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Spatial identification and dynamic analysis of land use functions reveals distinct zones of multiple functions in eastern China

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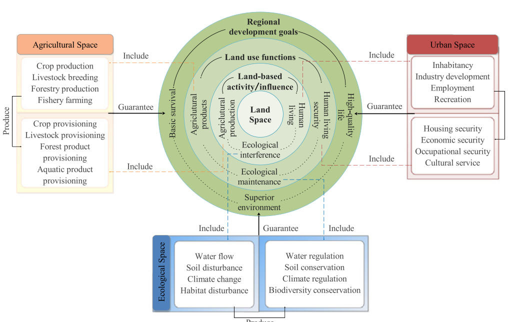
HIGHLIGHTS

- We identified and quantified 12 land use functions (LUFs) from the perspective of spatial planning
- We analyzed the change of LUFs between 2000 and 2015 at the county level
- We analyzed the correlations among 12 LUFs in 2000 and 2015
- We revealed four distinct zones of multiple functions at the county level

GRAPHICAL ABSTRACT



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ABSTRACT

Land use function (LUF) is a valuable concept that allows for more integrated assessments of land system change. Identifying the changes and relationships of multiple LUFs is pertinent to land use planning and management. Selection and quantification of LUF indicators are critical for LUFs assessment. However, past studies have mostly assessed LUFs using socioeconomic data, which are not suitable for spatial variable quantification. In this study, we proposed a new LUFs classification system based on spatial planning goals, and we applied the system to assess 12 LUFs across 63 counties in Jiangsu Province of eastern China based on multi-source data using geospatial modeling tools combined with statistical analysis of socioeconomic data. We also analyzed the change in LUFs between 2000 and 2015, as well as the interactions among multiple functions. Finally, we identified distinct function zones based on the LUFs assessment in 2000 and 2015 using *k*-means clustering. The result showed that 12 LUFs displayed significant changes and interactions between 2000 and 2015, which can be explained by differing topography and social-ecological characteristics among counties. Additionally, we found four distinct LUF zones that are spatially agglomerated in similar landscapes and characterize specific LUF relationships in each cluster. In the future, local LUFs and their changes over time should be taken into consideration for land use planning and management, which provide a reference for policy-makers to make decisions that better match local development realities.

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1. Introduction

Land use and land cover change has been identified as one of the primary determinants of global change, having major impacts on ecosystems, global biogeochemistry, climate change, and human vulnerability (Foley et al., 2005; Pijanowski and Robinson, 2011). Recently, the emergence of the interdisciplinary field of land change science (GLP, 2005; Turner et al., 2007; Verburg et al., 2009) has focused on the interactions within land use systems. Interacting land use systems can provide a wide variety of goods and services to human society, which are collectively referred to as land use functions (LUFs; MEA, 2005; Wiggering et al., 2006; Verburg et al., 2009). Land cover change can be determined by remotely sensed data or survey summary data (Pijanowski et al., 2014; W. Song et al., 2015); however, the changes of LUFs cannot be determined from observable land cover alone—social-ecological data are also needed to assess LUFs and their possible changes (Long, 2015; Song and Deng, 2017).

The concept of LUFs originated from agricultural research (Helming et al., 2008) and mainly refers to agricultural production functions (Verburg et al., 2009; Andersen et al., 2013). The Millennium Ecosystem Assessment (MEA) has stimulated extensive studies of ecosystem services (MEA, 2005; Bennett, 2017; Costanza et al., 2017; Jiang et al., 2018; Hu et al., 2018). However, in urban and cropland systems, ecosystem services are limited to those provided by a small proportion of natural capital (Gómez-Baggethun and Barton, 2013; Yang et al., 2015). To address the issue on artificial ecosystems, LUFs were proposed to present connotations related to economic, societal, and environmental fields which are broader than ecosystem services (Paracchini et al., 2011; Liu et al., 2016).

LUFs are the outputs provided by land use systems that refer to any type of ecosystem and contribute to human well-being directly or indirectly (Wiggering et al., 2006; Verburg et al., 2009; Yang et al., 2015). In different type of land use systems, LUFs refer to different goods and services. For example, in agricultural system, agricultural products (e.g., crop, livestock, forest and aquatic product) are the main outputs; living securities (e.g., residence, economic output, employment, recreation) are the key elements supported by urban system; regulation services, such as water regulation, soil retention, climate regulation, and biodiversity conservation are mainly provided by natural ecosystem. Assessing LUFs is critical to understanding the complexity of interactions among multiple land use systems to achieve sustainable regional development.

Previous studies of LUFs primarily have two foci. One focus is ecosystem services and landscape multi-functionality of a specific region (Raudsepp-Hearne et al., 2010; Leh et al., 2013; Queiroz et al., 2015; Peng et al., 2016; Mouchet et al., 2017; Baró et al., 2017). The second focus is on the function of a specific land use type, such as forests, cultivated land, urban land, or rural land (Barbier et al., 2010; Andersen et al., 2013; Lovell and Taylor, 2013; W. Song et al., 2015; X. Song et al., 2015; Jiang et al., 2016). The former are more systematic in the framework and approaches; they identified ecosystem service bundles or landscape multi-functionality and revealed the relationships among multiple services/functions. Nevertheless, these studies mainly referred to natural ecosystems and are difficult to employ in artificial ecosystem (e.g., urban and cropland system).

Some studies have focused on the dynamics of LUFs related to both socioeconomic and environmental fields at the regional scale (Zhou et al., 2017; Sun et al., 2017) and provided some feasible ways to analyze LUFs. However, the assessment and measurement of these functions are still challenging as most ecological functions are difficult to quantify using socioeconomic data (Turner and Daily, 2008; Norris, 2012). Additionally, multiple LUFs interact with each other in unpredictable ways, which results in trade-offs and synergies among LUFs (Bennett et al., 2009). Trade-offs reflect inverse relationships among LUFs, whereas synergies reflect direct relationships among LUFs (Bennett et al., 2009; Lin et al., 2018). Analyzing the interactions of multiple LUFs is helpful in evaluating the impact of land use policies on LUFs, especially for regions with a shortage of natural resources; however, most studies do not identify trade-offs and synergies among LUFs (Bennett et al., 2009; Raudsepp-Hearne et al., 2010; Peng et al., 2016).

The Jiangsu Province in eastern China is located within the largest economic zone in the nation, the Yangtze River Delta. By the end of 2015, the urbanization rate in the region was 66.5%, 10.4 percentage points higher than the national average. Agricultural and ecological space are heavily occupied and are threatened by the rapid expansion of urban space. During the period 2000 to 2015, per capita arable land dropped from 0.071 ha to 0.057 ha; ecological land (e.g. rivers, lakes, reeds, and beaches) has been reduced by approximately 0.18 million ha. These declines are the result of interactions among LUFs and will likely restrict regional sustainable development.

In this study, the social-ecological complexity of land use systems with a large proportion of urban and agricultural land was taken into consideration. We proposed a new LUFs classification system for assessing LUFs in Jiangsu Province, specifically, but which can be applied to any geographical area. We also used geospatial modeling tools, i.e., Integrated Valuation of Ecosystem Services and Tradeoffs (InVEST, Tallis et al., 2011) and Revised Universal Soil Loss Equation (RUSLE; Wischmeier and Smith, 1978), to quantify the ecological functions based on fine-scale data (e.g., land use spatial data, remote sensing data) to address the limitations of socioeconomic-data-based ecological indicators. These tools have been used to identify ecosystem services in many studies and have been shown to be more effective and reliable methods to assess the provisioning of ecological goods and services at a fine scale (Leh et al., 2013; Hamel et al., 2015; Jiang et al., 2018; Hu et al., 2018). In addition, we further analyzed the trade-offs of LUFs and revealed spatial variation of LUFs to provide a wider perspective for LUFs studies. The objectives of the study were to:

(1) Identify and quantify LUFs from the perspective of spatial planning.
(2) Measure the status of LUFs and analyze the change of LUFs between 2000 and 2015 at the county level.
(3) Analyze changes in spatial autocorrelation of LUFs and correlations among individual function.
(4) Identify distinct LUF zones based on the status and dynamics of LUFs at the county level.

2. Materials and methodology

2.1. Study area

Jiangsu Province is situated in the coastal center of eastern China, bordering the Yellow Sea and covering 107,200 km^2 (Fig. 1), and is an important strategic fulcrum of the Yangtze River Economic Belt. The area had a total population of 67.67 million people in 2015 and includes 63 county-level administration districts. Plains and surface water account for approximately 70% and 17% of the total area, respectively. The area is in the transitional zone between temperate and subtropical climates with mild temperatures, moderate rainfall, and distinct seasons. Superior environmental conditions provide an attractive foundation for rapid economic and social development in the area.

