Front. Earth Sci. 2016, 10(3): 527–545
DOI 10.1007/s11707-015-0531-6

RESEARCH ARTICLE

Exploring coupling coordination between urbanization and ecosystem quality (1985–2010): a case study from Lianyungang City, China

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Abstract Urbanization processes affect the ecosystem through alterations in ecological functions and landscape patterns. Currently, analysis of the total ecosystem services value (ESV) has targeted the overall benefits which human beings obtain from the regional ecosystem but does not generally include information regarding ecological structures and patterns. Therefore, the results cannot reflect the comprehensive state of the local ecosystem. We propose a new, integrative ecosystem quality indicator based on the ESV and landscape metrics for evaluating the quality of the regional ecosystem. We adopted the method of a coupled degree of coordination for evaluating the interrelationship between urbanization and ecosystem quality in Lianyungang City from 1985 to 2010. The coupling degree of coordination between urbanization and ecosystem quality showed an inverse U-shaped curve. At the primary stage of urbanization (1985−1995), the degree of coupling of urbanization and the ecosystem was just barely balanced. From 1995 until 2000, the coupling system reached a balanced condition, in which the urbanization level increased. Since 2000, the urbanization process has accelerated. The coordination between urbanization and the ecosystem achieved the optimum condition in 2005. A turning point appeared at the same time, and the degree of coupling coordination began falling from the optimum. Subsequently, the coupled system once more entered a barely balanced state. Overall, the comprehensive level of ecosystem quality decreased since 1985 and degraded sharply after 2005, suggesting an overall degradation of the local ecosystem quality.

Received December 16, 2014; accepted April 21, 2015

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Keywords urbanization, ecosystem services value, land use change, landscape metrics, ecosystem quality

1 Introduction

China has taken significant steps toward increasing urbanization in the last 20 years, particularly in the eastern area, and this trend should continue over the next two decades (Li et al., 2011; Gong et al., 2013b). It has been estimated that almost all of the world’s population growth between 2000 and 2030 will be concentrated in urban areas in developing countries (United Nations, 2005). Among developing countries, China shows one of the highest rates of urbanization. In the past two decades, “increasing economic liberalism, integration into the global economy and the policies designed to support these economic goals have favored rapid urbanization and economic growth, particularly in the coastal regions, and have become the dominant trends” (McGranahan and Tacoli, 2006).

Ecosystems are prone to disturbances and shifts typically resulting from anthropogenic drivers. New towns are springing up in many rural areas, and existing cities are booming. Much of this growth, however, has been uncontrolled and poorly planned. Such a marked transformation has resulted in a series of devastating consequences for the environment and the ecosystem. The degradation of the ecosystem is related to the rapid urbanization process (Li et al., 2010a, b; Gong et al., 2013a, b). In planning for sustainable development, the entire regional human-dominated system must depend on the natural ecosystem services (Sohngen and Borwm, 2006; Burkhard et al., 2010; de Groot et al., 2010). Ecosystem services signify the benefits that human-beings derive from ecosystems (Costanza et al., 1997b; Daily, 1997). Researchers have also explored ecosystem service valuations that define the ecosystem services as goods that contribute to human welfare and are provided directly and indirectly by ecosystems (Costanza et al., 1997a, b; Sherrouse et al., 2011; Bastian et al., 2012; Scolozzi et al., 2012). Ecosystem services and the ecosystem services value (ESV) approach provide a direct approach for evaluating the importance and health of the ecosystem and create a bridge between the socio-system and the ecosystem. The total ESV of a region can depict the ecosystem service capacity provided by the local ecosystem and can be considered as a proxy to show the general quality of the ecosystem in study area.

Ecosystem function is based on the ecosystem's structure and processes. Ecology-based landscape metrics are capable of quantitatively describing the landscape structure, which is a prerequisite for the analysis of the landscape function and process (McGarigal and Marks, 1995). Landscape metrics can characterize the spatial structure of a landscape at a set point in time and establish a relationship between the landscape structure and functions. Human activities, such as agriculture production, urban development, and other activities resulted in land use changes and are the main causes of habitat fragmentation and landscape heterogeneity (McGarigal, 1998). Some landscape metrics, such as dominance, fractal dimension, and contagion are recommended as indicators of landscape stability, biodiversity, resilience, and diversity in the USA and Europe.

In absolute terms, the long-term preservation of multi-ecosystem services should be the top priority. The design, implementation, and management of policies to deliver plans that incorporate biodiversity conservation and the multiple services provided by ecosystems are dependent on the availability of the explicit temporal and spatial information describing the socio-ecosystem. However, modeling the complex coupled socio-ecosystem is one of the main challenges facing ecological and trans-disciplinary researchers (Walker et al., 2006). It requires an interdisciplinary integration of ecological, social, and economic aspects with the appropriate simulation model, and implies a series of demands for data (Wallace, 2007). The ecosystem service value and the landscape ecological concepts provide an attainable and suitable way to characterize the complicated socio-ecosystem in a systematic and integrative manner. Therefore, we adopted several landscape metrics as part of our indices and integrated the metrics with ESV to evaluate the overall quality of the ecosystem in the study area. Policy decisions also need to be based on reliable estimates of the current state of the ecosystem quality1) and the level of social development, particularly when taking ecosystem conservation into consideration. Therefore, there is a dire need to solve the problems faced by cities using trans-disciplinary methods as cities are the systems upon which the future of humanity depends.

The entropy analyzing theory could eliminate subjected interference, especially for a complex system. At the same time, maintaining the coordination between urban development and the ecosystem is a decisive key to the sustainable development of developing countries. The coupled model, derived from physics theory, was used to depict the complicated interrelationship between two or more systems. The non-linear relationship between urbanization and the environment could be reflected by the coupled model (Huang and Fang, 2003; Liu and Song, 2005; Qiao and Fang, 2005). The coupling coordination analysis also crystallizes the interaction in a coupled socio-ecosystem, highlighting the negative influence that land-use changes in metropolitan areas can have on environmental problems or the ecosystem (Liu et al., 2005; Song and Liu, 2006; Liu et al., 2007; Xue and Zhang, 2009). Numerous studies were conducted in China due to its unique urbanization process, as judged by its breadth or influences (Friedmann, 2006; Normile, 2008; Hu et al., 2013), but the majority of the research is based on statistical data. Considering the ecosystem's heterogeneity and regional geographic disparities, a further coupling coordination analysis between urbanization and the ecosystem that considers the ecosystem, and in which spatial information is included, remains to be performed.

Lianyungang City borders the Yellow Sea in the east and is located in the northeast of Jiangsu Province and at the extreme northern edge of the Yangtze River Delta. The city is at the junction of China's coastal economic belt and the Longhai-Lanxin economic belt. In 1984, Lianyungang City became one of the fourteen coastal cities in which the Opening Up Policy was first implemented. In addition, Lianyungang is the bridgehead in the east of the New Eurasian Land Bridge, which starts at Lianyungang and reaches west to Rotterdam port in the Netherlands. Based on these remarkable characteristics, Lianyungang is experiencing an accelerated urbanization process. The striking transformation happening in the economic, social, and ecological environments provided an excellent laboratory in which to perform our research.

This paper empirically studied the coupling degree of coordination between urbanization and ecosystem quality; meanwhile the evolution of urbanization and the overall ecosystem quality was examined in Lianyungang City. The conceptual framework for the coupled degree of coordination analysis was shown as Fig. 1. The overall objective of this study was to answer the following two questions: 1) how did the ecosystem change in the context of the rapid urbanization process in the long term; and 2) did the urban development coordinate well with the local ecosystem in the urbanization process. This study provides a more

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1) In this study, ecosystem quality refers to the status of natural ecosystem, artificial and semi artificial ecosystem.

