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A new framework of land use efficiency for the coordination among food, economy and ecology in regional development

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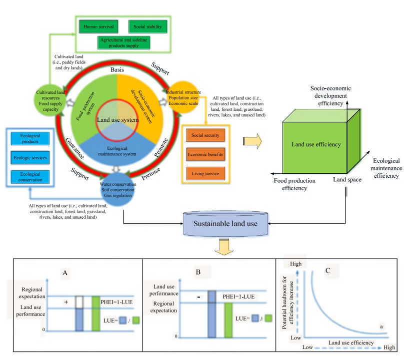
HIGHLIGHTS

- Proposing a new analytical framework of land use efficiency in food-economy-ecology.
- Identifying the coupling relationship among sub-categories and its impact factors.
- Analyzing the impact of land use efficiency on land use planning and management.

GRAPHICAL ABSTRACT



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ABSTRACT

Great challenges regarding land use conflicts in rapid urbanization call for deeper research on land use efficiency (LUE) from the perspective of sustainable land use for the coordination among food security, economic development, and ecological protection. This study firstly develops a new framework of LUE based upon the expectations in land use and the coordination among three sub-categories in food production, economic development, and ecological protection, then, uses the coupling coordination degree model to quantify the spatial differentiation characteristics and coupling coordination relationships among three sub-categories, and finally uses the multi-variable linear regression and geographical detectors to analyze the impact factors of sub-category efficiency. The framework is applied to Jiangsu Province in eastern China by using ten indicators (i.e., cultivated land quality, grain output, multiple cropping index, average GDP per km^2, population density, proportion of industry and service industry, vegetation cover index, water conservation index, soil retention index, and carbon sequestration index) in terms of food production, economy, and ecology analysis at the county level. Compared with expectations, the LUE of Jiangsu in food production, economic development, and ecological protection is 54.15%, 85.56%, and 54.95%, respectively, indicating that Jiangsu has great potential for sustainable land use. The coupling coordination degree in land use generally synchronizes with the coupling degree, accounting for 65.34% of the province's area, of which 75.00% are in lower-coupling & lower-coordination, medium-coupling & medium-coordination. Among all the factors, proportion of industry and service industry, population density, multiple cropping index, average GDP per km^2, and water conservation index have the most important roles in the coordinated development of land use sub-systems. Therefore, we suggest land use/urban management need to

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implement more integrated planning and differentiated strategies to stimulate land use potential and maintain efficient and sustainable land use.

1. Introduction

Human population increase and economic growth agendas (e.g., MBIE, 2015) increase the pressure on natural resources and ecosystems around the world (Herzig et al., 2018), 66% of the world's population is expected to live in urban areas by 2050 (Masini et al., 2018). Resource and environment issues caused by rapid urbanization have hindered sustainable development (Adam et al., 2015). These issues include the rapid expansion of construction land, the sharp decline of cultivated land resources, and environmental damage, etc. However, one of the greatest challenges associated with these issues is the contradiction of land use in food production, socio-economic development and ecological maintenance (Ellis, 1992; Lambin, 2012). In this case, improving land use efficiency is ideal for coordinating the above-mentioned land use contradictions and promoting sustainable development.

Land use efficiency (LUE) is a representative concept adhering to the sustainable development paradigm (Masini et al., 2018), and is also the result of dynamic processes driven by natural, economic, and social impacts (Wu et al., 2011). Previous studies on LUE primarily have two focus. One focus is to explore the LUE of a specific land use type, i.e., cultivated land (Lin and Hülsbergen, 2017; Yerseitova et al., 2018), industrial land (Xie et al., 2018a), urban construction land (Chen et al., 2016) or specific region, i.e., urban agglomeration (Cui et al., 2018), development zones (Huang et al., 2017a) in terms of spatial differences (Cao et al., 2019), saving potential (Fetzel et al., 2016; Xie et al., 2018a) and influencing factors (Bonfiglio et al., 2017; Miren et al., 2018). The second focus is to discuss the relationship between LUE and socio-economic development from the perspectives of resource utilization (Helena and Janne, 2016; Masini et al., 2018), urban growth (Halleux et al., 2012; John et al., 2015), environmental constraints (Saikku and Mattila, 2017; Searchinger et al., 2019) and economic transformation (Guastella et al., 2017; Lu and Ke, 2018). Generally, previous studies mainly focused on the comparison of regional differences but ignore the spatial interaction and impacts among land use sub-category efficiencies and the vast variances in land-use within the same area. In particular, there is still a gap in the integration of multi-source data in analyzing the coupling-related effects among land use sub-category efficiencies aiming at sustainable land use, especially the eco-environment data based on fine-scale data (e.g., land use spatial data, physical geographic data, remote sensing data, etc.). Overall, these studies have worked together to optimize the utilization of local land resources and have greatly expanded the breadth and depth of this topic.

However, it is also necessary to recognize that identifying LUE and thereby coordinating the effective utilization of land use among food production, economic development and ecological protection within a sustainable land use framework is still poorly addressed in the recent literature (Herzig et al., 2018; Melchiorri et al., 2019). Meanwhile, questions of data acquisition, comprehensive LUE evaluation-indexing system, and insufficient thorough understanding of land use patterns and interaction mechanisms have hindered the government from developing land use policies according to local conditions to tackle land use issues and improve LUE. Even if there are some individual case studies focusing on LUE across countries or cities (Zambon et al., 2018), to the best of our knowledge a comparative study guiding the optimal utilization of regional land resources through the comprehensive measurement of food production, economic development and ecological protection at regional scale is still missing.