Nevertheless, the area also suffers from severe resource shortage, with the per capita arable land (0.057 ha) equaling approximately half of the average amount in China and approaching the minimum amount of per capita arable land (0.053 ha) stipulated by Food and Agriculture Organization of the United Nations (Wang, 2001). The total population and economic output per square kilometer are five and eight times the average value of China, respectively. Land development intensity in the region was 4.7% greater than the national average during the study

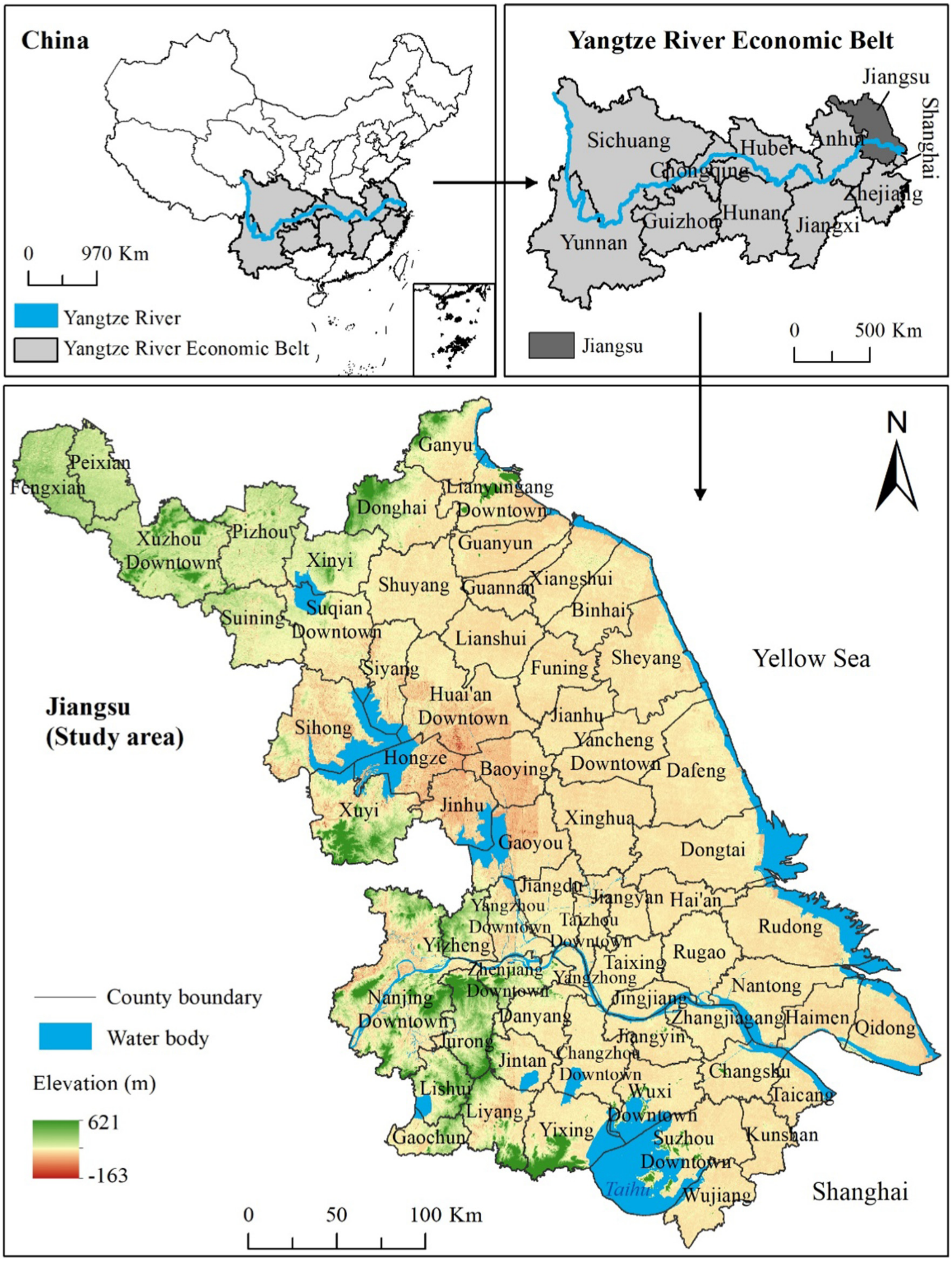

Fig. 1. Location of the study area in eastern China and the 63 counties across the area.

period. Therefore, the capacity for natural resources to support regional development is limited. This study provides a reference for land development pattern optimization to be used by land planners and policymakers in Jiangsu.

The data used in this study include statistical, spatial, and reference data. All spatial data were rescaled to county level using a Gauss-Kruger projection and the Xi'an 80 geographical coordinate system. Details about the data used for analysis and their sources are shown in Table 1.

2.2. Methods

2.2.1. Land use functions classification and quantification

The *National Land Planning Outline* (2016–2030) in China published in 2017 divided land space into three types: agricultural space, urban space, and ecological space. The dominant land use activities vary among land space types and can provide multiple goods and services for human beings to achieve different spatial planning objectives in each space. With this approach, we propose here a new classification

Table 1
Data sources and description of this study.

Data type	Data source	Time-series	Resolution
Land use/land cover data	Resource and Environment Science Data Center, Chinese Academy of Sciences	2000, 2015	1:10,0000
Socioeconomic data	Statistical Yearbook of Jiangsu	2000, 2015	County level
Agricultural data	Rural Statistical Yearbook of Jiangsu	2000, 2015	County level
DEM (ASTER GDEM V2)	Geospatial Data Cloud (http://www.gscloud.cn/)	2009	30 m × 30 m
Normalized Differential Vegetation Index (MYDND1M)		2000, 2015	500 m × 500 m
Net Primary Productivity (MOD17A3)	National Oceanic and Atmospheric Administration (http://www.noaa.gov/)	2000, 2015	1 km × 1 km
Evapotranspiration (MOD16A3)		2000, 2015	500 m × 500 m
Leaf Area Index (MOD15A2)		2000, 2015	1 km × 1 km
Soil data	The Second National Soil Census Data	1990s	1:100,0000
Precipitation	Meteorological data center of China Meteorological Administration	2000, 2015	Site
Environmental protection zone	National Earth System Scientific Data Sharing Infrastructure	2009	1:25,0000
Road data		2002, 2015	1:25,0000

framework for LUFs that considers the interdependence and interaction of land space, land use activities/influence, land use functions, and spatial planning objectives (Fig. 2).

Based on the classification framework of LUFs shown in Fig. 2, we proposed a LUFs classification system with three primary functions and 12 sub-functions (Table 2). For each sub-function, an indicator was defined and measured; the selection of these indicators was based on three main criteria: (1) relevance to the study area, mainly in terms of expected demand for regional development, (2) use in previous studies and/or public data sources as important to the sub-function, and (3) availability of data at the county level. Indicators and quantification methods for each sub-function can be found in Table 2.

2.2.2. Analyzing the change of land use functions

All indicators were averaged by county and normalized to enable comparison across counties of different sizes and to facilitate correlation and cluster analysis among functions using minimum and maximum values so that all indicator values ranged from 0 to 1 (Raudsepp-Hearne et al., 2010; Mouchet et al., 2014).

For each sub-function, a county was given a value of 1 if the indicator value was greater than or equal to the average value of the whole study area. Sub-functions were assumed to be substantial in the county if the indicator value was 1. Otherwise, a county was given a value of zero, and the sub-function was assumed to be a non-substantial function.

For each county, we also assessed the temporal change of 12 sub-functions based on time-dependent variables that determined the indicator value of the sub-function at a given time *t*. Changes in sub-function relative to its previous state can be calculated as.

$$LUFCI_{ij} = LUF_{ijt1} - LUF_{ijt2} \quad (1)$$

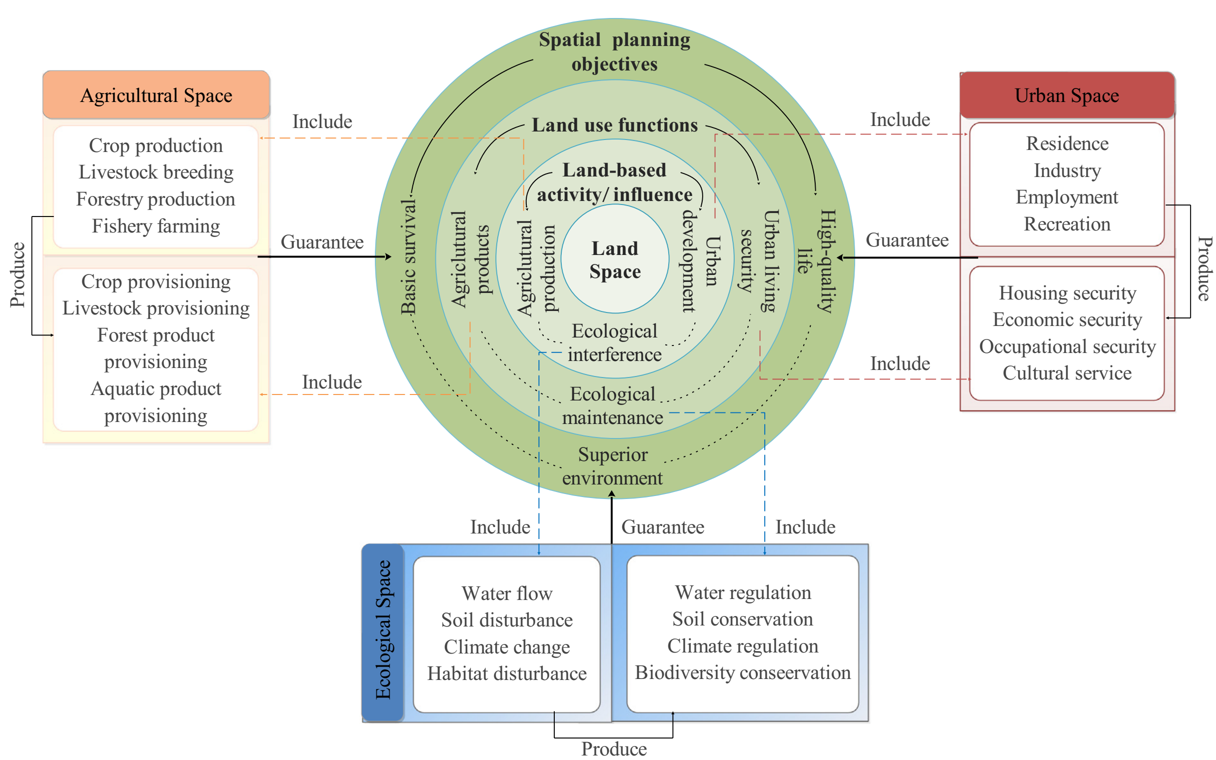

Fig. 2. Classification framework of land use functions. (1)The middle green shades indicate the hierarchical relationships of land space, land use activities/influence, land use functions and spatial planning objectives. (2) Inside the green shades, the solid lines point to the different types of land use activities/influence, land use functions and spatial planning objectives, the dashed lines point to the connection of these types. (3) Outside the green shades, the solid lines indicate the relationships of land use activities/influence, land use functions and spatial planning objectives in each space, the dashed lines point to the detailed contents of each item. (4) The left yellow shades indicate agricultural production activities and agricultural products provisioning functions in agricultural space. (5) The right red shades indicate urban development activities and urban living security functions in urban space. (6) The low blue shades indicate ecological interference activities and ecological maintenance functions in ecological space.