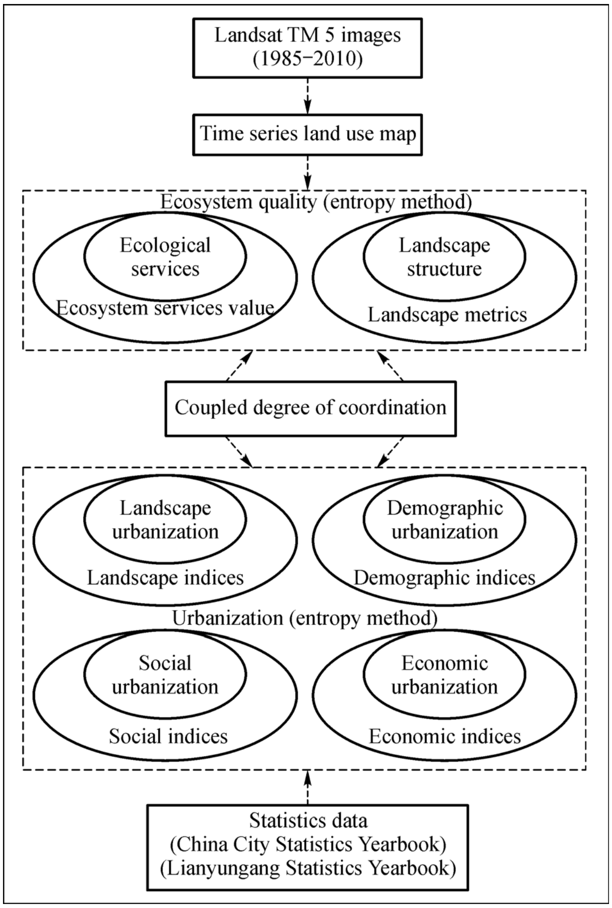

Fig. 1 Conceptual framework for the coupled degree of coordination analysis.

nuanced and comprehensive understanding of the close linkages between social and ecological systems. This study also reflects the increasing awareness for safeguarding ecosystem function and structure and the prerequisites for sustaining a balance between urban development and the local ecosystem over the long term for humans.

2 Study area and methodology

2.1 Study area

Lianyungang was called Yingzhou in ancient times, Quxian in the Qin Dynasty, and Haizhou during the Tang Dynasty. It has a long history and rich cultural heritage and is well known as "the giant city upon the Huaihe River Estuary" and "the famous prefecture of the East Sea." Located on the shores of the Yellow Sea (Fig. 2), midway along the coast in northeast Jiangsu Province, Lianyungang faces Japan and Korea across the sea to the east. It extends from 33°59′ to 35°07′N in latitude, and from 118°4′ to 119°48′E in longitude. Lianyungang is situated in a transitional climate zone between a warm and wet zone and a subtropical zone, has an average annual temperature of 14°C, an average annual rainfall of 930 millimeters, and 220 days without frost every year.

Lianyungang Port is the transportation hub of Jiangsu Province and China (Li et al., 2010a, b). It is situated at a juncture between land and sea and between south and north. It constitutes the T-shaped intersection of two development structures: the coastal industrial zone and the belt along East Longhai, which is also well known as the eastern bridgehead of the New Eurasian Land Bridge. It has become the backbone of economic development in northern Jiangsu and the "two-first" strategy of Jiangsu. Inevitably, this acceleration of coastal urbanization and industrialization will lead to a vast increase in demand for land, competition for space, and environmental changes. According to the Environmental Quality Report of Lianyungang (1995, 2000, 2010; Lianyungang Environmental Monitoring Center), the total area of natural wetland decreased radically, and a reduction of lake area of no fewer than 10,000 hectares was witnessed in the years from 1985 to 2010. A total of 705.4 square kilometers was subjected to soil erosion due to deforestation and the reduction of tidal land in the past two decades. The six major rivers and four reservoirs have been suffering from eutrophication since the 1990s. Serious

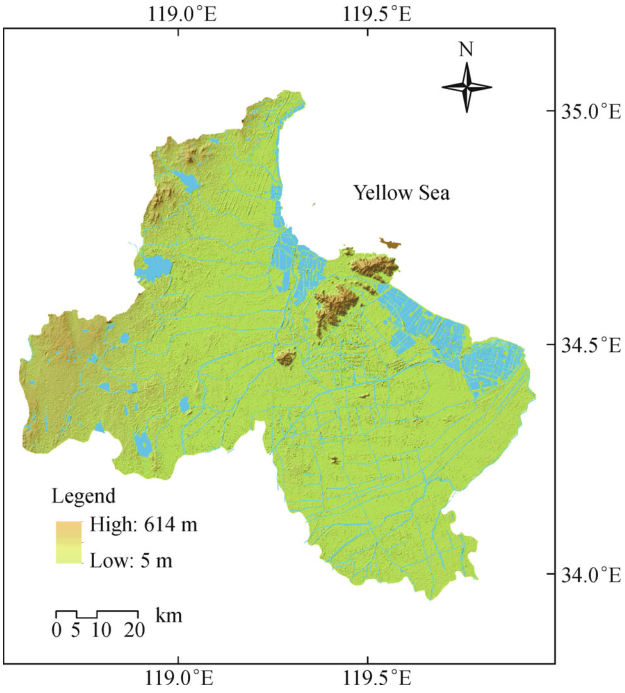

Fig. 2 Location of the study area in Jiangsu Province, China.

contamination of fresh water and inland coastal water has caused a drastic decline in biodiversity. The number of fish species noticeably declined from 105 in 1985 to 56 in 2005.

2.2 Methodology

2.2.1 Data resources

Land use data for the years 1985, 1995, 2000, 2005, 2008, and 2010 were obtained from the National R&D Infrastructure and Facility Development Program of China: Data Sharing Infrastructure of Earth System Science—Data Sharing Centre of the Yangtze River Delta (http://nnu.geodata.cn). The municipal boundaries were obtained from the National Geomatics Centre of China (http://nfgis.nsdi.gov.cn).

2.2.2 Data pre-processing

The relative social and economic statistic data (1986–2011) were acquired from the Statistical Yearbook of Lianyungang City (Lianyungang Municipal Bureau of Statistics, 1986–2011), and the others from China City Statistical Yearbook (National Bureau of Statistics of the People's Republic of China, 1986–2011). All data were normalized by means of Standardization of Data Range shown as Eq. (1) and Eq. (2) to exclude the influence of dimension, magnitude, and positive and negative orientation.

$$X'_{ij} = (X_{ij} - \min\{X_j\})/(\max\{X_j\} - \min\{X_j\}), \tag{1}$$

$$X'_{ij} = (\max\{X_j\} - X_{ij})/(\max\{X_j\} - \min\{X_j\}), \tag{2}$$

where X_{ij} means the value of indicator j in year i, and max $\{X_j\}$ and min$\{X_j\}$ represents the maximum and minimum value of indicator j in all years.

2.2.3 Quantification of ecosystem services value and landscape metrics

1) Land-use map

Land use and land cover data serve as common resources since they are often used for climate modeling, biodiversity monitoring, and urban expansion simulations. Land cover information documents the physical land type of a region, (forest, wetlands, city, and other land types), whereas land use is commonly defined as a series of operations on land with the intention to obtain products and/or benefits through using land resources.

In the study, Landsat 5 Thematic Mapper remote sensing images (acquired in April 8, 1985, April 20, 1995, May 19, 2000, May 9, 2005, May 1, 2008, and August 10, 2010) were used to produce the land use map. The World Reference System (WRS) number of the image utilized is 120/36. The TM images were rectified using a 1: 50,000 topographic map provided by the Lianyungang Environmental Protection Bureau. Image processing techniques followed the man-machine interactive interpreting method by ArcGIS software. The main procedures include geometric correction and human-machine interactive classification. The images of each county were rectified to the WGS_1984 datum and Albers conical equal area projection coordinated system with the central meridian 110°E, original latitude 0°N. The root mean square error was less than one pixel. Different land use types were then categorized by using human-machine interactive classification. This study employed eleven categories of land use type: cropland, forest, shrub, orchard, grassland, water body, tidal land, urban, rural, industrial land, and bare land. The nearest-neighbor algorithm was used to resample all the images to a spatial resolution of 30 m. The classification accuracy was evaluated using the field investigation and high precision multi-temporal remote sensing images obtained from 2000 to 2010 in Google Earth and TIANDITU (http://www.tianditu.cn/map/index.html); the overall classification accuracy was not less than 90% for each land use type.

2) ESV calculation

Ecosystems provide various services that are essential to human well-being, and these services can be quantified by monetary valuation methods (Costanza et al., 1997b; Costanza et al., 2014). The ESV per unit area for each land use type are shown in Table 1 and referenced the values suggested by Costanza et al. (1997b), Xie et al. (2003), Wu et al. (2013) and Costanza et al. (2014). The value was then assigned to the corresponding land use category in each land use map across the different years. The total ESV across the different years in the study area was calculated as follows:

$$\mathrm{ESV} = \sum_{i=1}^{m} \sum_{j=1}^{n} A_i \times VC_{ij}, \tag{3}$$

where A_i is the area (ha) of land use type i and VC_{ij} represents the value coefficient of ecosystem service type j (CNY/ha) assigned to land use type i. The estimated ESV in 2000 was set as the baseline and the ESV for each year was estimated according to the value coefficient in 2000. Consequently, the temporal analysis of all the ESVs could be achieved.