An exhaustive analysis of land-use performance both at regional and local spatial scales contributes to finding alternative choices better designed for assuring LUE and long-term sustainability (Salvati, 2013; Salvati et al., 2018), especially within the framework of sustainable land use. As such, to fill the gaps of existing LUE studies and the needs for sustainable practices, this paper presents an empirical case study of Jiangsu Province in eastern China. A new conceptual index system for LUE assessment is put forward incorporating the aspects of food production, economic development, and ecological protection. On this basis, we identify the spatial differentiation characteristics, coupling relationships, and impact factors of LUE in rapidly urbanizing areas to obtain important discoveries for land use and land management. Specifically, the main objectives of this study include:

(1) Proposing a new analytical framework of land use efficiency from the perspective of sustainable land use (or regional expectation) in food-economy-ecology.
(2) Analyzing the spatial disparities, coupling coordination relationships and impact factors of land use sub-categories efficiency among food, economy, and ecology at the county level.

2. Theoretical framework

2.1. Structure and classification of land use system

Food security, economic development and ecological stability are the basic and most important needs for human well-being (Wang et al., 2018), and they are deeply affected by human land use behavior. Reflected in land use, that is, interaction among the diversified land use types, natural features of land resources, human activities and the external environment forms a complex land use system (Fig. 1), which consists of sub-systems that function in regard to food production, socio-economic development, and ecological preservation (Bach et al., 2015; Verstegen et al., 2016; Zhou et al., 2017).

Fig. 1 illustrates the coupled symbiotic relationship among the land use sub-systems. Structurally, the food production system serves as the foundation, the socio-economic development system has the goal of feedback support, and the ecological maintenance system guarantees the maintenance of service provision. Among them, the food production system provides agricultural and sideline products for human survival, mainly referring to cultivated land, namely paddy fields and dry lands. The socio-economic development system offers economic benefits, social security and living services. Improvements in socio-economic level can support regional agriculture production and ecological protection through the provision of funds, technology, and other resources. Spatially, the socio-economic development system mainly points to the entire national land space (Li and Fang, 2016; Zhang et al., 2019), including cultivated land (i.e., paddy fields and dry lands), construction land (i.e., urban land, rural residential land, and other construction lands), ecological land (i.e., forest land, grassland, rivers, and lakes), and unused land. The ecological maintenance system provides the high-quality provision of ecological products, services, and conservation (Groot, 2006). Particularly, the ecological maintenance system targets the prerequisite requirements of sustainable land use system. Therefore, the ecological maintenance system also points to the entire national land space (as mentioned above), which is the same as the socio-economic development system. In particular, the construction of greening facilities in urban and rural construction land also has certain ecological protection functions (Liu et al., 2011).

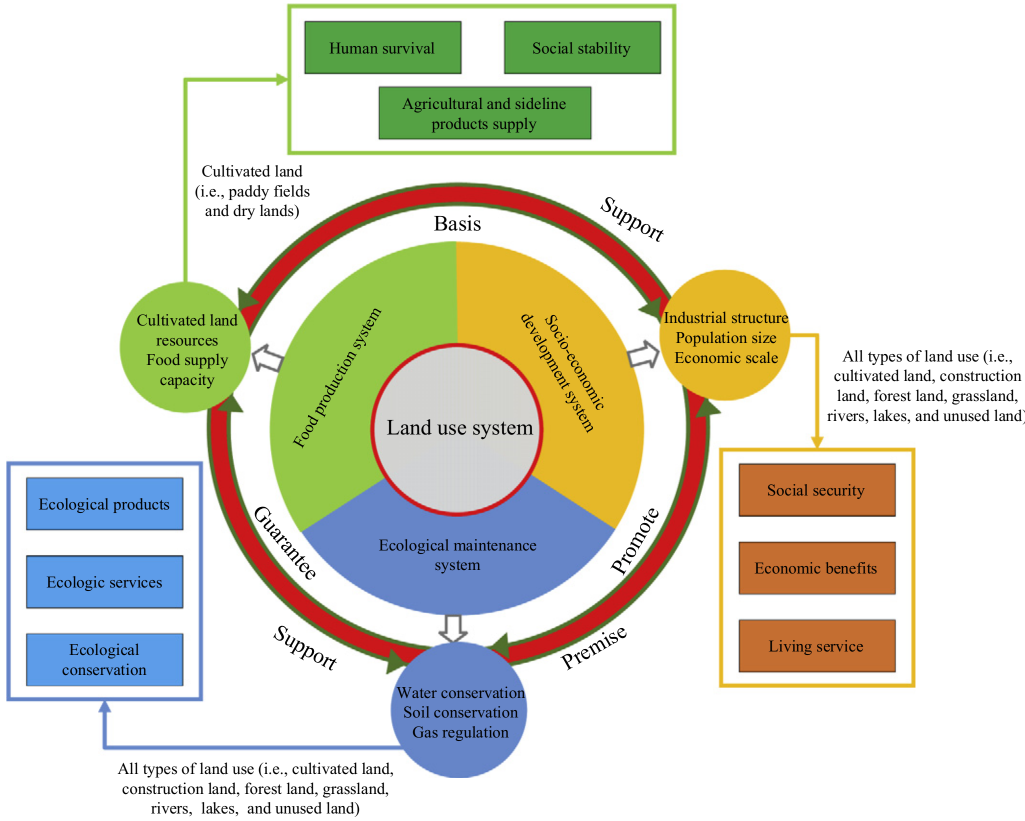

Fig. 1. Structure of the land use system improved from Zhou et al. (2017). The solid red line represents the land use system, including the sub-systems of the food production system (light green), socio-economic development system (orange) and ecological maintenance system (blue). Green arrows indicate the interaction mechanism among the land use sub-systems; gray arrows indicate the key elements of sub-systems; light green, orange, and blue boxes indicate the dominant functions and land use targets of various types of sub-systems in the regional development; light green, orange and blue arrows point to different land use types to achieve the dominant functions and development goals of the corresponding sub-systems, respectively.