Table 2
Overview of land use functions, indicators, quantification methods, and key references used in this study. N_C indicates the content of carbon in carbon dioxide (CO_2), that is 27.27%. β indicates that CO_2 content needed to be absorbed and immobilized for 1 g dry biomass produced per plant, that is 1.63 g.

Primary functions	Sub-functions	Indicators	Unit	Quantification method and key references
Agricultural production function	Crop provisioning	Per unit area crop yield	kg ha^{-1}	Total crop yield/crop sown area
	Livestock provisioning	Density of head of livestock (including pigs, cattle, sheep)	Livestock units km^{-2}	Total amount of pigs, cattle, sheep/total land area
	Forest product provisioning	Forest product yield	kg ha^{-1}	Total forest product yield/total land area
	Aquatic product provisioning	Aquatic product yield	kg ha^{-1}	Total aquatic product yield/total land area
Urban living function	Housing security	Population density	Inhabitants km^{-2}	Total inhabitants/total land area
	Economic security	Per unit area non-agricultural output values	\$ km^{-2}	Total non-agricultural output values/construction land area
	Occupational security	Percentage of non-agricultural employees	People km^{-2}	Total non-agricultural employees/total employees
	Cultural service	Acceptable amount of visitors	People km^{-2}	Total acceptable amount of visitors/total land area
Ecological maintenance function	Water regulation	Water yield	mm km^{-2}	InVEST
	Soil conservation	Sediment retention	kg km^{-2}	RUSLE
	Climate regulation	Carbon sequestration	kg C ha^{-1}	$Nc \times \beta \times \sum NPP$
	Biodiversity conservation	Habitat quality	#	InVEST

where $LUFCI_{ij}$ is the Land Use Function Change Index of function ij ($i = 1,2,3$; $j = 1,2,3,4$), LUF_{ijt1} and LUF_{ijt2} are the LUF state values of function ij at times $t1$ and $t2$, respectively. In this study, $t1$ is 2015 and $t2$ is 2000.

LUFCI ranges from negative one to positive one and represents the relative increase or decrease of each function. A negative/positive LUFCI indicates a decrease/increase in function among years; an LUFCI of 0 indicates no change. Furthermore, we identified eight function change patterns (Table 3) based on the direction (i.e., positive or negative LUFCI) of changes in function type (i.e., substantial function or non-substantial function) from 2000 to 2015. We also used ArcGIS 10.2 (ESRI, 2014) to map the spatial distribution of LUFs change over time.

2.2.3. Assessing hot and cold spots of land use functions

Each primary function was quantified using an unweighted summation of the LUF state values of corresponding sub-functions for 2000 and 2015. Spatial cold and hot spot analysis was conducted for each primary function using the hot spot analysis tool in ArcGIS10.2. A Z-score was calculated to identify the locations of the spatial aggregation of high and low values for primary functions in each county. A county was considered a statistically significant hot spot only if it had a high positive Z-score and was surrounded by counties with similar high values. Conversely, when a county had a low negative Z-score and was surrounded by counties with similar low values, the county was a statistically significant cold spot.

2.2.4. Analyzing interactions among multiple functions

We used Pearson parametric correlation analysis to identify trade-offs and synergies among the all pair combinations of the 12 sub-functions in 2000 and 2015. In this study, synergies or trade-offs indicate positive or negative relationships between two functions, respectively, that could reveal the associations between pairs of LUFs. The relationships were mapped using R package corrplot (Wei and Simko, 2017).

2.2.5. Identifying land use function zones

All sub-functions calculated in 2000 and 2015 were considered for cluster analysis. We classified 63 counties into clusters to characterize LUF zones based on similar combinations of LUF values using *k*-means clustering (Jain, 2010) which minimizes within-group variability. The number of clusters was determined by analyzing the robustness and relevance of different clusters with the support of rose-wind diagrams which were mapped by the R package vegan (Oksanen et al., 2013). The spatial distribution of LUF zones was mapped using ArcGIS10.2.

3. Results

3.1. Change patterns of land use functions from 2000 to 2015

The spatial distribution of the 12 sub-functions varied substantially across the study area within the years 2000 and 2015 (Figs. S1, S2). The spatiotemporal variation patterns of 12 sub-functions (Fig. 3) at the county level also revealed clear similarities and dissimilarities among functions.

For agricultural production functions between 2000 and 2015, crop and livestock provisioning showed an overall increase, but forest product and aquatic product provisioning showed an overall decrease. Specifically, crop and livestock provisioning were clustered in northern Jiangsu both in 2000 and 2015. Crop provisioning showed a more prominent increase in northern Jiangsu than in southern Jiangsu. Southern Jiangsu, however, experienced a substantial decrease in livestock

Table 3
The change patterns of land use functions. (1) A substantial function is one with an indicator value greater than or equal to the average value of the whole study area in the year; otherwise, it is a non-substantial function. (2) The sign '−' represents a decrease in function between 2000 and 2015; '+' represents an increase in function between 2000 and 2015.

Classification	Function type		Function change direction	Function change pattern
	2000	2015		
C1	Substantial function	Non-substantial function	−	High-level decrease
C2	Non-substantial function	Non-substantial function	−	Substantial decrease
C3	Substantial function	Substantial function	−	Low-level decrease
C4	Non-substantial function	Substantial function	−	Nominal decrease
C5	Substantial function	Non-substantial function	+	Nominal increase
C6	Non-substantial function	Non-substantial function	+	Low-level increase
C7	Substantial function	Substantial function	+	Substantial increase
C8	Non-substantial function	Substantial function	+	High-level increase

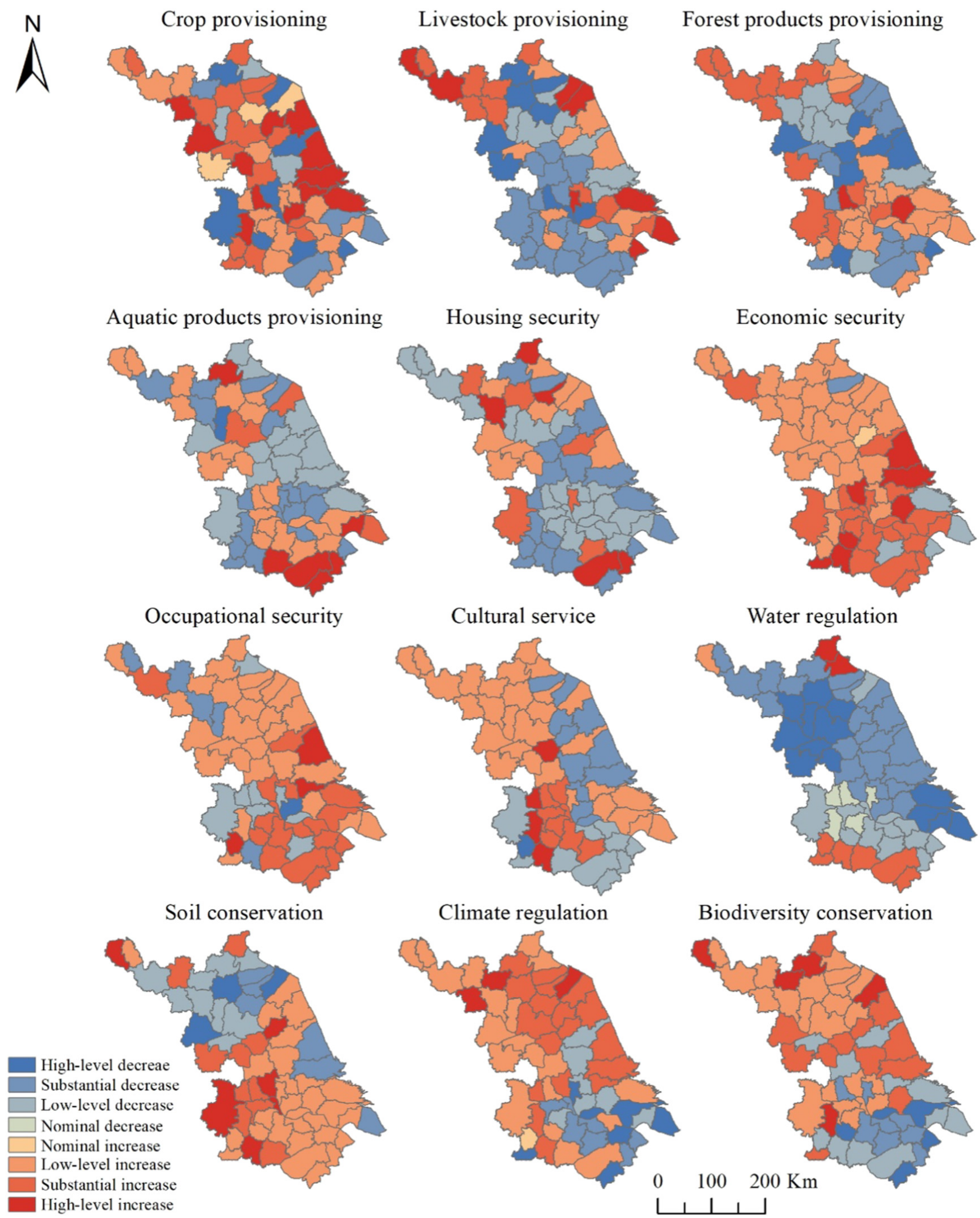

Fig. 3. Spatial distribution of the change patterns of land use functions between 2000 and 2015 at the county level in Jiangsu. Blue shades indicate decreases in functions between 2000 and 2015, and red shades indicate increases in functions between 2000 and 2015. Darker shades of blue and red, indicate decreases and increases in functions that are of greater magnitude.

provisioning. Forest product provisioning was concentrated and increased in the northern Jiangsu between 2000 and 2015. Aquatic product provisioning was high along the coast of the Yellow Sea, but showed a low-level decrease in the area among years.