3) Quantification of landscape metrics

A large collection of landscape metrics has been developed in recent years. The abilities of landscape metrics to signify an ecological process have been discussed in numerous reports (e.g., Ribeiro and Lovett, 2009; Su et al., 2011). The landscape metrics at the class and landscape level were selected as partial indicators of the ecosystem structure and process. The landscape metric selection was based on the following criteria (Su et al., 2012): 1) compared with previous landscape ecological studies (Botequilha and Ahern, 2002; Kromroy et al., 2007; Weng, 2007; Solon, 2009; Pôças et al., 2011; Su et al., 2011); 2) capable of revealing ecological conditions (Ribeiro and Lovett, 2009; Su et al., 2011); 3) low redundancy among landscape metrics (Botequilha & Ahern, 2002); and 4) capability to crystallize the characteristics of landscape patterns for the featured land use category (natural capital) and the whole study area. The selected class-level metrics in the natural capital category included the total core area (TCA), core area percentage of landscape (CPLAND), number of disjunct core area (NDCA), shape index (SHAPE_MN), effective mesh size (MESH), and contiguity index (CONTIG_MN). The selected landscape-level metrics included the total edge contrast index (TECI), similarity index (SIMI_MN), effective mesh size (MESH), splitting index (SPLIT), contagion index (CONTAG), and Shannon's evenness index (SHEI). All of the landscape metrics were calculated by Fragstats 4.1 (McGarigal and Marks, 1995).

2.2.4 Indices and method for evaluating urbanization and ecosystem quality

As a complex social and economic phenomenon, the urbanization process is taking place in developing countries at an unprecedented rate, especially in China, with no sign of slowing. It consists of multi-dimensional

Table 1 Annual average ESV per unit area for different land use types (CNY/ha)

ES type	Cropland	Forest	Shrub	Orchard	Grassland	Water body	Tidal land	Urban	Rural	Industrial land	Bare land
Gas regulation	442.4	3097.0	1769.7	1769.7	707.9	0	0	0	0	0	0
Climate regulation	787.5	2389.1	1588.3	1588.3	796.4	407.0	203.5	0	0	0	0
Water supply	530.9	2831.5	1681.2	1681.2	707.9	18033.2	9029.9	0	0	0	0
Soil protection	1291.9	3450.9	2371.4	2371.4	1725.5	8.8	13.3	0	0	0	0
Waste purification	1451.2	1159.2	1287.2	1287.2	1159.2	16086.6	8047.7	0	0	0	0
Biodiversity protection	628.2	2884.6	1756.4	1756.4	964.5	2203.3	1252.1	0	0	0	0
Food production	884.9	88.5	177.0	177.0	255.5	88.5	48.7	0	0	0	0
Raw material	88.5	2300.6	1194.6	1194.6	44.2	8.8	4.4	0	0	0	0
Recreation and culture	8.8	1132.6	570.7	570.7	35.4	3840.2	1924.5	153.6	0	0	0
Sum	6114.3	19334.0	12396.5	12396.5	6406.5	40676.4	20523.9	153.6	0	0	0

attributes, including population immigration, economic development, space expansion, and societal development. As stated previously, the study area has witnessed a dramatic change in economic structure, percentage of urban population, social development, and landscape structure. Therefore, the urbanization process of our study area could be measured in four aspects; namely landscape, demographic, economic, and social (Bao and Fang, 2007; Chen et al., 2009). According to the investigation of the study area, the credibility of data sources, and the representativeness of the indices, a total of 25 indicators were chosen from numerous indices (Table 2). Usually Gross Domestic Production (GDP), GDP Density, Per Capita GDP, Percentage of GDP of the Added Value of Secondary and Tertiary Industries, Total Investment in Fixed Assets, and Local Financial Revenue were used to depict the economic performance of a city (Xuan et al., 2005; Li et al., 2012). Population Density, Urban Population Density, Percentage of Nonagricultural Population, Total Population, Proportion of Population Engaged in Secondary and Tertiary Industry, and Rate of Urban Population Growth were employed to represent population shift and composition of a city (Shen and Zhang, 2006; Zheng et al., 2007). Likewise, seven indices in landscape aspects and six indices in social aspects were also selected (Ou et al., 2008; Chen et al., 2009).

The level of urbanization was quantified by the entropy method (Chen et al., 2009; Li et al., 2012). The weight of each indicator was computed according to information entropy and variations in the indicators. The calculation procedures used were as follows (Eqs. (4)–(9)):

Proportion of indicator j in year i:

$$Y_{ij} = X_{ij} / \sum_{i=1}^{m} X'_{ij}. \tag{4}$$

Information entropy of the indicator:

$$e_j = -\frac{1}{\ln m} \sum\nolimits_{i=1}^{m} (Y_{ij} \times \ln Y_{ij}). \tag{5}$$

Entropy redundancy:

$$d_j = 1 - e_j. \tag{6}$$

Weight of the indicator:

$$w_j = d_j / \sum\nolimits_{j=1}^{n} d_j. \tag{7}$$

Evaluation of a single indicator:

$$S_{ij} = w_j \times X'_{ij}\ . \tag{8}$$

Comprehensive level in year i:

$$S_i = \sum\nolimits_{j=1}^{n} S'_{ij}\ , \tag{9}$$

where n is the number of indicators, and m is the number of years.

The original data (1985–2010) describing the 25 urbanization indicators of Lianyungang City were processed using these steps over the same time scale (Eqs. (4)–(9)).

In order to test the applicability of the entropy assessing method and avoid misleading conclusions, a principle component analysis (PCA) was also executed, and the sub-system and comprehensive urbanization level in the years from 1985 to 2010 were obtained according to the results of the PCA analysis. The PCA analysis results are shown in Table S1, Table S2, and Fig. S1. Quite similar results are presented in Fig. 5 and Fig. S1. Therefore, the entropy analysis method was performed throughout the entire study.

2.2.5 Coupling degree between urbanization and ecosystem quality

The coupling degree of coordination was determined using Eq. (10).

$$C = \left\{ \frac{f(X) \cdot g(Y)}{\left[\frac{f(X) + g(Y)}{2} \right]^2} \right\}^k, \ D = \sqrt{C \cdot T}, \text{ and}$$

$$T = \alpha f(X) + \beta g(Y), \tag{10}$$

where C is the degree of coupling, k is the regulation factor ($k \geqslant 2$), $f(X)$ is the level of urbanization sub-system, and $g(Y)$ is the ecosystem sub-system quality. In different cases, the sum of $f(X)$ and $g(Y)$ is constant and C represents the degree of coupling between urbanization and the ecosystem. In Eq. (10), $f(X)$ and $g(Y)$ can be derived from Eq. (1) to (9), D is the degree of coupling coordination, and T reflects the overall coordinating level of urbanization and the ecosystem (Chen et al., 2009; Li et al., 2012). The variables α and β depict the contribution of the urbanization and ecosystem sub-systems to the socio-ecological system.

We established three cases in which the urbanization and ecosystem sub-systems were assigned different values to explore the degree to which the weights of urbanization and the ecosystem influence the coupling degree of coordination. In the first case, the values for urbanization and the ecosystem, i.e., α and β, were 1/3 and 2/3, respectively. These values indicate that the maintenance of urbanization development takes precedence over the ecosystem quality. In the second case, both α and β were assigned 1/2, indicating that urbanization development and preserving ecosystem quality were equally important. In the third case, the values of α and β were 1/3 and 2/3, respectively, which indicate that the maintenance of ecosystem quality takes precedence over urbanization development.