2.2. Connotation of LUE

2.2.1. Conceptual overview

In general, scholars from various countries have discussed the concept of LUE from four perspectives. First, earlier studies investigated the notion of LUE in terms of economic output for each land unit (Barbosa et al., 2015; Masini et al., 2018). In this regard, Wu et al. (2017) described LUE as "the ratio of the total output value of secondary and tertiary industries to the area of urban land". Second, some studies have linked the conceptual design of LUE to the maximum benefits or minimum costs of resource use. More recently, Herzig et al. (2018) defined the resource-use efficiency of land use as "the ratio of land-use performance over maximum land-use performance". Third, other studies have associated the notion of LUE to the long-term sustainability of development (Jaeger et al., 2010; Salvati, 2013; Pili et al., 2017). In this regard, Zitti et al. (2015), Zambon et al. (2018), and Masini et al. (2018) employed the ratio of built-up areas to resident population to reflect the LUE, holding that the concept of LUE was linked to the "hectares of new development in relation to the number of people supported" (Ceccarelli et al., 2014; Colantoni et al., 2016). Fourth, some scholars regarded the process of land use as an input-output system to evaluate LUE from the aspects of material input (Zhang and Jiao, 2015), economic expected output (Moutinho et al., 2017), and environmental undesirable output (Robaina et al., 2015) during the process of land use, especially for the specific economic sectors or businesses. In addition, several indicators have also been used to measure such a complex concept, such as pure technical efficiency (Barath and Ferto, 2015) and eco-efficiency (Camarero et al., 2013).

In summary, there is no single commonly agreed definition of LUE (Zhang and Jiao, 2015). Throughout the existing conceptual understanding of LUE, economic benefits, land productivity, environmental efficiency, and eco-efficiency are often classified into the scope of LUE, resulting in a broader comprehensive concept (Chen and Wu, 2014). In reality, these extensive conceptual designs are of great significance in guiding the efficiency improvement of the specific economic sectors, while having limited supports for guiding the optimal utilization of land resources at larger scales. Because the regional differences in the stock of land resources and the utilization potential (Huppes and Ishikawa, 2007) lead to the disconnect between land use targets at larger scales and efficiency improvements in specific economic sectors.

With the increasing pressure on global natural resources and ecosystems, LUE should not only focus on the economic benefits but also attempt to achieve the unity of economy, society and ecology (Kades, 2000; Salvati, 2013; Pili et al., 2017). Therefore, in the context of the call to use resources and the environment more efficiently and sustainably to satisfy the increasingly diversified demands for human survival and development, two questions arise: 1) what is the new connotation of LUE from the perspective of sustainable land use? 2) how do we measure it?

2.2.2. LUE from the perspective of sustainable land use

Efficiency refers to the degree and quality of achieving desirable goals of promoting the optimal operation of the system (Fare et al., 1985; Heijungs, 2007; Pouriyeh et al., 2016). It also means the efficient allocation of resources (Davidoff and Reiner, 1973). However, we note that LUE in some of the studies mentioned in Section 2.2.1 is measured by the maximum performance of land use as the reference value.

However, the “maximum value” does not mean the “best value” due to that “maximum value” does not account for the differences in regional development foundations and conditions (Coelli et al., 2007). To a certain extent, it may lead to the spatial mismatch between expected land use objectives and actual land use performance, thus underestimating or overestimating the true level of LUE (Huppes and Ishikawa, 2007; Herzig et al., 2018). In that context, determining authoritative, reasonable, and achievable reference values to quantify LUE may be an ideal solution to the above spatial mismatch.

Our well-being depends on the products and services provided to us by the land use system. Therefore, we believe that land use sub-systems with different functions can provide the expected land use performance (i.e., regional expectations or sustainable land use targets) for human well-being based on existing resource conditions (e.g., land, population, etc.) and production technologies. These regional expectations are not necessarily the maximum value of resource utilization in the region but rely on the coordination and common development of society, economy, agriculture, ecology, resources, and environment. Its connotation is that it can attain the stage of development needs for social construction, and at the same time not endanger the sustainable utilization of resources. Generally, the expectations are defined by the values and objectives of the stakeholders in a specific region and are translated into a set of environmental and socio-economic land-use performance indicators and associated thresholds (Herzig et al., 2018). These indicators and thresholds represent the expected or sustainable land use performance levels of a given region at the specific stage of socio-economic development and are issued to the community through relevant policies and documents (Roetter et al., 2005). Potential stakeholders could be national or regional governments or agencies, such as ministries and council (Herzig et al., 2018). Especially, these regional expectations are characterized by regionality and variability. Regionality refers to the differentiated standards implemented by stakeholders based on regional variations in resource endowments and development levels; while variability mainly refers to that these expectations will change along with the advances in technology, economics, and social consciousness. In general, with the development of the above factors, the expectations will increase accordingly.