The four urban living sub-functions were highly concentrated in southern Jiangsu and increased substantially in the whole area between 2000 and 2015. Economic security and occupational security grew more in southern Jiangsu than in northern Jiangsu between 2000 and 2015. In most counties, housing security showed a low-level or substantial decrease, and the decrease was more prominent in southern Jiangsu. Although cultural service was not a prominent function in northern Jiangsu, it showed a low-level increase there. Cultural service near Nanjing, the provincial capital of Jiangsu, experienced a large increase.

In general, water regulation and climate regulation functions were high and relatively evenly distributed among counties in 2000. However, water regulation decreased substantially between 2000 and 2015, especially in northern Jiangsu, and remained high in southern Jiangsu. Excluding water regulation, all ecological maintenance sub-functions showed an overall increase in the whole of the study area between 2000 and 2015. Soil conservation increased substantially in the southwest hilly areas and southern Jiangsu, but was mainly concentrated and showed a low-level decrease in northern Jiangsu between 2000 and 2015. Additionally, biodiversity conservation was highest near the Yellow Sea, likely due to a mosaic landscape of diverse habitats, and increased substantially in northern Jiangsu.

3.2. Change analysis on hotspots and interactions of land use functions

The hot and cold spots of three primary functions are shown in Fig. 4. In both years, hot spots for agricultural production and ecological maintenance functions overlapped in northern Jiangsu, and cold spots for these two primary functions overlapped in southern Jiangsu, whereas the hot spots of urban living functions partially overlapped the cold spots of the two other primary functions. The hot spots of agricultural production were more concentrated in northern Jiangsu in 2015 than in 2000; a similar change occurred in the cold spots of urban living functions. From 2000 to 2015, the ecological maintenance hot spots decreased in northern Jiangsu, but increased in southwest Jiangsu, where forests are abundant. Ecological maintenance cold spots in southeast Jiangsu were more numerous in 2015 than in 2000.

We also found distinct interactions among the 12 sub-functions, both in 2000 and 2015 (Fig. 5). In both years, urban living functions were significantly negatively correlated with agricultural production functions and ecological maintenance functions, and the correlation was stronger in 2015 than in 2000. This corroborated the opposing spatial distributions of hot and cold spots of the three functions.

With the exception of housing security, urban living sub-functions (i.e., economic security, occupational security, cultural service) were significantly negatively correlated with livestock and forest product provisioning. Although, the negative correlation between the three urban living sub-functions and forest product provisioning was weaker in 2015 than in 2000. Aside from water regulation, the remaining ecological maintenance sub-functions were significantly negatively correlated with urban living sub-functions. Climate regulation and biodiversity conservation had stronger negative correlations with urban living functions in 2015 than in 2000; however, soil conservation and urban living functions showed a decreased trade-off between 2000 and 2015. Additionally, there was a trade-off between water regulation and urban living functions, which was more prominent in 2015.

We also found a weak positive relationship between agricultural production functions and ecological maintenance functions, overall. Specifically, forest product provisioning was significantly positively correlated with soil conservation, and aquatic product provisioning was significantly positively correlated with biodiversity conservation; these relationships were more significant in 2015 than in 2000. Conversely, forest product provisioning was significantly negatively correlated with water regulation in 2000 and 2015. A strong trade-off also existed between livestock provisioning and water regulation in 2015.

3.3. Spatial distribution of land use function zones

Cluster analysis grouped 63 counties into four clusters, which varied in different functions, hence revealing four distinct LUF zones (Table 4; Fig. 6). We named the four clusters based on dominant LUFs and the main land cover and land use pattern of each cluster.

3.3.1. Riverside metropolis development zone (Cluster 1)

Cluster 1 ($n = 17$) includes counties with a high density of water bodies and high urbanization and population density, most of which are located along the Yangtze River. Water regulation was higher in this cluster than others, despite experiencing a low-level decrease between 2000 and 2015. Other ecological maintenance sub-functions had overall low mean values. Climate regulation and biodiversity conservation decreased substantially between 2000 and 2015. Cluster 1 showed the highest values for urban living sub-functions and the lowest values for agricultural production functions, revealing a disparity between agricultural production and urban development. Additionally, except for housing security and livestock provisioning, all other urban living and agricultural production sub-functions increased between 2000 and 2015.

3.3.2. Cropland ecological protection zone (Cluster 2)

Cluster 2 ($n = 14$) comprises counties in which cropland is the primary land use and are mostly located around the Yangtze River, Hongze Lake, and Gaoyou Lake. This area had the highest values for crop provisioning in Jiangsu and showed an overall increase in crop provisioning between 2000 and 2015. All ecological maintenance functions in this cluster were at a moderate level and were relatively stable over time, but increased slightly between 2000 and 2015. Urban living functions,

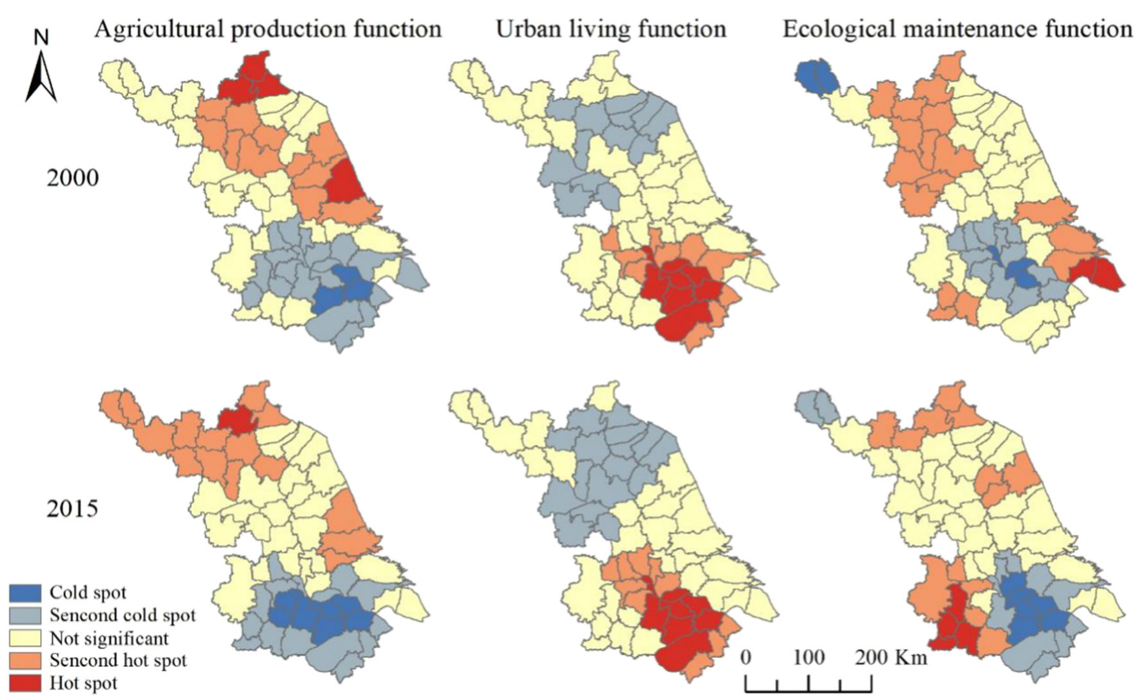

Fig. 4. Hot and cold spots for three primary land use functions in 2000 and 2015 in Jiangsu. Each function is divided into five zones according to Z-score of hot spot analysis: cold spot ($Z < -2.58$), secondary cold spot ($-2.58 \le Z < -1.96$), not significant ($-1.96 \le Z \le 1.96$), secondary hot spot ($1.96 < Z \le 2.58$), and hot spot ($Z > 2.58$).