Table 2 Index system used for evaluating the relationship between urbanization and the ecosystem

Sub-system	Index	
Integration value of urbanization	Landscape aspects	Districts constructed in urban areas/km^2
		Proportion of districts constructed in urban areas/%
		Districts in constructed areas per capita/m^2
		Area of public green space in urban areas/km^2
		Public green space area per capita/m^2
		Proportion of public green space area in districts in constructed Areas (%)
		Road area per capita in urban areas/m^2
	Demographic aspects	Population density/(persons·km^{-2})
		Urban population density/(persons·km^{-2})
		Percentage of nonagricultural population/%
		Total Population/person
		Proportion of population engaged in secondary and tertiary Industry (%)
		Rate of urban population growth/%
	Economic aspects	Gross Domestic Production/(million CNY)
		GDP density/(million CNY·km^{-2})
		Per capita GDP/CNY
		Percentage of GDP of the added value of secondary and tertiary Industries (%)
		Total investment in fixed assets/(million CNY)
		Local financial revenue/(million CNY)
	Social aspects	People with college degrees per 10,000 people
		Number of hospital beds per 10,000 people
		Number of doctors per 10,000 people
		Number of public transportation vehicles per 10,000 people
		Annual total disposable income per capita of urban residents (CNY)
		Average social wages/CNY
Integration value of ecosystem	Ecosystem services aspects	Total ecosystem service value/(million CNY)
		Ecosystem services value per capita/CNY
	Natural capital landscape metrics (class level)	Total core area/ha
		Core area percentage of the landscape/%
		Number of disjunct core areas
		Shape index
		Effective mesh size
		Contiguity Index
	Local area landscape metrics (landscape level)	Total edge contrast index
		Similarity index
		Effective mesh size
		Splitting index
		Contagion index
		Shannon's diversity index

3 Results

3.1 Change in land use, ESV, and landscape metrics

3.1.1 Land use structure dynamics

Figure 3 illustrates changes in each land use type during the study time. Table 3 summarizes the overall state of land use structure change from 1985 to 2010 in Lianyungang City. Cropland was the largest land use type during the study period, but the ratio of it to the whole area decreased from 68.1% to 64.4%. During the study period, the areas of forest, grassland, shrub, and tidal land all decreased, whereas the urban, rural, and industrial land area increased. The urban area in 2010 was more than twice the urban area in 1985. Based on the data presented in Table 3, it was concluded that most of the lost cropland was converted to urban land. The conversion rate started to accelerate noticeably after 2000, following a slight increase from 1995 to 2000. This increased rate of conversion was a combined result of the landscape urbanization processes in which farmland was converted to urban construction land and a partial reclamation of the grassland and forests.

To study the ecosystem quality, we applied land use categories including forest, shrub, grassland, water body, and tidal land as natural capital class based on the essential role that they play in supplying ecosystem services. Over the past 25 years, the area of total natural capital land including forest, shrub, grassland, water body, and tidal land, decreased from 67,776.7 ha to 63,996.6 ha and the proportion decreased from 9.3% to 8.8%.

3.1.2 Change of ESV and landscape metrics

The total and respective ESVs for each land use category during the study time are shown in Table 4. Overall, the total ESV has declined since 1985, with the exception of a transitory increase between 1985 and 1995. Compared with 1985, the total ESV in 2010 decreased approximately 3.8% (Table 5); this loss was mainly due to reductions in cropland and forest. Cropland presented the largest proportion in the study area, and forest had the third highest value coefficient. The area of water bodies grew slightly from 1985 and 2010, which resulted in an increase in the total ESV to its highest value coefficient. The increase in the ESV generated by water bodies compensated for the ESV loss caused by reductions in cropland and forest areas from 1985 to 2010 (Table 3). The values of the individual ecosystem services are displayed in Table 4. The changes in the contribution of each ecosystem service to the total ESV were very small.

Table 4 and Figure 4 show the spatial patterns of the ESV in Lianyungang City from 1985 to 2010. It is clear that the regions surrounding the study area were classified as natural capital land and presented a higher ESV during the study period. However, the natural capital regions constituted only a small portion of the total land area (Table 3). Most of the region was covered by croplands and built-up areas. The reduction of cropland areas around the built-up regions was responsible for the majority of the total ESV loss (Table 5). The ESV derived from natural capital areas (forest, shrub, grassland, water bodies, and tidal land) declined based on reductions in these areas. At the class level, the landscape characteristics of the natural capital area were vulnerable to the expansion of the built-up area. The fragmentation and loss of natural capital areas are demonstrated by decreases in the TCA, CPLAND, and NDCA values. The declines in the natural capital land area and number of patches usually coincided with the degradation of the capacity for supporting biodiversity. The slight decline in SHAPE_MN in the natural capital land signified that the patch shape of the natural capital land was more regular and less complicated. The values of MESH provided a relative measure of the natural capital structure. Therefore, the decrease in the MESH value described a reduction in the single natural capital patch and the fragmentation of patches. The decline in CONTIG_MN showed the decrease in the spatial connectedness among natural capital patches caused by urban expansion.

At the landscape level (Table 6), the increase in the TECI value reflected the increase in the total number of patches in the study region. Rapid urban sprawl generated numerous small patches of built-up land, which could give rise to the increase in the value of SHEI. The consequence of this increase in the number of small patches is also shown by the decrease in the MESH value. CONTAG measures the relative aggregation of patches of different types at the landscape scale. The decrease in CONTAG indicates that the landscape became fragmented and heterogeneous. The increasing number of small built-up and natural capital patches aggravated the fragmentation trend, and thereafter the SPLIT and SIMI_MN values increased across the study period. The increased SIMI_MN values illustrated that the natural capital patches were surrounded by an increasing amount of built-up areas at a rate that kept pace with the acceleration of urbanization (Fig. 3).

3.2 Results of the development of urbanization and ecosystem

As shown in Table 5, the aspects of landscape, population, economy, and society had distinct weights at the comprehensive level in Lianyungang City. Economic aspects held the maximum weight, followed by the social, landscape, and demographic aspects. The varied weights are displayed in Fig. 5. In general, the economic and social aspects appear to have a shape that is more similar to the comprehensive urbanization curve, implying the supreme and secondary effects on the overall urbanization process. In contrast, the difference in the curves between compre-

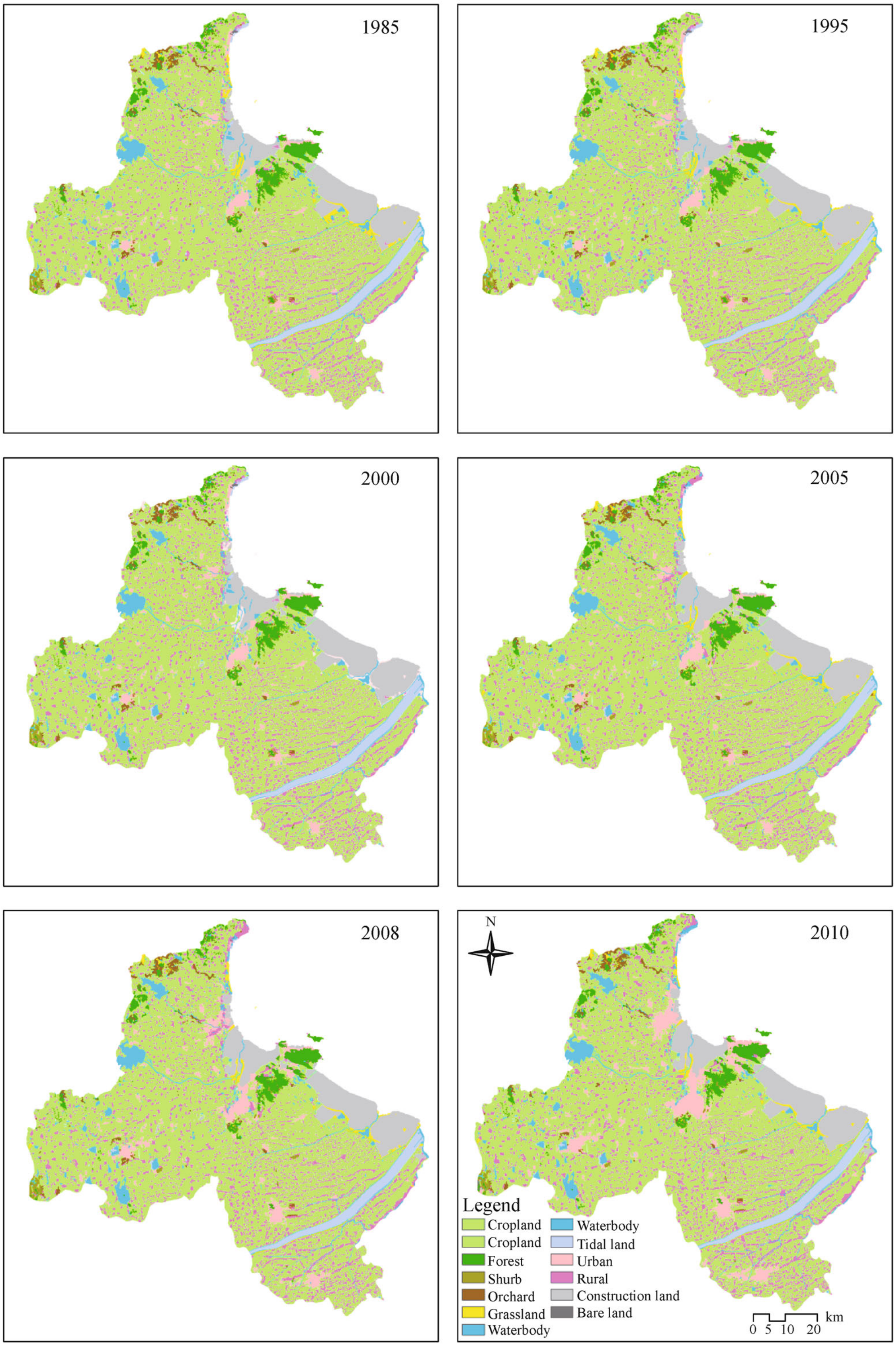

Fig. 3 Spatial changes in land use structure in study area from 1985 to 2010.