Fig. 2 reflects the connotation of LUE under sustainable land use. As such, referring to these regional expectations and following Fare et al. (1985) and Herzig et al. (2018), we understand the LUE as the degree to which land use sub-systems of different functions and types utilize the available natural resources to realize these regional expectations for providing benefits to human well-being. As such, the land use sub-category efficiencies, including food production efficiency, socio-economic development efficiency, and ecological maintenance efficiency, are respectively expressed as the ratio of current land use performance of sub-categories over the corresponding regional expectations. Land use performance represents the actual level of land resource utilization in each land use sub-system. Among them, food production efficiency is mainly aimed at the utilization of cultivated land, referring to the extent to which the actual food production performance in the cultivated land utilization achieves the regional expected food production level; while the socio-economic development efficiency and ecological maintenance efficiency are directed to the global space, the former refers to the degree to which the actual level of socio-economic development has reached regional expectations, while the latter refers to the extent to which the ecological maintenance function in the land use achieves regional expectations.

Hence, the fractal dimension LUE < 1 indicates that human's resource utilization level in the corresponding land use sub-system has not reached the regional expectations of resource utilization, and where there is still a large and reasonable utilization potential to be tapped into via improved land use planning and management and applying certain technologies; while the fractal dimension LUE ≥ 1represents that human's resource utilization level has reached or exceeded the expected level of resource utilization, which has different significance for land use in different dimensions. Specifically, in terms of agricultural production and ecological maintenance, LUE ≥ 1 indicates that the existing resource conditions or utilization intensity can provide products or services equal or higher than expected for human well-being for food production and ecological maintenance, which implies that existing resources and environmental conditions should be further improved or at least maintained in land use and management; while in economic development, LUE ≥ 1 may have sacrificed certain resources or the environment, indicating that it is necessary to enhance the capacity of regional sustainable development through land use policy, planning, and management, while maintaining or further developing the existing socio-economic achievements. On this basis, we further estimate the potential headroom for efficiency increase (PHEI) of each fractal dimension by “1-LUE” to quantify the gap between current land use performance in the corresponding land use sub-system and regional expectation. The headroom represents the unused potential of land use,

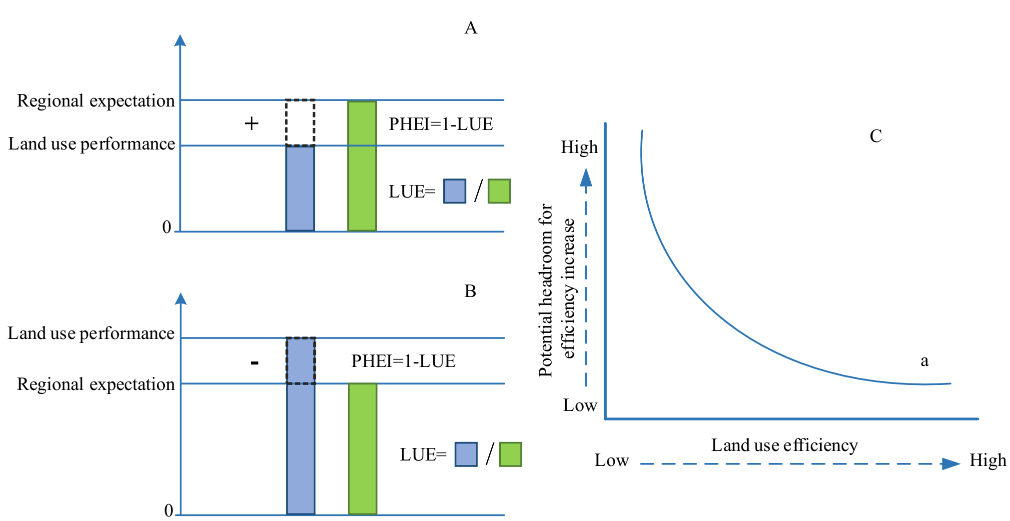

Fig. 2. The connotation of LUE improved from Herzig et al. (2018). The blue shades indicate land use performance in the corresponding land use sub-system; green shades represent the regional expectation of land use, i.e., the status of sustainable land use, and are determined by the corresponding national planning and technical standards. Black dotted boxes represent potential headroom for efficiency increase (PHEI) in land use with two categories of A and B. For A, “+” stands for LUE < 1 or PHEI >0. For B, “-” represents LUE ≥ 1 or PHEI ≤0. The curve a in C characterizes the relative trend between the LUE and the PHEI of the fractal dimension, that is, the higher the LUE, the lower the corresponding PHEI of the fractal dimension; conversely, the lower the LUE, the higher the corresponding PHEI.

indicating the maximum possible performance increase (Herzig et al., 2018) subject to regional expectation. Correspondingly, the significances of PHEI >0 and PHEI ≤0 vary greatly for land use in different dimensions, corresponding to the above-mentioned scenarios of LUE < 1 and LUE ≥ 1, respectively.

3. Materials and methods

3.1. Study area

Jiangsu Province is located within the eastern coastal center of China near lower reaches of the Yangtze River (Fig. 3), with an area of 107,200 km^2 and a total population of approximately 79.6 million. It is the frontier area of China's industrialization and urbanization, with a national land area of 1.12% carrying a population of 5.78% and a total economic output of 10.22% due to its superior geographical location and mild climate. Nevertheless, the area also suffers from severe resource shortage, with a per capita arable land area of only 0.057 hm^2, which is only 60.96% and 24.78% of the average national and global level, respectively. With rapid economic and social development, regional urban construction has a significant crowding effect on agriculture and ecological space (Xie et al., 2018a). As with other regions in China, Jiangsu Province is also faced with development constraints such as intensified conflicts in land space utilization, reduction in cultivated land resources, environmental damage, loss of biodiversity, and widening development gaps between regions (Zhou et al., 2017). More importantly, as a typical economically developed area in eastern China (Liu et al., 2019), Jiangsu Province serves as an excellent example of regional development for other areas in China and developing countries in the world. Particularly, it presents a typical case study for assessing land use sub-category efficiencies and coordinating conflicts based on food production, economic development, and ecological protection.