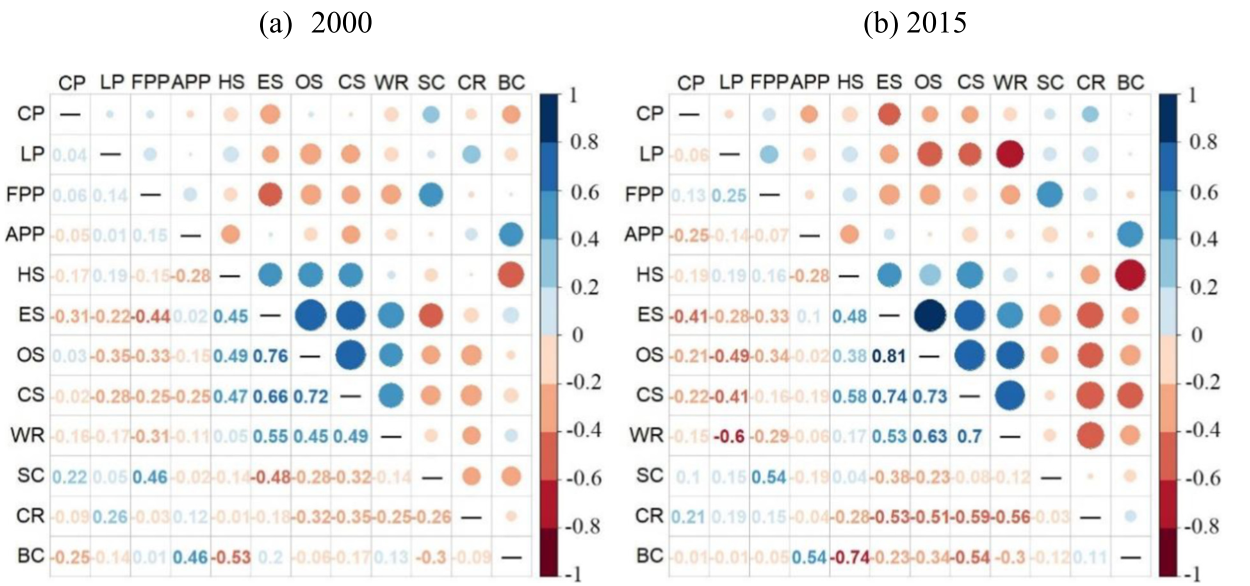

Fig. 5. Results of a pairwise correlation analysis of land use functions in 2000 and 2015 using a Pearson correlation test. (1) The numbers in the lower left indicate the correlation coefficients of pairs of functions. Positive values indicate a synergy between two functions and negative value indicates a trade-off between two functions. When the absolute value of coefficient is >0.24, the correlation between two functions is significant with a 95% confidence level. (2) The shaded circles in the upper right indicate the direction and magnitude of the interactions between two functions. Blue shades represent positive correlations and red shades represent negative correlations between two functions. The darker the blue/red shades, the greater the positive/negative correlations are between two functions. (3) The abbreviations in the upper and left axes are as follows: CP represents crop provisioning; LP represents livestock provisioning; FPP represents forest product provisioning; APP represents aquatic product provisioning; HS represents housing security; ES represents economic security; OS represents occupational security; CS represents cultural service; WR represents water regulation; SC represents soil conservation; CR represents climate regulation; BC represents biodiversity conservation.

except for occupational security, in this cluster had relatively lower mean values than other clusters in both years, but had higher mean values in 2015 than 2000.

3.3.3. Coastal wetland exploitation zone (Cluster 3)

Cluster 3 (n = 9) includes counties near the Yellow Sea with a moderate amount of urban land. Aquatic product provisioning was high in this group, but decreased substantially between 2000 and 2015. Conversely, crop provisioning was low, but increased significantly among years. Cultural service in this group was lowest in both years. Occupational security and economic security functions had moderate mean values that increased slightly among years; however, housing security was low and decreased further from 2000 to 2015. Water regulation also decreased significantly between 2000 and 2015. Climate regulation and biodiversity conservation had higher mean values overall in this cluster than in others.

3.3.4. Mosaic cropland livestock reserve zone (Cluster 4)

Cluster 4 (n = 23) is the largest zone by number of counties and comprises counties with abundant cropland, some forested areas, and relatively small urban settlements. This group was heterogeneous, combining the highest livestock provisioning, forest product provisioning, and soil conservation, as well as the lowest economic and occupational security functions, all of which increased among years of 2000 and 2015. Soil conservation was also higher in this cluster than the other three clusters in 2000 and 2015. Crop provisioning had a relatively high and increased performance between 2000 and 2015. With the exception of water regulation, the remaining three ecological maintenance sub-

Table 4
Standardized mean values for each land use function indicator within each function zone. The number of counties per cluster is indicated with n.

Land use functions	Clusters							
	Riverside metropolis development zone (n = 17)		Cropland ecological protection zone (n = 14)		Coastal wetland exploitation zone (n = 9)		Mosaic cropland livestock reserve zone (n = 23)	
	2000	2015	2000	2015	2000	2015	2000	2015
Crop provisioning	0.47	0.50	0.52	0.61	0.42	0.51	0.50	0.58
Livestock provisioning	0.15	0.14	0.13	0.10	0.24	0.22	0.25	0.30
Forest product provisioning	0.08	0.09	0.23	0.16	0.14	0.07	0.28	0.27
Aquatic product provisioning	0.09	0.12	0.20	0.17	0.46	0.40	0.11	0.11
Housing security	0.62	0.60	0.20	0.19	0.32	0.26	0.47	0.44
Economic security	0.59	0.73	0.13	0.23	0.39	0.47	0.09	0.16
Occupational security	0.83	0.88	0.42	0.52	0.40	0.55	0.29	0.40
Cultural service	0.51	0.52	0.17	0.18	0.05	0.06	0.09	0.11
Water regulation	0.75	0.61	0.63	0.53	0.52	0.18	0.49	0.24
Soil conservation	0.08	0.18	0.30	0.39	0.05	0.07	0.36	0.36
Climate regulation	0.48	0.45	0.52	0.60	0.79	0.79	0.67	0.79
Biodiversity conservation	0.31	0.23	0.52	0.55	0.69	0.74	0.22	0.36

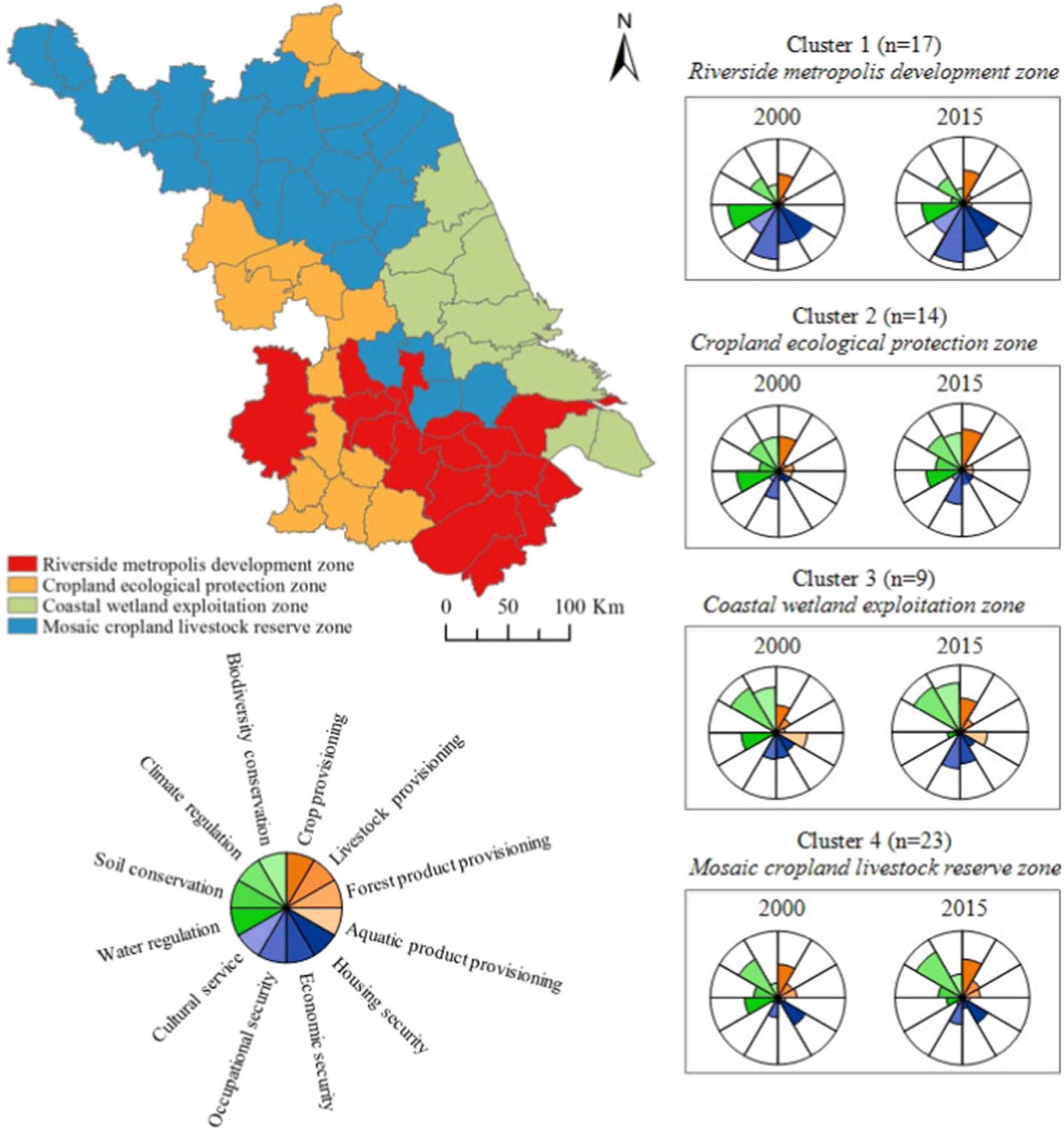

Fig. 6. Spatial distribution of land use function zones and standardized mean indicator values found within each cluster (represented in wind-rose plots). A sector in wind-rose plots represents a sub-function shown in the lower left corner. A higher surface area indicates a higher function value. The number of counties per cluster is indicated with n.

functions increased between 2000 and 2015. Climate regulation was higher in this group than in other clusters in 2015.