hensive urbanization and the landscape and demographic aspects reflects the small influence that both of these aspects imposed on the comprehensive urbanization level. According to the curve in Fig. 5, the comprehensive urbanization process experienced roughly three main stages: the first stage (1985–1991), the second stage (1992–2002) and the third stage (2003–2010). In the first stage, the comprehensive urbanization level and the social and economic aspects maintained slow rates of increase, whereas the landscape aspects had the fastest growth. The

Table 3 Land use dynamics from 1985 to 2010 (ha)

Land Use Types	Year					
	1985	1995	2000	2005	2008	2010
Cropland	495,090.5 (68.1%)	489,174.4 (67.3%)	494,897.8 (68.1%)	489,759.3 (67.4%)	478,404.3 (65.8%)	468,184.8 (64.4%)
Forest	19,427.7 (2.7%)	19,319.2 (2.7%)	19,356.5 (2.7%)	19,803.3 (2.7%)	19,697.49 (2.7%)	18,067.1 (2.5%)
Shrub	2,992.3 (0.4%)	2,997.0 (0.4%)	2,960.0 (0.4%)	2,960.2 (0.4%)	2,577.1 (0.4%)	2,306.3 (0.3%)
Orchard	7,140.4 (1.0%)	7,348.3 (1.0%)	7,118.3 (1.0%)	7,229.16 (1.0%)	7,218.7 (1.0%)	6,928.4 (1.0%)
Grassland	8,752.9 (1.2%)	7,320.8 (1.0%)	7,252.1 (1.0%)	6,853.4 (0.9%)	6,754.1 (0.9%)	6,574.6 (0.9%)
Water body	19,259.5 (2.7%)	21,075.7 (2.9%)	19,198.4 (2.6%)	19,582.4 (2.7%)	19,452.51 (2.7%)	20,451.42 (2.8%)
Tidal land	17,334.3 (2.4%)	17,352.3 (2.4%)	17,322.8 (2.4%)	16,629.2 (2.3%)	16,620.5 (2.3%)	16,597.2 (2.3%)
Urban	15,747.8 (2.2%)	16,419.6 (2.3%)	16,527.2 (2.3%)	15,916.7 (2.2%)	27,159.7 (3.7%)	38,955.7 (5.4%)
Rural	89,131.2 (12.3%)	93,689.2 (12.9%)	91,494.7 (12.6%)	93,624.1 (12.9%)	93,644.9 (12.9%)	95,221.3 (13.1%)
Industrial land	52,031.5 (7.2%)	52,220.7 (7.2%)	50,779.9 (7.0%)	54,695.3 (7.5%)	55,423.8 (7.6%)	53,630.3 (7.4%)
Bare land	186.9 (0.0%)	187.8 (0.0%)	187.2 (0.0%)	51.8 (0.0%)	51.8 (0.0%)	188.0 (0.0%)
Sum	727,105.0 (100%)	727,105.0 (100%)	727,105.0 (100%)	727,105.0 (100%)	727,105.0 (100%)	727,105.0 (100%)

Table 4 Change in the ESV of ecosystem services of the study area from 1985 to 2010

Types of ecosystem services	ESV/($\times 10^6$ CNY$\cdot$yr^{-1})					
	1985	1995	2000	2005	2008	2010
Gas regulation	303.32 (6.42%)	299.73 (6.30%)	301.87 (6.41%)	300.88 (6.42%)	294.94 (6.40%)	284.08 (6.25%)
Climate regulation	470.73 (9.96%)	465.75 (9.79%)	469.11 (9.96%)	465.99 (9.94%)	456.20 (9.90%)	443.46 (9.75%)
Water supply	845.10 (17.88%)	873.73 (18.37%)	842.27 (17.88%)	841.36 (17.95%)	832.05 (18.05%)	838.57 (18.44%)
Soil protection	746.18 (15.79%)	736.21 (15.48%)	742.99 (15.77%)	737.44 (15.73%)	721.54 (15.66%)	700.84 (15.41%)
Waste purification	1,213.67 (25.68%)	1,232.77 (25.92%)	1,210.27 (25.69%)	1,203.60 (25.67%)	1,184.34 (25.70%)	1,182.44 (26.00%)
Biodiversity protection	457.46 (9.68%)	456.42 (9.60%)	455.43 (9.67%)	453.27 (9.67%)	444.92 (9.65%)	434.63 (9.56%)
Food production	446.49 (9.45%)	441.07 (9.27%)	445.90 (9.47%)	441.31 (9.41%)	431.16 (9.36%)	421.89 (9.28%)
Raw material	101.25 (2.14%)	100.68 (2.12%)	100.94 (2.14%)	101.62 (2.17%)	100.02 (2.17%)	94.57 (2.08%)
Recreation and culture	142.23 (3.01%)	149.20 (3.14%)	141.89 (3.01%)	142.44 (3.04%)	143.27 (3.11%)	146.55 (3.22%)
Sum	4,726.44 (100%)	4,755.57 (100%)	4,710.65 (100%)	4,687.92 (100%)	4,608.43 (100%)	4,547.04 (100%)

Table 5 Total ESV for each land use category in Lianyungang City from 1985 to 2010

Land use type	ESV/($\times 10^6$ CNY·yr^{-1})					
	1985	1995	2000	2005	2008	2010
Cropland	3,027.13 (64.05%)	2,990.96 (62.89%)	3,025.95 (64.24%)	2,994.54 (63.88%)	2,925.11 (63.47%)	2,862.62 (62.96%)
Forest	375.61 (7.95%)	373.52 (7.85%)	374.24 (7.94%)	382.88 (8.17%)	380.83 (8.26%)	349.31 (7.68%)
Shrub	37.09 (0.78%)	37.15 (0.78%)	36.69 (0.78%)	36.70 (0.78%)	33.19 (0.72%)	28.59 (0.63%)
Orchard	88.52 (1.87%)	91.09 (1.92%)	88.24 (1.87%)	89.62 (1.91%)	89.49 (1.94%)	85.89 (1.89%)
Grassland	56.08 (1.19%)	46.90 (0.99%)	46.52 (0.99%)	43.91 (0.94%)	43.27 (0.94%)	42.12 (0.93%)
Water body	783.82 (16.58%)	857.28 (18.03%)	780.92 (16.58%)	796.54 (16.99%)	791.26 (17.17%)	831.89 (18.30%)
Tidal land	355.77 (7.53%)	356.14 (7.49%)	355.53 (7.55%)	341.30 (7.28%)	341.12 (7.40%)	340.64 (7.49%)
Urban	2.42 (0.05%)	2.52 (0.05%)	2.54 (0.05%)	2.44 (0.05%)	4.17 (0.09%)	5.98 (0.13%)
Rural	0.00 (0.00%)	0.00 (0.00%)	0.00 (0.00%)	0.00 (0.00%)	0.00 (0.00%)	0.00 (0.00%)
Construction	0.00 (0.00%)	0.00 (0.00%)	0.00 (0.00%)	0.00 (0.00%)	0.00 (0.00%)	0.00 (0.00%)
Bare land	0.00 (0.00%)	0.00 (0.00%)	0.00 (0.00%)	0.00 (0.00%)	0.00 (0.00%)	0.00 (0.00%)
Total	4,726.43 (100%)	4,755.56 (100%)	4,710.65 (100%)	4,687.91 (100%)	4,608.43 (100%)	4,547.04 (100%)

demographic aspects showed small fluctuations in 1988 and 1991. In the second stage, the comprehensive level grew at a modest rate, similar to the other four aspects. During the third stage, the comprehensive urbanization level and the other three aspects exhibited significant increases, with the exception of two minor fluctuations in demographic urbanization that occurred in 2006 and 2010.