3.2. Workflow of this study and data sources

Based on the theoretical analysis of land use system and LUE, the workflow of our study is designed (Fig. 4) for the two objectives proposed in the Introduction. The analytical framework presented has the potential to make an essential contribution to the existing literature as it enriches the connotation of LUE to a certain extent and expands its content. As for land use and land management, the information derived from this analysis might not only be used to support regional planning and policy-making, for example, to identify the current resource utilization levels and quality, savings potential, and interrelationships among food production, economic development and ecological protection for sustainable land use, but also has theoretical and practical significance for optimal allocation of land resources and formulation of regional development strategies to narrow development gaps and enhance sustainable development capabilities.

In addition, this study focuses on the administrative division of Jiangsu Province at the county level in 2015, including 104 research objects. The data used in this study and their sources are shown in Table 1.

3.3. Multidimensional evaluation of LUE

We propose a conceptual index system for LUE assessment in terms of three aspects of land use efficiencies of food-economy-ecology in a land use system. The definition and quantitative method of each indicator are shown in Table 2.

We estimate fractal dimension LUE by relating (current) land use performance to the expected land use performance, which is in line with the stakeholders' expectations and objectives (Section 2.2.2), and further, calculate the potential headroom for efficiency increase (PHEI). The calculation method of each index is shown in Formulas 1–3.

$$LUP_i = \sum_{j=1}^{m} w_{ij} I_{ij} \tag{1}$$

$$LUE_{i,E} = \frac{LUP_i}{\sum_{j=1}^{m} w_{ij} I_{ij,E}} \times 100\% \tag{2}$$

$$PHEI_{i,E} = 1 - LUE_{i,E} \tag{3}$$

where, LUP_i denotes current land use performance of dimension i, reflecting the actual level of land resources utilization; $LUE_{i,E}$ denotes

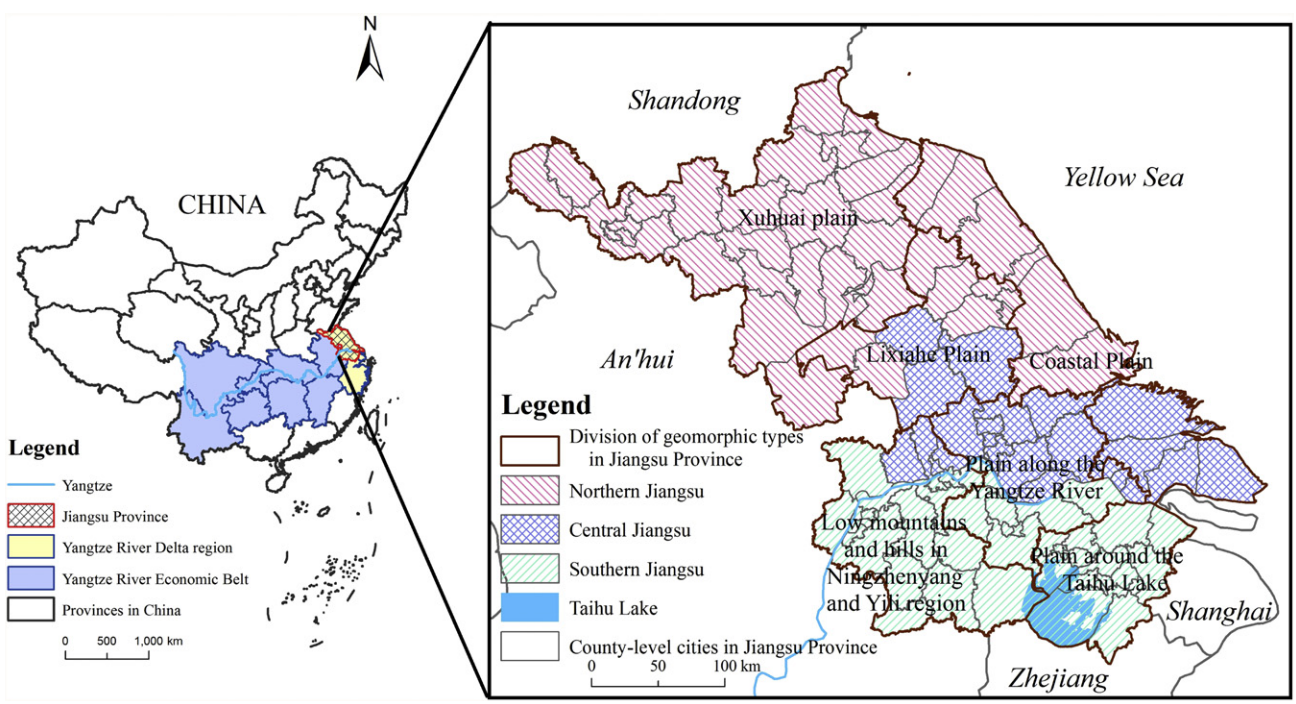

Fig. 3. Study area.