4. Discussion

4.1. Insights into the change of land use functions

LUF is determined by various social-ecological elements of land use systems and indicates the ability of land use systems to provide goods and services for supporting human well-being (GLP, 2005; Wiggering et al., 2006; Verburg et al., 2009). This study presented significant geographic differences in the change patterns of LUFs from 2000 to 2015 in the study area. Urban living functions have increased substantially between 2000 and 2015, and the functions had more prominent performance in southern Jiangsu where was of higher population and industry density. Nevertheless, high population densities can constrain agricultural production and ecological maintenance functions, as the case of crop and livestock provisioning as well as climate regulation and biodiversity conservation, which were lower and decreased more significantly in highly populated areas of southern Jiangsu. This finding agrees with those studies using similar approaches in the Yangtze River Delta city cluster and Swedish landscape (Yang et al., 2015; Queiroz et al., 2015). Ecological maintenance functions also showed an overall low and decreased status in southern Jiangsu with higher urban living functions, especially for climate regulation and biodiversity conservation. Water regulation showed an overall decreased status in the study area, especially in the northern Jiangsu where forest product provisioning is higher and increased significantly. This might be explained by the evapotranspiration of new plantations consuming groundwater and runoff was reduced when grasslands and shrublands were afforested (see also Wayland et al., 2003; Farley et al., 2005; Sun et al., 2006; Ray et al., 2010; Wiley et al., 2010; Yang et al., 2010 for similar reports in other areas of the world). Meanwhile, proportional reductions in annual runoff caused by afforestation were significantly larger in drier areas (Farley et al., 2005).

LUF is also related to land cover and its change, therefore, results from local changes in land cover (Verburg et al., 2009). Land cover distribution varied in distinct regions of LUFs change patterns in 2000 and 2015 (Fig. S3). Increased crop and livestock provisioning were mainly distributed in a mosaic-type landscape with related share of farmland, forest, grassland, water, and urban land. This might be due to the relatively low intensity of agricultural practices in the regions where agricultural areas hold a diverse number of habitats (Sporrong, 2008). Forest and aquatic product provisioning increased more significantly in forested and coastal areas, respectively. Also, forest product provisioning showed a more prominent increase in denser urban areas. Urban living functions were more likely to increase in areas where built-up land also increased. This corroborates urban expansion as a determining factor of urban and industrial development (X. Song et al., 2015). In the areas where woodland decreased greatly between 2000 and 2015, water regulation increased, whereas climate regulation decreased. Soil and biodiversity conservation decreased substantially in areas of urban expansion, which indicates that urban expansion negatively affects ecological space.

4.2. Trade-offs among multiple land use functions

Trade-offs among LUFs can occur through many possible mechanisms (Raudsepp-Hearne et al., 2010). Sometimes trade-offs are the results of direct interactions among LUFs; in other cases, they are associated with different social-ecological systems and can be produced by spatial incompatibilities and societal feedbacks.

In this study, we presented empirical evidence for strong, increasing trade-offs between urban living functions and agricultural production functions at the county level, which are consistent with those reported in the Yangtze River Delta (Yang et al., 2015) and have been identified as a cause for concern. Urban expansion for residence and industrial development has resulted in lost, fragmented, transformed, and isolated agricultural landscapes and a decline in agricultural land use intensity, which may undermine the sustainability of agricultural production (Su et al., 2011; Jin et al., 2016; Zhong et al., 2017). Additionally, widespread urban expansion may have a harmful impact on climate, soil, and biodiversity. For example, the emission of greenhouse gasses may lead to increased surface temperatures and decreased net primary production (NPP) (Kalnay and Cai, 2003; Fu et al., 2016; Davis et al., 2016). Urbanization may also lead to biotic homogenization (Vörösmarty et al., 2010; Concepción et al., 2015). Correspondingly, urban living functions were significantly negatively correlated with soil conservation, climate regulation, and biodiversity conservation, which is similar to findings in Denmark (Turner et al., 2014). The effects urban land use are often delayed by slow environmental processes, like groundwater flow, thus land use legacies are potentially important to consider for long-term planning (Pijanowski et al., 2007; Tayyebi et al., 2015).

Prominent and increased synergies between water regulation and urban living functions were consistent with those reported at a watershed scale (Qiu and Turner, 2013). This is primarily due to superior natural resources and transportation along the Yangtze River and Yellow Sea, which are important for socioeconomic development. Despite the requirement of local governments to pay for water-quality treatment and improvement and of tourism operators to suspend water recreation when water quality is poor (Raudsepp-Hearne et al., 2010), water regulation generally decreased between 2000 and 2015. Water regulation had a positive impact on urban development; however, the great demand for water in developing intensive agriculture to improve crop and livestock provisioning, as well as afforestation and reforestation for improving forest product provisioning and carbon sequestration, have been the drivers of trade-offs between water regulation and both agricultural production functions and climate regulation (Long and Pijanowski, 2017).

4.3. Implications for land use planning and management

In this study, we identified four LUF zones that were associated with distinct social-ecological systems and were spatially aggregated in the study area. These patterns can be explained by historical social-ecological interactions among people and nature (Raudsepp-Hearne et al., 2010; Andersson et al., 2015; Queiroz et al., 2015). Identifying distinct function zones at the county level is one effective approach for integrated land use planning and management (Bennett et al., 2009).

As expected, our results showed that the *riverside metropolis development zone* had dense, widespread urbanization and had the highest disparity between agricultural production and urban development. It is necessary for the region to put land use transition into practice to reduce stresses on the limited natural resources (Long, 2015). The intelligent manufacturing industry and modern service industry should be encouraged to improve land use efficiency. Food security and resilience should also be considered in strategic land use planning (Daily et al., 2009; Camps-Calvet et al., 2016). In addition, green infrastructure planning as a land sharing approach should be considered in land use planning as it can improve the environment in the area (Stott et al., 2015; Baró et al., 2016).

The *cropland ecological protection zone* and *mosaic cropland livestock reserve zone* are both sparsely urbanized and populated, which explains the low observed values for urban living functions. Both regions are important bases for agricultural production; although, despite already high values, it is important to strengthen basic farmland construction and manage for the stability and improvement of agricultural production in these areas. However, increasing crop and livestock provisioning pose a considerable threat to sustainable land use through agricultural non-point source pollution (Shen et al., 2014; Ouyang et al., 2014). Unique agricultural industries, such as ornamental agriculture and agritourism, are key aspects of the efficient and low-pollution development models of modern agriculture. Also, the occupation of arable land for non-agricultural development must be strictly limited and the exploitation of ecological protection zones must be prohibited.

The *coastal wetland exploitation zone* was located along the Yellow Sea and had appreciably higher aquatic product provisioning than other zones. Sea aquaculture and port industry development based on abundant resources in this zone have improved agricultural provisioning and promoted regional socioeconomic development effectively. However, a weak economic foundation and homogeneous industrial structure have become limiting factors for sustainable development in the region. In terms of spatial planning, this area requires a combination of industrial expansion and industrial clustering development to realize intensive land use. Green space also should be preserved for land sparing during the land use planning process (Stott et al., 2015); arranging ecological corridor construction between clustering urban and industrial spaces is a way for increased ecological security.

4.4. Limitations and research prospect

Data similar to those used in this study are likely available for other regions. Although we consider the indicators selected to be relevant to the study area and LUFs assessment to be credible and salient for regional spatial planning purposes since all the indicators have been applied in other assessments of LUFs (Polasky et al., 2011; Leh et al., 2013), our study was challenged by the limitations of data collection and quantification methods. For example, cultural service needs to be analyzed from social-behavioral perspectives, but the lack of data for large-scale assessments makes it difficult to fully integrate it in an operational quantification process (Paracchini et al., 2014). Validation or improvement of cultural service assessment could be achieved through detailed surveys of human behavior, natural protection zones, public cultural facility, etc., which are costly and time-consuming in the study area considering the broad geographical area and large population.

Another limitation of this study was the spatial scale. Our study was conducted at, and provided directions for, strategic spatial planning and management at the county level. A refinement of spatial scale is needed in future research for the application of these kinds of assessments to identify problematic areas and address specific problems in land use practice. Satellite-based method is a key technique for LUFs assessment and allows for a more systematic assessment of large areas than statistical data at a fine scale due to its convenience and low cost (Rötzer et al., 2014; Zawadzki et al., 2016; Zhang et al., 2016). For example, medium and high-resolution satellite data (e.g., GLDAS, SMOS and ASCAT, LANDSAT TM/ETM+) are available for monitoring cones of depression caused by intensive pumping of water from aquifers for consumption, irrigation, industrial, or mining purposes (Rötzer et al., 2014; Zawadzki and Kędzior, 2014; Zawadzki et al., 2016; de Jeu and Dorigo, 2016). Cones of depression can limit biomass productivity, and therefore has a straightforward influence on agricultural production (Zawadzki and Kędzior, 2014; Zawadzki et al., 2016). Synthetic aperture radar (SAR) data can be used to map urban impervious surfaces, which is important for broadening the contents of urban living functions (Zhang et al., 2014; Zhang et al., 2016). All these methods are necessary endeavors for improving analysis of fine-scale LUFs assessment in the future.