In contrast to the comprehensive urbanization level, the comprehensive level of ecosystem quality has decreased since 1985. The natural capital landscape metric aspects exhibited the greatest impact on the comprehensive ecosystem quality level, followed by the local area landscape metric aspects and then the ecosystem service aspects (Table 7). As shown in Fig. 6, the comprehensive ecosystem quality level and the three aspects declined slowly prior to 1995. Between 1995 and 2005, the comprehensive level, ecosystem service aspects, and natural capital landscape metric aspects exhibited a decrease in acceleration, but the drop-off trend slowed after 2000. During the study period, the local area landscape metric aspects exhibited a fluctuation in 2000 and then decreased moderately. Since 2005, the comprehensive level of ecosystem quality and all three aspects decreased sharply, suggesting an overall degradation of ecosystem quality.

3.3 Coordinating the urbanization and ecosystem results

We established three cases with different values for urbanization and the ecosystem to examine the influence of both on the coordinating degree of coupling. The degrees of coupling between urbanization and the ecosystem for each case from 1985 to 2010 are shown in Fig. 7. The three coupling results exhibited a similar overall profile during the study period, although the curves were slightly different in appearance. The outcomes indicated that the coordination degree of coupling was not significantly impacted by the weight of urbanization factors and ecosystem quality factors. As a consequence, the changing process of coordinated coupling between urbanization and ecosystem quality became our main concern during the study period. From 1985 to 2010, the degree of coordinated coupling curves first increased and then decreased to yield an inverse U shape. The transformed course could be divided into two stages based on the degree of coordinated coupling.

From 1985 to 2005, the degree of coupling coordination increased gradually until it reached a turning point in 2005. During this period, the urbanization comprehensive level stayed low for a long time, and all of the urbanization aspects were less developed but increased more rapidly. In

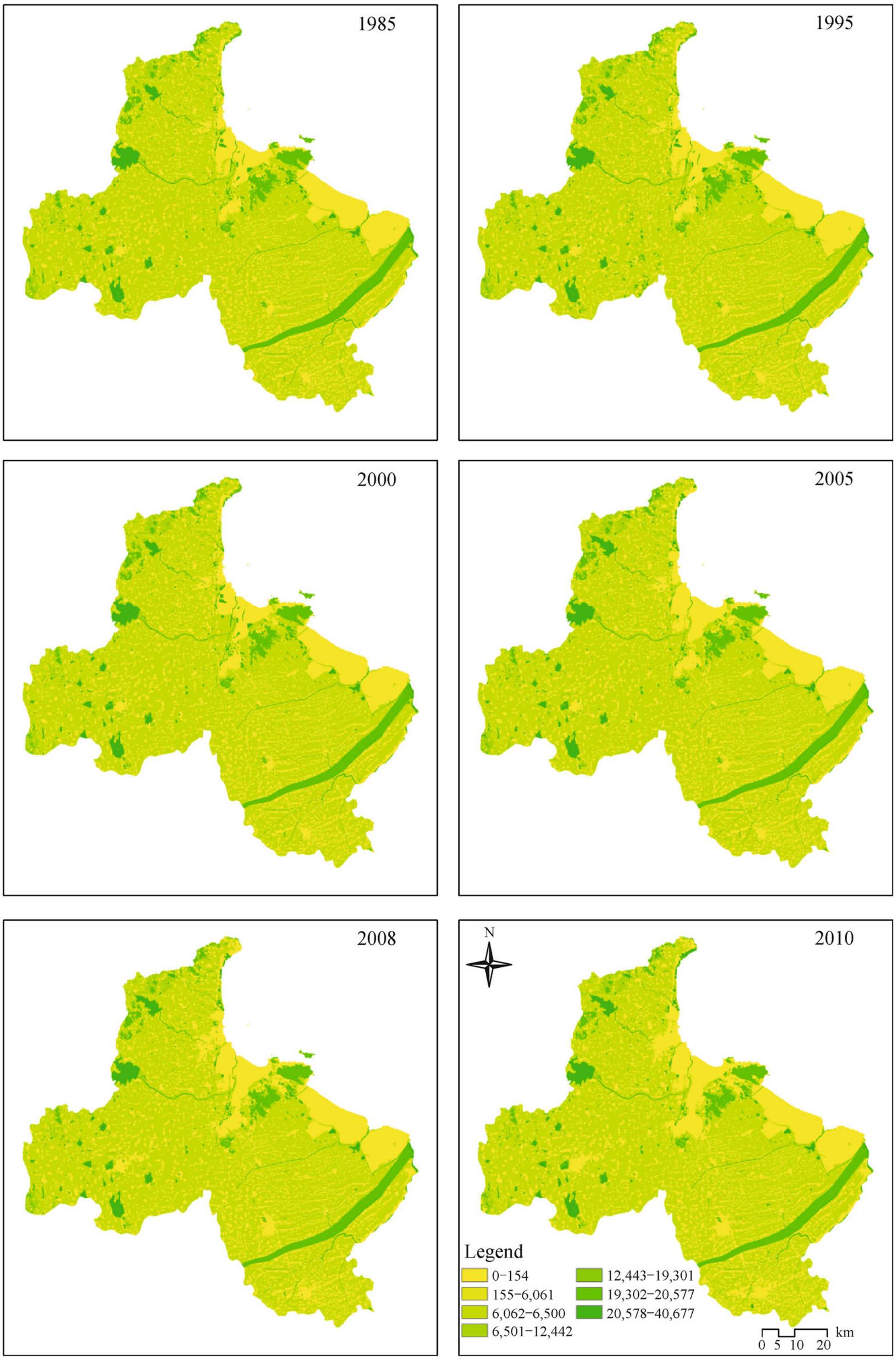

Fig. 4 Spatial patterns of the ESV (CNY/yr) in the study area from 1985 to 2010.

addition, the overall ecosystem quality continually decreased. The degree of coordinated coupling was slightly unbalanced due to the lag in urban development in the early part of the first stage. However, as the urbanization level advanced, the ecosystem quality level began to decline, but the degree of coupling coordination increased at an alarming rate, indicating a typical rapid urbanization process that occurred at the cost of ecosystem quality.

A turnaround occurred in 2005 and the degree of

Table 6 Change in the landscape metrics in study area from 1985 to 2010

Metrics		Year					
		1985	1995	2000	2005	2008	2010
Class level (Natural capital class)	TCA	55,795.86	54,988.92	54,190.44	54,318.42	53,814.42	53,312.85
	CPLAND	3.522	3.471	3.420	3.428	3.396	3.365
	NDCA	683	833	676	641	639	626
	SHAPE_MN	1.630	1.597	1.611	1.610	1.608	1.584
	MESH	238.53	234.01	233.58	235.33	232.48	229.65
	CONTIG_MN	0.862	0.849	0.844	0.838	0.838	0.837
Landscape level	TECI	59.573	59.759	59.811	59.880	60.055	61.226
	SIMI_MN	196,140	195,466	194,928	194,402	187,359	163,146
	MESH	23,607	22,957	23,429	23,190	22,157	18,488
	SPLIT	67.104	69.006	67.631	68.328	71.512	85.704
	CONTAG	60.428	60.045	60.406	60.255	59.331	58.749
	SHEI	0.715	0.720	0.715	0.718	0.736	0.748