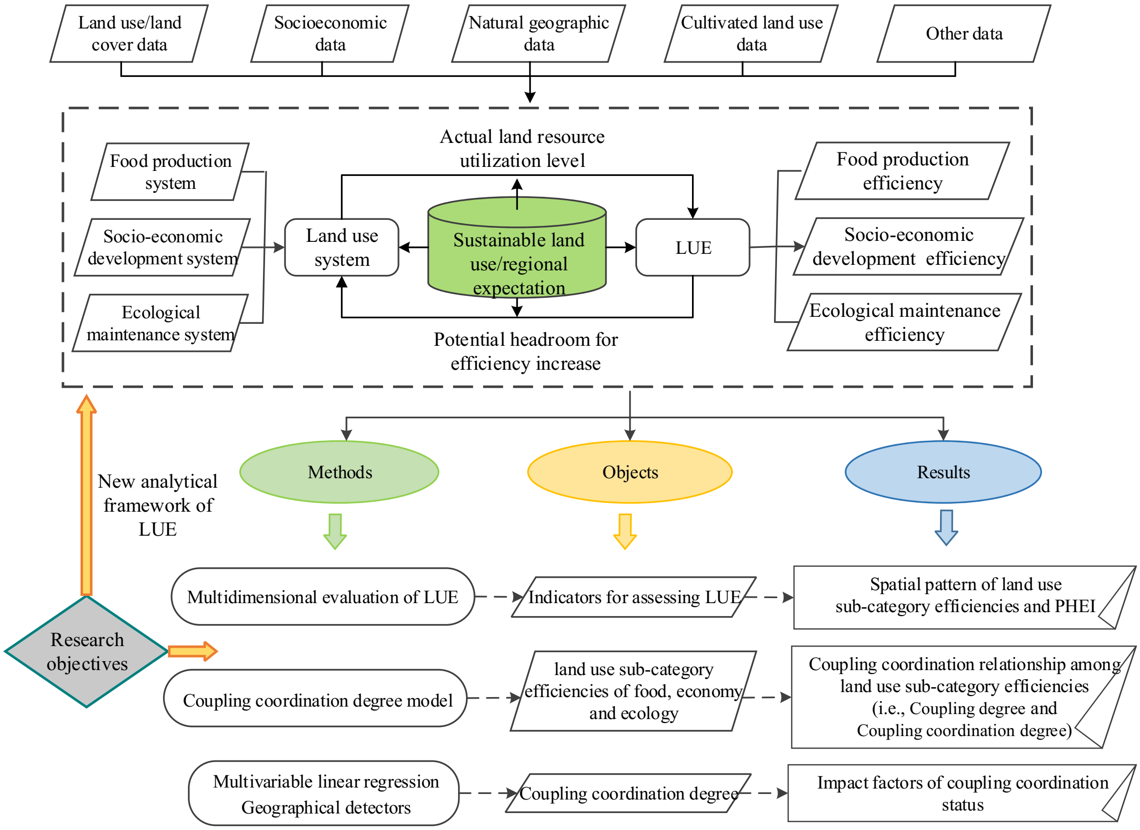

Fig. 4. The workflow of this study. "LUE" and "PHEI" indicate the land use efficiency and the potential headroom for efficiency increase, respectively.

the land use efficiency of dimension i, which is the degree to which the regional expectation of land resource utilization is realized in the corresponding dimension; $PHEI_{i,E}$ represents the potential headroom for efficiency increase in dimension i affected by regional expectation; m is the number of indicators in dimension i; I_{ij} is the normalized value of the indicator j in dimension i; $I_{ij,E}$ means the regional expectations of the j-th indicator in dimension i; w_{ij} represents the weight of the j-th indicator in i. The weights of indicators (Table 3) are calculated by combining the entropy weight method (EWM) and analytic hierarchy process method (AHP) (Liu et al., 2018). Among them, the basic principle of EWM is to determine the objective weights according to the variability of indicators and the size of the information entropy (Shemshadi et al., 2011). AHP is a method for determining indicators' weights by comparing, judging and calculating the relative importance or the order of advantages and disadvantages of indicators in different levels according to the interrelation and subordination among elements (Nikkhah et al., 2019). The combination of EWM and AHP can effectively make up for the limitations of the excessive dependence of EWM on evaluation data and the subjective randomness of AHP (Liu et al., 2018).

Further, the land use sub-category efficiencies of Jiangsu were calculated and divided into five grades (i.e., lowest, lower, medium, higher, and highest) by using the *Natural Break Method* in ArcGIS10.2 (ESRI, 2014).

The regional expectations simulate the ideal scenario of resource utilization under existing resource and technology constraints. Practically, these regional expectations of sub-categories efficiency are determined

Table 1
Data sources and descriptions.

Data name	Data source	Data type	Time-series	Resolution
Cultivated land quality data	Results of national survey of cultivated land quality (Cheng et al., 2014)	Vector	2010	1:10,0000
Land use/land cover data	National Earth System Science Data Center (Institute of Geographic Sciences and Natural Resources Research, CAS, 2015)	Vector	2015	1:10,0000
Multiple cropping index data	China cultivated land multiple cropping index dataset (Ding et al., 2015)	Grid	2013	1 km × 1 km
Socioeconomic data	Jiangsu Statistical Yearbook (Statistics Bureau of Jiangsu Province, 2016)	Txt	2016	County level
Normalized differential vegetation index (MODND1M)	Geospatial data cloud (Institute of Geographic Sciences and Natural Resources Research, CAS, 2009–2015)	Grid	2015	500 m × 500 m
DEM (ASTER GDEMV2)		Grid	2009	30 m × 30 m
Leaf area index (MOD15A2)		Grid	2015	1 km × 1 km
Precipitation	National Meteorological Information Center	Txt	2015	On-site
Temperature	(China Meteorological Administration, 2015)			
Soil data	Nationwide soil dataset based on the Second National Soil Survey (Institute of Soil Science, CAS, 1978-1984)	Vector	1990s	1:100,0000

Table 2
Indicators for assessing LUE.