5. Conclusions

In this study, we presented a novel classification system for assessing LUFs from the perspective of spatial planning. We combined geospatial modeling methods (e.g., InVEST, RUSLE) based on fine-scale data with statistical summary methods based on socioeconomic data to comprehensively assess LUFs. To our knowledge, this is the first study to use this combination of data; although, geospatial modeling methods have been employed to assess ecosystem services in other studies. The application of these methods improves the reliability of indicators for LUFs assessment. Our results showed that agricultural production functions increased more significantly in northern Jiangsu than in southern Jiangsu between 2000 and 2015, which is likely associated with the large swaths of plains and contiguous high-quality farmland in northern Jiangsu. The hot spots of urban living functions were highly concentrated in southern Jiangsu, which corresponds to the highly urbanized area and diverse industries in the area in both years. This corroborates the growing negative correlation between agricultural production functions and urban living functions. Urban living functions are also negatively correlated with ecological maintenance functions; the hotspots of ecological maintenance functions in northern Jiangsu decreased significantly during the study period. Finally, this study presented four types of function zones based on LUFs assessments in 2000 and in 2015. We found that significant differences of LUFs in distinct function zones. The proposal of function zones can provide a feasible approach to spatial planning and the implementation of land management policies in Jiangsu Province, as well as a pathway for achieving integrated social-ecological systems and sustainable development.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.scitotenv.2018.05.383.

References

Andersen, P.S., Vejre, H., Dalgaard, T., Brandt, J., 2013. An indicator-based method for quantifying farm 634 multifunctionality. Ecol. Indic. 25, 166–179.
Andersson, E., Nykvist, B., Malinga, R., Jaramillo, F., Lindborg, R., 2015. A social–ecological analysis of ecosystem services in two different farming systems. Ambio 44 (1), 102–112.
Barbier, E.B., Burgess, J.C., Grainger, A., 2010. The forest transition: towards a more comprehensive theoretical 640 framework. Land Use Policy 27 (2), 98–107.
Baró, F., Palomo, I., Zulian, G., Vizcaino, P., Haase, D., Gómez-Baggethun, E., 2016. Mapping ecosystem service capacity, flow and demand for landscape and urban planning: a case study in the Barcelona metropolitan region. Land Use Policy 57, 405–417.
Baró, F., Gómez-Baggethun, E., Haase, D., 2017. Ecosystem service bundles along the urban-rural gradient: insights for landscape planning and management. Ecosyst. Serv. 24, 147–159.
Bennett, E.M., 2017. Research frontiers in ecosystem service science. Ecosystems 20 (1), 31–37.
Bennett, E.M., Peterson, G.D., Gordon, L.J., 2009. Understanding relationships among multiple ecosystem services. Ecol. Lett. 12, 1–11.
Camps-Calvet, M., Langemeyer, J., Calvet-Mir, L., Gómez-Baggethun, E., 2016. Ecosystem services provided by urban gardens in Barcelona, Spain: insights for policy and planning. Environ. Sci. Pol. 62, 14–23.
Concepción, E.D., Moretti, M., Altermatt, F., Nobis, M.P., Obrist, M.K., 2015. Impacts of urbanisation on biodiversity: the role of species mobility, degree of specialisation and spatial scale. Oikos 124 (12), 1571–1582.
Costanza, R., de Groot, R., Braat, L., Kubiszewski, I., Fioramonti, L., et al., 2017. Twenty years of ecosystem services: how far have we come and how far do we still need to go? Ecosyst. Serv. 28, 1–16.
Daily, G.C., Polasky, S., Goldstein, J., Kareiva, P.M., Mooney, H.A., Pejchar, L., et al., 2009. Ecosystem services in decision making: time to deliver. Front. Ecol. Environ. 7 (1), 21–28.
Davis, A.Y., Jung, J., Pijanowski, B.C., Minor, E.S., 2016. Combined vegetation volume and "greenness" affect urban air temperature. Appl. Geogr. 71, 106–114.
de Jeu, R., Dorigo, W., 2016. On the importance of satellite observed soil moisture. Int. J Appl. Earth Obs. 45, 107–109.
Environmental Systems Research Institute (ESRI), 2014. ArcGIS Desktop Help 10.2 Geostatistical Analyst. http://resources.arcgis.com/en/help/main/10.2/index.html.
Farley, K.A., Jobbágy, E.G., Jackson, R.B., 2005. Effects of afforestation on water yield: a global synthesis with implications for policy. Glob. Chang. Biol. 11 (10), 1565–1576.
Foley, J.A., DeFries, R., Asner, G.P., Barford, C., Bonan, G., Carpenter, S.R., et al., 2005. Global consequences of land use. Science 309, 570–574.
Fu, W., Randerson, J.T., Moore, J.K., 2016. Climate change impacts on net primary production (NPP) and export production (EP) regulated by increasing stratification and phytoplankton community structure in the CMIP5 models. Biogeosciences 13 (18), 5151.
Global Land Project (GLP), 2005. Global Land Project: Science Plan and Implementation Strategy. IGBP Secretariat, Stockholm, Sweden.
Gómez-Baggethun, E., Barton, D.N., 2013. Classifying and valuing ecosystem services for urban planning. Ecol. Econ. 86, 235–245.
Hamel, P., Chaplin-Kramer, R., Sim, S., Mueller, C., 2015. A new approach to modeling the sediment retention service (InVEST 3.0): case study of the Cape Fear catchment, North Carolina, USA. Sci. Total Environ. 524, 166–177.
Helming, K., Tscherning, K., König, B., Sieber, S., Wiggering, H., Kuhlman, T., et al., 2008. Ex ante impact assessment of land use changes in European regions:the SENSOR approach. In: Helming, K., Pérez-Soba, M., Tabbush, P. (Eds.), Sustainability Impact Assessment of Land Use Changes. Berlin & Heidelberg, Germany, pp. 77–105 Springer.
Hu, Y., Peng, J., Liu, Y., Tian, L., 2018. Integrating ecosystem services trade-offs with paddy land-to-dry land decisions: a scenario approach in Erhai Lake Basin, southwest China. Sci. Total Environ. 625, 849–860.
Jain, A.K., 2010. Data clustering: 50 years beyond K-means. Pattern Recogn. Lett. 31 (8), 651–666.
Jiang, G.H., He, X., Qu, Y.B., Zhang, R.J., Meng, Y., 2016. Functional Evolution of Rural Housing Land: A Comparative Analysis across Four Typical Areas Representing Different Stages of Industrialization in China. Land Use Policy 57 (57), 645–654.
Jiang, C., Zhang, H., Zhang, Z., 2018. Spatially explicit assessment of ecosystem services in China's Loess Plateau: patterns, interactions, drivers, and implications. Glob. Planet. Chang. 161, 41–52.
Jin, X.B., Zhang, Z.H., Wu, X.W., Xiang, X.M., Sun, W., Bai, Q., et al., 2016. Co-ordination of land exploitation, exploitable farmland reserves and national planning in China. Land Use Policy 57, 682–693.
Kalnay, E., Cai, M., 2003. Impact of urbanization and land-use change on climate. Nature 423 (6939), 528–531.
Leh, M.D., Matlock, M.D., Cummings, E.C., Nalley, L.L., 2013. Quantifying and mapping multiple ecosystem services change in West Africa. Agric. Ecosyst. Environ. 165, 6–18.
Lin, S., Wu, R., Yang, F., Wang, J., Wu, W., 2018. Spatial trade-offs and synergies among ecosystem services within a global biodiversity hotspot. Ecol. Indic. 84, 371–381.
Liu, C., Xu, Y.Q., Sun, P.L., Liu, J., 2016. Progress and prospects of multi-functionality of land use research. Prog. Geogr. 35 (9), 1087–1099 (in Chinese).
Long, H.L., 2015. Land use transition and land management. Geogr. Res. 35 (9), 1607–1618 (in Chinese).