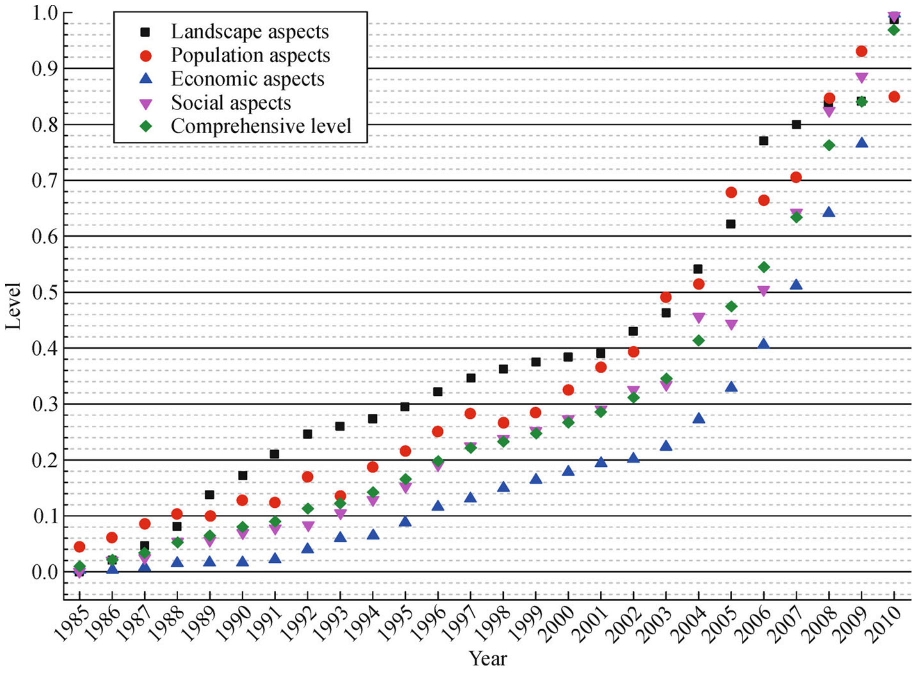

Fig. 5 Trends for the comprehensive levels in the urbanization sub-system from 1985 to 2010.

coupling coordination started to rapidly decrease, leading to an unbalancing of the coupled system. After 2008, the decreasing tendency accelerated progressively, and the degree of coupled coordination declined to the barely balanced state. During this period, the urbanization process was in the third stage (Fig. 5), during which more rapid urbanization development produced severely negative impacts on ecosystem quality, as reflected by the degradation of the comprehensive level and the three aspects of ecosystem quality (Fig. 6). By 2010, the coupling coordination degree was markedly diminished as the unprecedented urbanization progressed and the ecosystem degraded.

4 Discussion

4.1 Urbanization process and change in ecosystem quality

The temporal urbanization process analyzed in Lianyungang City has shown that the landscape and the demographic aspects could not accurately depict the level of observed change. This finding implied that the urbanization process typically measured by metrics such as non-agricultural population and urban area cannot be utilized by these aspects. On the contrary, the economic and social aspects were the most, and the second most (respectively), influential factors in deciding the level of

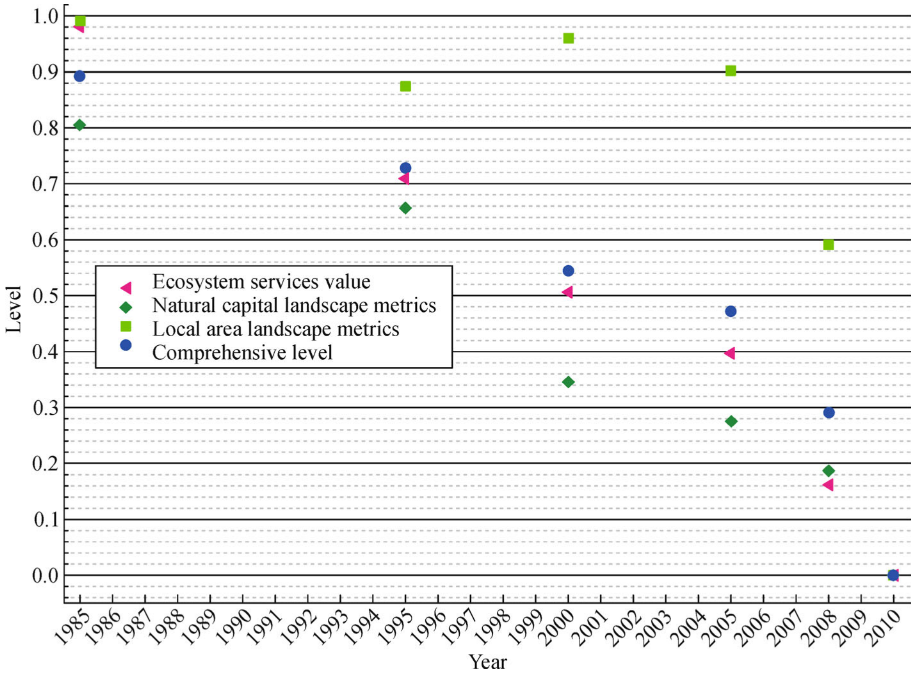

Fig. 6 Tendency of comprehensive levels in the ecosystem sub-system from 1985 to 2010.

urbanization. The landscape and demographic aspects were the third and fourth most important factors influencing the comprehensive level, but a landscape change occurred during the study period. Uncontrolled and unmanaged expansion of urban areas not only induced a loss of natural capital lands (Wu et al., 2013; Chen et al., 2014) but also changed the landscape structure and landscape metrics (Su et al., 2012). Over the past 20 years, Jiangsu Province, where the study area is located, was one of the fastest growing provinces (Xu et al., 2014). Additionally, the proportion of the population living in urban areas was considered the index for measuring the urbanization rate in China. Our results indicate that social factors, and not economic factors, should play a more prominent role in the urbanization process to ensure the maintenance of sound development (Li et al., 2012).

In this study, we applied the method proposed by Costanza et al. (1997b) and modified by Xie et al. (2003) to account for Chinese conditions, and we estimated the ESV in Lianyungang City by multiplying the area of a given land-use type by the corresponding ecosystem value coefficient. Our estimated results for Lianyungang City revealed that the ecosystem quality, demonstrated by integration of the ESV and landscape metrics, decreased as a result of urbanization from 1985 to 2010. The expansion of built-up land and the substantial growth of the economy could induce decreases in the regional total ESV (Liu et al., 2012; Wu et al., 2013). A decrease of only 3.7% was found for the total ESV loss in 2010 compared with that in 1985. However, considering the increase in the population over the last 25 years, the ESV per capita remained at approximately 69%. The general trend in the ESV change mainly reflects the transitions between different land use types (Kreuter et al., 2001). The expansion of built-up areas, particularly urban areas, has resulted in a loss of natural capital lands, which is mirrored by changes in the landscape metrics such as ECA, CPLAND, and NDCA. The shape of natural capital patches (i.e., water bodies, forest, and tidal land) became more regular, and their connectedness decreased such that the capacity for supporting biodiversity degraded. Regarding the entire landscape of the study region, the rapid urban sprawl markedly altered the structure of the regional landscape and generated numerous small built-up patches, thereby exacerbating the fragmentation and the split of the entire landscape. Therefore, the landscape metrics in the natural capital category and at the landscape level provided indicators for the change in the landscape structure. These metrics can supply essential information for monitoring the state and quality of the ecosystem. The monitoring of landscape metrics offers supplementary structural information that is not usually included in the ESV. Consequently, the approach involving integration of the ESV and landscape metrics may provide a more comprehensive and accurate evaluation of the state of the local ecosystem.

4.2 Coupling coordination between urbanization and ecosystem

The degree of coupling coordination presented an inverse

Table 7 Weight of indicators of the urbanization and ecosystem sub-system (1985−2010)

Sub-system	Items	Index	e_j	d_j	w_j
Integration value of urbanization	Landscape aspects	Districts constructed in urban areas/km^2	0.902	0.098	0.031
		Proportion of districts constructed in urban Areas/%	0.923	0.077	0.025
		Districts constructed in urban area per capita/m^2	0.920	0.080	0.025
		Area of public green space in urban areas/km^2	0.901	0.099	0.032
		Public green space area per capita/m^2	0.909	0.091	0.029
		Proportion of public green space area in districts constructed in urban areas/%	0.949	0.051	0.050
		Urban areas per capita/m^2	0.918	0.082	0.025
	Demographic aspects	Population density/(persons · km^{-2})	0.963	0.037	0.012
		Urban population density/(persons · km^{-2})	0.939	0.061	0.019
		Percentage of nonagricultural population/%	0.837	0.163	0.052
		Total population/person	0.948	0.052	0.017
		Proportion of population engaged in Secondary and Tertiary Industries/%	0.858	0.142	0.045
		Rate of urban population growth/%	0.913	0.087	0.028
	Economic aspects	Gross domestic production/(million CNY)	0.838	0.162	0.052
		GDP density/(million CNY · km^{-2})	0.845	0.155	0.050
		Per capita GDP/CNY	0.836	0.164	0.053
		Percentage of GDP of the added value of Secondary and Tertiary Industry/%	0.913	0.087	0.028
		Total investment in fixed assets/(million CNY)	0.743	0.257	0.082
		Local financial revenue/(million CNY)	0.674	0.325	0.104
	Social aspects	People with college degrees per 10,000 People	0.867	0.133	0.043
		Number of hospital beds per 10,000 People	0.725	0.275	0.088
		Number of doctors per 10,000 People	0.959	0.041	0.013
		Number of public transportation vehicles per 10,000 People	0.894	0.106	0.034
		Annual total disposable income per capita of urban residents/CNY	0.871	0.129	0.041
		Average social wages/CNY	0.828	0.172	0.055
The integration value of ecosystem	Ecosystem services aspects	Total ecosystem services value/(million CNY)	0.863	0.137	0.057
		Ecosystem services value per capita/CNY	0.734	0.256	0.110
	Natural capital landscape metrics (class level)	Total core area/ha	0.821	0.179	0.074
		Core area percentage of the landscape/%	0.819	0.181	0.075
		Number of disjunct core areas	0.639	0.361	0.149
		Shape index	0.858	0.142	0.059
		Effective mesh size	0.855	0.145	0.060
		Contiguity index	0.670	0.330	0.136
	Local area landscape metrics (landscape level)	Total edge contrast index	0.895	0.105	0.044
		Similarity index	0.895	0.105	0.043
		Effective mesh size	0.895	0.105	0.044
		Splitting index	0.896	0.104	0.043
		Contagion index	0.869	0.131	0.054
		Shannon’s diversity index	0.873	0.127	0.053