Targets (A)	Corresponding land use types	Indicators (X)	Unit	Quantification method and key references
Food production efficiency (A_1)	Cultivated land (i.e., paddy fields and dry lands)	Cultivated land quality (X_{11})	Grade	Results of national survey of cultivated land quality (Cheng et al., 2014)
		Grain output (X_{12})	Kg/km^2	Grain yield / cultivated land area
		Multiple cropping index (X_{13})	Time	Crop sown area / cultivated area (Ding et al., 2015)
Socio-economic development efficiency (A_2)	All types of land use	Average GDP per km^2 (X_{21})	10,000 RMB/km^2	The gross domestic product (GDP) / total land area (Sun et al., 2017b)
		Population density (X_{22})	Capita/km^2	Total population / total land area
		Proportion of industry and service industry (X_{23})	%	The gross output value of industry and services/gross domestic product
Ecological maintenance efficiency (A_3)	All types of land use (i.e., cultivated land, construction land, forest land, grassland, rivers, lakes, and unused land)	Vegetation cover index (X_{31})	%	NDVI (Huang et al., 2017b)
		Water conservation index (X_{32})	Mm/km^2	InVEST (Tallis et al., 2011; Hu et al., 2018)
		Soil retention index (X_{33})	Kg/km^2	RUSLE (Wischmeier and Smith, 1978)
		Carbon sequestration index (X_{34})	T/km^2	Ground investigation data and spatialization of remote sensing data (Xu et al., 2018)

Note: For validation of the InVEST, please see Appendix 2.

accordingly by a series of more specific sub-categories of land use system. The determination basis and results of regional expectations are shown in Table 4.

3.4. Quantifying the coupling coordination relationship among land use sub-category efficiencies

The coupling coordination degree model (Jiang et al., 2017) is used to quantify relationships among the three land use sub-category efficiencies.

$$C = \left[(APSEI \times SEDEI \times ESMEI) / \left(\frac{APSEI + SEDEI + ESMEI}{n}\right)^3\right]^k \tag{4}$$

$$T = aAPSEI + bSEDEI + cESMEI \tag{5}$$

$$D = \sqrt{C \times T} \tag{6}$$

where, *APAEI*, *SEDAEI*, *EMAEI* are the standardized LUE in food production, socio-economic development, and ecological maintenance, respectively; C is the coupling degree among sub-category efficiencies, $C \in [0, 1]$, which characterizes the intensity of interactions and influences between sub-systems; T denotes the overall level of land use efficiency; D is the coupling coordination degree, $D \in [0, 1]$, which represents the degree of coordination of the interactions among sub-category efficiencies; a, b and c represent the contribution of *APAEI*, *SEDAEI*, *EMAEI* ($a + b + c = 1$), respectively. We consider that food production, socio-economic development, and ecological protection are equally important, as such, $a = b = c = 1/3$ (Ma et al., 2012); k is the regulation factor ($2 \le k \le 5$), this paper sets $k = 4$ to enhance the regional differences (Guan and Xu, 2014). The median segmentation method (Ma et al., 2012) is used to classify the coupling coordination types of land use sub-systems (Table 5).

Table 3
Evaluation index weight of LUE. "+" represents positive indicators, and "-" indicates negative indicators.

Targets (A)	Indicators (X)	Expected property	Weight of indicator
A_1	X_{11}	−	0.282
	X_{12}	+	0.447
	X_{13}	+	0.271
A_2	X_{21}	+	0.337
	X_{22}	+	0.351
	X_{23}	+	0.312
A_3	X_{31}	+	0.127
	X_{32}	+	0.331
	X_{33}	+	0.308
	X_{34}	+	0.234

3.5. Analyzing the impact factors of coupling coordination status

3.5.1. Multivariable linear regression

The multivariate linear regression (Liu et al., 2019) in SPSS 22.0 (Kirkpatrick and Feeney, 2014) is used to explore the statistical relationships among the coupling coordination degree (D) and the indicators in Table 2. D is used as the dependent variable and indicators in Table 1 as independent variables. Before regression analysis, multicollinearity diagnostics among independent variables are performed by determining the size of the variance inflation factor (*VIF*) of each variable. Generally, if the *VIF* of each variable is below 10, it means that there is no collinearity among variables (O'Brien, 2007; Xie et al., 2018a). All calculated *VIF*s in this paper were below 4.325. In addition, to establish a full regression model of variables, the "*Enter*" method is used for the selection of variables.

3.5.2. Geographical detectors

A geographical detectors model (Wang et al., 2010) was implemented to analyze the impact magnitude of the major coordination-contributing factors on D (coupling coordination degree), which was complementary to the multivariable linear regression method. Assuming that $A = \{A_h, h = 1, 2, \ldots, L$, where L is the factor classification number$\}$ are the attributes associated with the geographical stratum of a suspected D, the power of the determinant $A = \{A_h, h = 1, 2, \ldots, L\}$ to D is given by:

$$q = 1 - \frac{1}{n\sigma^2}\sum_{h=1}^{L} n_h {\sigma_h}^2 \tag{7}$$

where, q is the influence power of various factors on the geographical differentiation of coupling coordination degree; n_h is the number of samples in the sub-region h of the determinant A_h; n is the total number of samples of interest over the entire region A; σ_h^2 and σ^2 indicate the dispersion variance of sub-region h and the entire region A, respectively. The range of q is [0,1]. A larger value of q suggests more obvious spatial differentiation of D and stronger spatial determination of the independent variable X_i to D.