Long, K., Pijanowski, B.C., 2017. Is there a relationship between water scarcity and water use efficiency in China? A national decadal assessment across spatial scales. Land Use Policy 69, 502–511.
Lovell, S.T., Taylor, J.R., 2013. Supplying urban ecosystem services through multifunctional green infrastructure in the United States. Landsc. Ecol. 28 (8), 1447–1463.
Millennium Ecosystem Assessment (MEA), 2005. Ecosystems and Human Well-Being: Synthesis. Island Press, Washington, DC.
Mouchet, M.A., Lamarque, P., Martín-López, B., Crouzat, E., Gos, P., Byczek, C., et al., 2014. An interdisciplinary methodological guide for quantifying associations between ecosystem services. Glob. Environ. Chang. 28, 298–308.
Mouchet, M.A., Paracchini, M.L., Schulp, C.J.E., Stürck, J., Verkerk, P.J., Verburg, P.H., et al., 2017. Bundles of694 ecosystem (dis) services and multifunctionality across European landscapes. Ecol. Indic. 73, 23–28.
Norris, K., 2012. Biodiversity in the context of ecosystem services: the applied need for systems approaches. Philos. Trans. Roy. Soc. B: Biol. Sci. 367, 191–199.
Oksanen, J.F., Blanchet, G., Kindt, R., Legendre, P., Minchin, P.R., O'Hara, R.B., et al., 2013. Vegan: Community Ecology Package. R Package Version 2.0-9. Retrieved 4 January 4, 2014, from. http://CRAN.R-project.org/package=vegan.
Ouyang, W., Song, K., Wang, X., Hao, F., 2014. Non-point source pollution dynamics under long-term agricultural development and relationship with landscape dynamics. Ecol. Indic. 45, 579–589.
Paracchini, M.L., Pacini, C., Jones, M.L.M., Pérez-Soba, M., 2011. An aggregation framework to link indicators associated with multifunctional land use to the stakeholder evaluation of policy options. Ecol. Indic. 11 (1), 71–80.
Paracchini, M.L., Zulian, G., Kopperoinen, L., Maes, J., Schägner, J.P., Termansen, M., et al., 2014. Mapping cultural ecosystem services: a framework to assess the potential for outdoor recreation across the EU. Ecol. Indic. 45, 371–385.
Peng, J., Chen, X., Liu, Y., Lü, H., Hu, X., 2016. Spatial identification of multifunctional landscapes and associated influencing factors in the Beijing-Tianjin-Hebei region, China. Appl. Geogr. 74, 170–181.
Pijanowski, B.C., Robinson, K.D., 2011. Rates and patterns of land use change in the Upper Great Lakes States, USA: a framework for spatial temporal analysis. Landsc. Urban Plan. 102 (2), 102e116.
Pijanowski, B.C., Ray, D.K., Kendall, A.D., Duckles, J.M., Hyndman, D.W., 2007. Using backcast land-use change and groundwater travel-time models to generate land-use legacy maps for watershed management. Ecol. Soc. 12 (2):25 [online] URL. http://www.ecologyandsociety.org/vol12/iss2/art25/.
Pijanowski, B.C., Tayyebi, A., Doucette, J., Pekin, B.K., Braun, D., Plourde, J., 2014. A big data urban growth simulation at a national scale: configuring the GIS and neural network based land transformation model to run in a high performance computing (HPC) environment. Environ. Model. Softw. 51, 250–268.
Polasky, S., Nelson, E., Pennington, D., Johnson, K., 2011. The impact of land-use change on ecosystem services, biodiversity and returns to landowners: a case study in the state of Minnesota. Environ. Resour. Econ. 48, 219–242.
Qiu, J., Turner, M.G., 2013. Spatial interactions among ecosystem services in an urbanizing agricultural watershed. Proc. Natl. Acad. Sci. 110 (29), 12149–12154.
Queiroz, C., Meacham, M., Richter, K., Norström, A.V., Andersson, E., Norberg, J., Peterson, G., 2015. Mapping bundles of ecosystem services reveals distinct types of multifunctionality within a Swedish landscape. Ambio 44 (1), 89–101.
Raudsepp-Hearne, C., Peterson, G.D., Bennett, E.M., 2010. Ecosystem service bundles for analyzing tradeoffs in diverse landscapes. Proc. Natl. Acad. Sci. 107, 5242–5247.
Ray, D.K., Duckles, J.M., Pijanowski, B.C., 2010. The impact of future land use scenarios on runoff volumes in the Muskegon River Watershed. Environ. Manag. 46 (3), 351–366.
Rötzer, K., Montzka, C., Bogena, H., Wagner, W., Kerrc, Y.H., Kidd, R., et al., 2014. Catchment scale validation of SMOS and ASCAT soil moisture products using hydrological modeling and temporal stability analysis. J. Hydrol. 519, 934–946.
Shen, Z., Qiu, J., Hong, Q., Chen, L., 2014. Simulation of spatial and temporal distributions of non-point source pollution load in the Three Gorges Reservoir Region. Sci. Total Environ. 493, 138–146.
Song, W., Deng, X., 2017. Land-use/land-cover change and ecosystem service provision in China. Sci. Total Environ. 576, 705–719.
Song, W., Pijanowski, B.C., Tayyebi, A., 2015a. Urban expansion and its consumption of high-quality farmland in Beijing, China. Ecol. Indic. 54, 60–70.
Song, X., Huang, Y., Wu, Z., Ouyang, Z., 2015b. Does cultivated land function transition occur in China. J. Geogr. Sci. 25 (7), 817–835.
Sporrong, U., 2008. The Stockholm-Ma¨laren Region. National Atlas of Sweden. 1st edn. SNA Editors, Italy, p. 224.
Stott, I., Soga, M., Inger, R., Gaston, K.J., 2015. Land sparing is crucial for urban ecosystem services. Front. Ecol. Environ. 13 (7), 387–393.
Su, S., Jiang, Z., Zhang, Q., Zhang, Y., 2011. Transformation of agricultural landscapes under rapid urbanization: a threat to sustainability in Hang-Jia-Hu region, China. Appl. Geogr. 31 (2), 439–449.
Sun, G., Zhou, G., Zhang, Z., Wei, X., McNulty, S.G., Vose, J.M., 2006. Potential water yield reduction due to forestation across China. J. Hydrol. 328 (3), 548–558.
Sun, P.L., Xu, Y.Q., Liu, Q.G., Liu, C., Huang, A., 2017. Spatiotemporal differentiation and driving factors of multi-functionality of land use in county scale in poverty belt around Beijing and Tianjin. Trans. Chin. Soc. Agric. Eng. (Trans. CSAE) 33 (15), 283–292 (in Chinese).
Tallis, H.T., Ricketts, T., Guerry, A.D., Wood, S.A., Sharp, R., Nelson, E., et al., 2011. InVEST 2.2.1 User's Guide. The Natural Capital Project, Stanford.
Tayyebi, A., Pijanowski, B.C., Pekin, B.K., 2015. Land use legacies of the Ohio River Basin: using a spatially explicit land use change model to assess past and future impacts on aquatic resources. Appl. Geogr. 57, 100–111.
Turner, R.K., Daily, G.C., 2008. The ecosystem services framework and natural capital conservation. Environ. Resour. Econ. 39, 25–35.
Turner, B.L., Lambin, E.F., Reenberg, A., 2007. Land change science special feature: the emergence of land change science for global environmental change and sustainability. Proc. Natl. Acad. Sci. 104, 20666–20671.
Turner, K.G., Odgaard, M.V., Bocher, P.K., Dalgaard, T., Svenning, J.-C., 2014. Bundling ecosystem services in Denmark: trade-offs and synergies in a cultural landscape. Landsc. Urban Plan. 125, 89–104.
Verburg, P.H., Van De Steeg, J., Veldkamp, A., Willemen, L., 2009. From land cover change to land function dynamics: a major challenge to improve land characterization. J. Environ. Manag. 90 (3), 1327–1335.
Vörösmarty, C.J., McIntyre, P.B., Gessner, M.O., Dudgeon, D., Prusevich, A., Green, P., et al., 2010. Global threats to human water security and river biodiversity. Nature 467 (7315), 555.
Wang, W.M., 2001. The perspective of 0.8 Mu warning line of cropland per capita. Chin. Land 10, 32–33.
Wayland, K.G., Long, D.T., Hyndman, D.W., Pijanowski, B.C., Woodhams, S.M., Haack, S.K., 2003. Identifying relationships between baseflow geochemistry and land use with synoptic sampling and R-mode factor analysis. J. Environ. Qual. 32 (1), 180–190.
Wei, T.Y., Simko, V., 2017. R Package "corrplot": Visualization of a Correlation Matrix (Version 0.84). Available from. https://github.com/taiyun/corrplot.
Wiggering, H., Dalchow, C., Glemnitz, M., Helming, K., Muller, K., Schultz, A., et al., 2006. Indicators for multifunctional land use – linking socio-economic requirements with landscape potentials. Ecol. Indic. 6, 238–249.
Wiley, M.J., Hyndman, D.W., Pijanowski, B.C., Kendall, A.D., Riseng, C., Rutherford, E.S., et al., 2010. A multi-modeling approach to evaluating climate and land use change impacts in a Great Lakes River Basin. Hydrobiologia 657 (1), 243–262.
Wischmeier, W.H., Smith, D.D., 1978. Predicting Rainfall Erosion Losses – A Guide to Conservation Planning. Agriculture Handbook No. 537 USDA/Science and Education Administration. US Govt. Printing Office, Washington, DC.
Yang, G., Bowling, L.C., Cherkauer, K.A., Pijanowski, B.C., Niyogi, D., 2010. Hydroclimatic response of watersheds to urban intensity: an observational and modeling-based analysis for the White River Basin, Indiana. J. Hydrometeorol. 11 (1), 122–138.
Yang, G., Ge, Y., Xue, H., Yang, W., Shi, Y., Peng, C., et al., 2015. Using ecosystem service bundles to detect trade-offs and synergies across urban–rural complexes. Landsc. Urban Plan. 136, 110–121.
Zawadzki, J., Kędzior, M., 2014. Statistical analysis of soil moisture content changes in Central Europe using GLDAS database over three past decades. Open Geosci. 6 (3), 344–353.
Zawadzki, J., Przeździecki, K., Miatkowski, Z., 2016. Determining the area of influence of depression cone in the vicinity of lignite mine by means of triangle method and LANDSAT TM/ETM+ satellite images. J. Environ. Manag. 166, 605–614.
Zhang, Y., Zhang, H., Lin, H., 2014. Improving the impervious surface estimation with combined use of optical and SAR remote sensing images. Remote Sens. Environ. 141, 155–167.
Zhang, H., Lin, H., Li, Y., Zhang, Y., Fang, C., 2016. Mapping urban impervious surface with dual-polarimetric SAR data: an improved method. Landsc. Urban Plan. 151, 55–63.
Zhong, T., Mitchell, B., Scott, S., Huang, X., Li, Y., Lu, X., et al., 2017. Growing centralization in China's farmland protection policy in response to policy failure and related upward-extending unwillingness to protect farmland since 1978. Environ. Plan. C Polit. Space 35 (6), 1075–1097.
Zhou, D., Xu, J., Lin, Z., 2017. Conflict or coordination? Assessing land use multi-functionalization using production-living-ecology analysis. Sci. Total Environ. 577, 136–147.