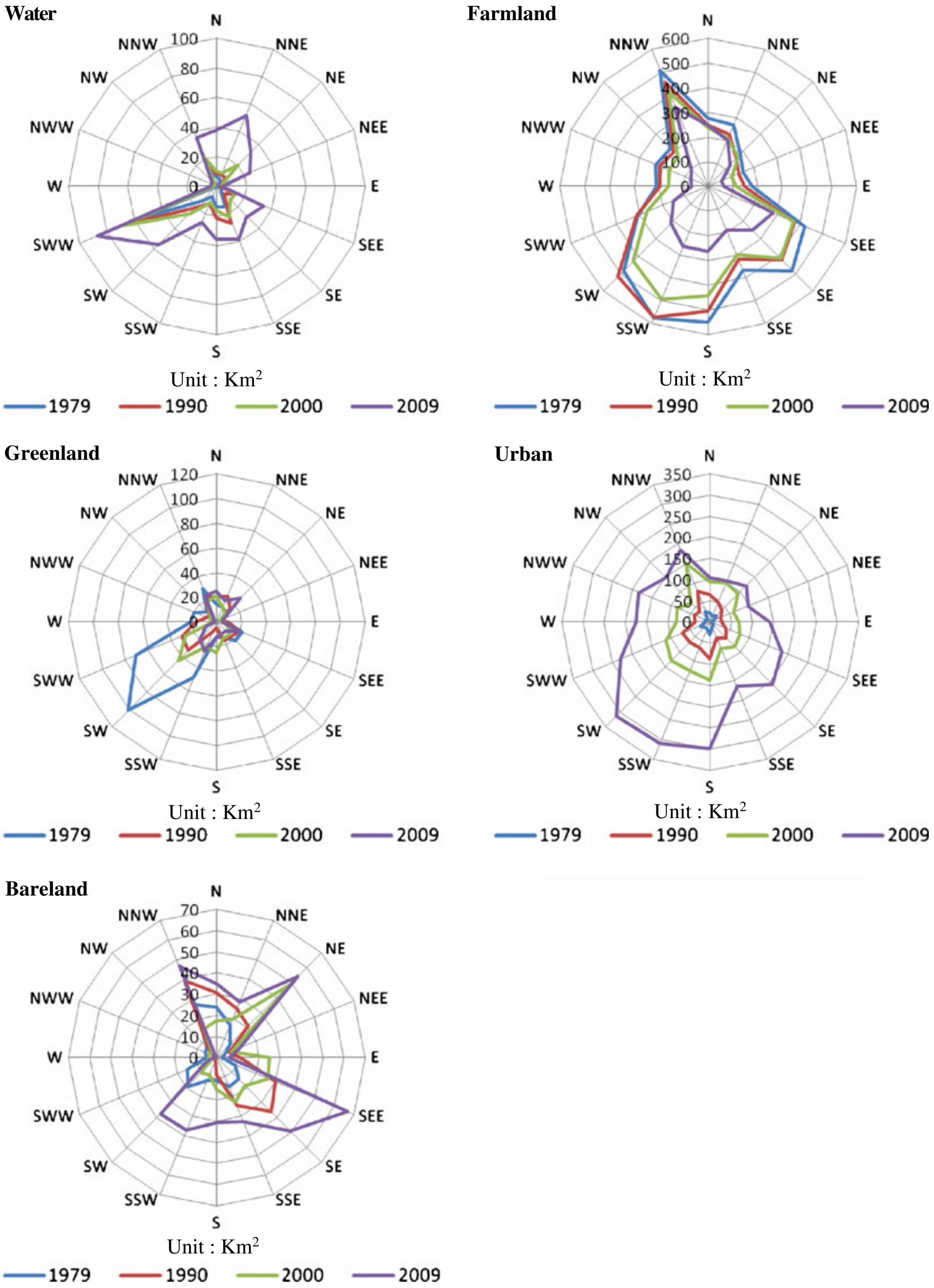


Fig. 4 Variation in area of each class of land use by distance from urban center, 1979–2009

but a rapid disappearance from 2000 to 2009 in the northwest, west, southwest, south, and southeast directions. Between 2000 and 2009, water body expansion in Shanghai showed a clear orientation toward the southwest and northeast. The major directions of bare land expansion were to the northwest, northeast, southeast, and southwest. A significant decrease in green land was particularly observed to the southwest between 1979 and 1990.

Dramatic urban expansion and subsequent LULC change has evidently led to a wide range of eco-environmental problems in Shanghai. For instance, the heating effect resulting from impervious surfaces has increased in proportion with the rapid expansion of built-up areas and reduction of farmland and green land (Li et al. 2009). Urban development has also been shown to have a negative impact on natural habitats and biodiversity. According to Wang et al. (2008a, b), 178 natural seed plants have disappeared from western Shanghai since the 1950s. Consequently, the local ecosystem's service value has decreased (Cheng et al. 2009) while the associated ecological deficit has increased (Liang and Wang 2002), implying an unsustainable development of Shanghai. Over-exploitation of groundwater, construction of high-rise buildings, and municipal engineering has resulted in rapid land subsidence in Shanghai (Wu et al. 2008; Gong et al. 2008). Urbanization may also be responsible for the majority of the increase



Water

Farmland

Greenland

Urban

Bareland

Fig. 5 Spatial orientation of each type of land use, 1979–2009 in surface runoff, thus making the city more vulnerable to flooding (Li 2008). In addition, many studies have shown a close relationship between environmental pollution (soil, water, and air) and urban development (Wang et al. 2008a, b; Xie et al. 2009; Yin and Xu 2007).

Conclusion

This study adopted a combined methodology of multi-temporal remote sensing image interpretation and GIS spatial analysis to quantitatively characterize the dynamics of urban expansion and land use/land cover change in Shanghai metropolitan area during the transitional economy period (1979–2009). The results of the study have indicated that Shanghai has experienced rapid changes in LULC, particularly in terms of urban/built-up area. Over the past 30 years, urban/built-up areas have increased by 2,713 km^2, about 11 times the urban area in 1979, resulting in a substantial reduction in the area of farmland and green land. Urbanization has accelerated at an unprecedented scale and rate. Comparative analysis of AUEII during the 1979–1990, 1990–2000, and 2000–2009 periods revealed that urban expansion in Shanghai was relatively minor before 1990, but became increasingly significant from 1990 to 2000 and dramatic after 2000. Spatially, the leading direction of urban expansion before 1990 was on a north–south axis. From 1990 to 2009, however, Shanghai metropolitan area's urban sprawl spread in all directions, both from existing urban areas and along major transport routes, a pattern identical to that seen in other large cities in Asia, such as Tokyo and Beijing (Liu et al. 2000; Sorensen 2000; Xiao et al. 2006). Urban expansion and subsequent LULC change in Shanghai appears to have been largely driven by policy reform, population growth, and economic development, causing extensive and varied eco-environmental degradation.

To alleviate the negative impacts of urban expansion, policy makers, urban planners, and stake-holders should consider appropriate adaptation options, based on past and present land cover changes. They should also work together to effectively implement and sequence appropriate policy, planning, and management choices for sustainable development, before such problems become irreversible. Above all, the current developmental ideology of 'economic development first' should be adjusted to one of 'sustainability first'. Urban expansion on or near water bodies, wetlands, vegetation, and eco-environmentally sensitive areas should be restrained. Engineering measures must be initiated to repair degraded areas, including: urban afforestation, pollution control, urban renewal, and others. Small-scale illegal encroachments should be prevented. Furthermore, regional and local management policy and planning regulations of different government agencies need to be enforced, with effective coordination by a single nodal agency.

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