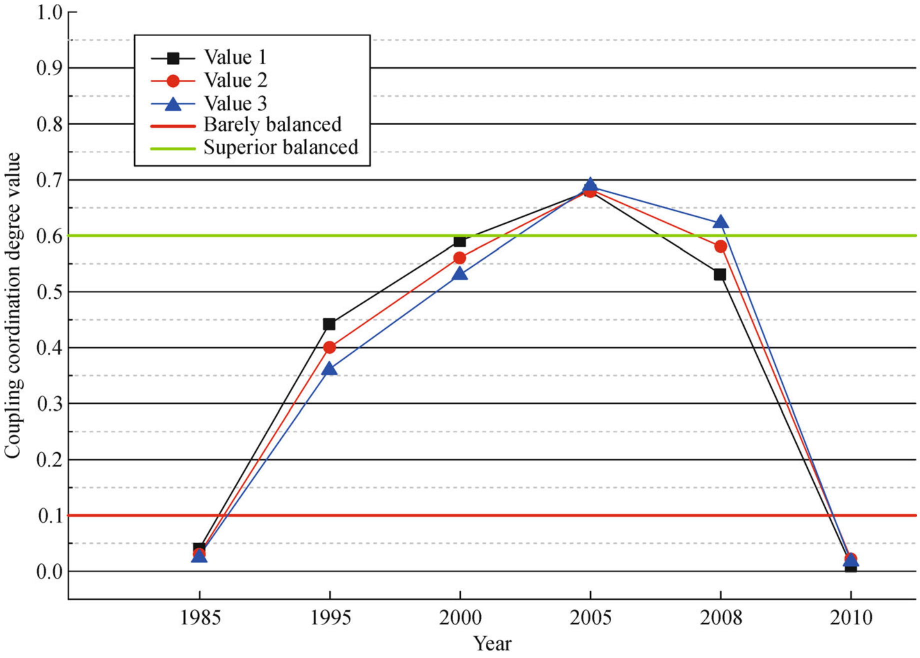

Fig. 7 Trends of the degree of coordinated coupling system.

U-shaped curve during the study time. This finding was in step with the coupling research between urbanization and eco-environment performed in Jiangsu Province, China (Liu et al., 2005). According to the T value, the coupling degree of coordination between urbanization and eco-environment could be divided into four stages: slight coordinating stage ($T < 0.3$), medium coordinating stage ($0.3 < T < 0.5$), medium coordinating stage ($0.5 < T < 0.8$) and medium coordinating stage ($0.8 < T < 1$) (Hu et al., 2013). At the primary stage of urbanization (1985−1995), the local ecosystem was in good condition and the urbanization level lagged behind the ecosystem (Huang and Fang, 2003; Liu and Song, 2005). The degree of coupling of urbanization and the ecosystem was in a slightly balanced state because economic and social development was moving very slowly. During the early period of urbanization, the comprehensive urbanization level remained lower than the ecosystem quality. At the same time, poorly designed urban development had an adverse effect on the ecosystem, because local governors concentrated on the city's development, especially on economic growth and area expansion (Li et al., 2012).

From 1995 to 2000, the coupling system reached a balanced condition in which the urbanization level was clearly increasing. From this point, the urbanization process accelerated, as urbanization all across China sped up. The coordination between urbanization and the ecosystem achieved the optimum condition in 2005. However, the turning point appeared at the same time, and the degree of coupling coordination began falling from the optimum level, and the comprehensive ecosystem level started to decrease sharply. The accelerated urbanization trend resulted in a striking decline in the ecosystem, and subsequently, the coupled system entered into a barely balanced state once more. But the barely balanced state was a side effect of poorly managed urban expansion, especially in spatial terms. According to the S type development mechanism, the coupled system, namely urbanization and ecosystem, had entered the quickly developing phase (Song et al., 2000; Xu et al., 2003). However, in the study, the ecological quality state or ecological capacity was falling behind the urbanization process. The U-shaped curve of degree of coordinated coupling implies that urban development decision-makers had not considered ecosystem protection to be a priority at any stage of the process of urbanization.

Therefore, the new urbanization should deemphasize the landscape aspects of the urbanization process, but highlight economic and social development. The industrialization roadmap, (e.g., the development of a circular economy) featuring high technological content, high economic returns, low resource consumption, and less ecosystem disturbance would mitigate the negative impacts of rapid urbanization on the ecosystem. Our results provide a suggestion to the regional governors that they pay more attention to sustainable development and ecological conservation and recovery, not merely in Lianyungang City, but also in other cities experiencing rapid urbanization. Maintaining the coordination degree between urban development and the ecosystem in a balanced state is important for a city's future development plans.

5 Conclusions

Taking Lianyungang City as an example, an analysis was performed to quantitatively evaluate the coupled degree of coordination between urbanization and ecosystem quality from 1985 to 2010. The research results showed an inverse U-shaped curve during the years from 1985 to 2010 under conditions of rapid urbanization. The coupling coordination status in Lianyungang switched from barely balanced development to extremely balanced development, and then decreased again to barely balanced development. After 2003, the urbanization process of Lianyungang City rapidly increased, in which the areas of landscape, demography, and economy exerted a great influence on the local ecosystem's structure and function. The trend in the degree of coupling coordination started to decrease until it reached a maximum value in 2005. Moreover, a precipitous decline in the local ecosystem was also discovered.

With the coastal development of Lianyungang City and the creation of a new industrial development zone and port expansion, local ecological issues — such as a decrease in ecosystem services, a loss of natural capital land, and an increase in fragmentation — became increasingly predominant. Research indicates that decision makers and city officals should be more aware of the recent ecological degradation, as the ecosystem provides great benefits for future sustainable development and for human life. In other words, with the aim of establishing a coordinated development plan in the coupling system for the integration of urbanization and the ecosystem, the degrading ecosystem sub-system should be the critical limiting aspect. The related government agencies and managers, including the manufacturers of electronic products, new materials, and pharmaceuticals, should pay more attention to the cultivation of new industries to convert the resource-dependent economy to the technology-based economy. However, some methodological issues of this research still remain to be addressed, such as the data source quality, the analysis of the scale effects, and the selection of indices in the entropy analysis. In this paper, the metric analysis was performed considering the study region as a whole unit, and it therefore failed to detect variations within each eco-region in the study area. In addition, the question of whether there is a threshold of ecological quality or a coupled degree of coordination needs further investigating.

Acknowledgements We appreciate the contributions made by the reviewers to improve the paper's quality. This study was financially supported by the National Natural Science Foundation of China (Grant No. 41271008), the Fundamental Research Funds for the Central Universities of China (20720150074), the Key Laboratory of the Coastal Zone Exploitation and Protection, Ministry of Land and Resource of China (2013CZEPK07), Innovation Fund for Ph.D Students of Jiangsu Province (Grant No. CXLX12-0057) and Research Project of the State Key Laboratory of Pollution Control and Resources Reuse.

Supplementary material is available in the online version of this article at http://dx.doi.org/10.1007/s11707-015-0531-6 and is accessible for authorized users.

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