Table 4
Regional expectations of evaluation indexes.

Targets (A)	Indicators (X)	Districts and expected values			References
A_1		Huang-Huai-Hai District	Middle-Lower reaches of the Yangtze River		Comprehensive agricultural regionalization of China
	X_{11}	5	4		Regulation for gradation of agricultural land quality (GBT28407-2012) Results of national survey of cultivated land quality
	X_{12}	700,000	814,000		National and provincial demonstration areas for basic farmland construction
	X_{13}	2	3		
A_2		Urban planning area	Outside the urban planning area		City Planning Law of the People's Republic of China
	X_{21}	39,700	10,300		13th Five-Year Plan for Land and Resources Protection and Utilization of Jiangsu Province
	X_{22}	10,000	1,700		Technical regulations for evaluation of urban land intensive use potential
	X_{23}	95	90		China's top 100 townships in 2017 in Jiangsu Province
A_3		Natural ecosystem	Constructive land ecosystem	Farmland ecosystem	Land use types
	X_{31}	78	63	72	Ecological protection and construction plan of Jiangsu Province (2014-2020)
	X_{32}	180	40	110	National nature reserve in Jiangsu Province
	X_{33}	16,300	4,000	7,800	National demonstration area of ecological civilization construction in Jiangsu
	X_{34}	11,000	300	1,040	Province

Note: (1) For the food production efficiency, the expected values are determined by the optimal values in the secondary division of the agricultural division scheme proposed by the National Agricultural Regionalization Commission. Specifically, Jiangsu is divided into *Huang-Huai-Hai District* and *Middle-Lower reaches of the Yangtze River* (Fig. S1) according to the spatial variation of natural geographical factors in temperature, precipitation, and soil conditions, etc. Among them, the annual rainfall of *Huang-Huai-Hai District* is about 500–800 mm. Drought, flood, and soil salinization are the main unfavorable factors affecting agricultural production in this region. In comparison, *Middle-Lower reaches of the Yangtze River* is rich in water and heat resources, with an annual rainfall of about 800–2000 mm, which is a region with a high level of agricultural modernization. (2) For the socio-economic development efficiency, land space is divided into space within and outside the urban planning area (Fig. S2), according to its location conditions. Among them, "Urban planning area" refers to the regions with strict planning and control due to the urban construction and development, which are the highly concentrated regions of population, industry, finance, productivity, science and technology, and are the core of regional economic activities; while "Outside the urban planning area" includes suburbs, outer suburbs, and rural areas with low level of socio-economic development. (3) For the ecological maintenance efficiency, the division of land space is based on different land use types (Fig. S3), namely, natural ecosystem, constructive land ecosystem, and farmland ecosystem. Among them, "natural ecosystem" mainly includes forest lands, grasslands, rivers, and lakes; "constructive land ecosystem" mainly includes urban land, rural residential land, and other construction land; and "farmland ecosystem" mainly targets cultivated land, including land use types such as paddy fields and dry lands. The land use types in Jiangsu in 2015 are presented in Fig. S4.

4. Results

4.1. Spatial pattern of land use sub-category efficiencies and PHEI

The PHEI of land use will generally exhibit the opposite spatial pattern characteristics to LUE. Table 6 shows the average value of the fractal dimension LUE in Jiangsu Province.

The province's land use performance in food production only accounts for 54.15% of the national or regional expectations, and the northern Jiangsu is significantly higher than the central and southern Jiangsu (Fig. 5(a)). This indicates that Jiangsu still has an average of 45.85% sustainable food production potential to be improved. Besides, from the spatial pattern of food production efficiency in Jiangsu, it can be inferred that the high-value areas of PHEI in food production are mainly concentrated in the southwestern low hills, plains along the Yangtze River and the Taihu Lake plains. In particular, the regions with a higher- or highest-grade are mainly distributed in the urban planning areas.

The spatial difference of socio-economic development efficiency in Jiangsu is obvious, which contradicts the food production efficiency (Fig. 5(b)). Compared with the efficiency of food production and ecological maintenance, the unbalanced development in socio-economic is still prominent, with a standard deviation of 23.61%, which is significantly higher than the standard deviation of 17.96% of food production efficiency and 17.44% of ecological maintenance efficiency. Further, Table 6 also shows that compared with the expected socio-economic development goals, the province still has an average of 14.44% sustainable economic development potential to be strengthened. The PHEI of socio-economic development is characterized by high-potential clusters in northern Jiangsu and low-potential clusters in central and southern Jiangsu.

The average provincial ecological maintenance efficiency is 54.95%. The proportion of regions at lowest, lower, medium, higher, and highest grades in the province is 16.35%, 26.92%, 26.92%, 21.53%, and 8.65%, respectively (Fig. 5(c)). Among them, the highest grade is mainly distributed in the low hills of Yili in the southwest. Conversely, the PHEI in ecological maintenance in Jiangsu is mostly at the medium and lower level with the average value of PHEI = 45.05%.

4.2. Coupling coordination relationship among land use sub-category efficiencies

The intensity of interaction among food production, economic development and ecological maintenance in land use system of Jiangsu is generally at a medium coupling level (Fig. 6(a)) with the average value of $C = 0.458$. From the perspective of spatial distribution, benign level coupling areas ($C > 0.8$) are concentrated in the south of the plains along the Yangtze River and the east of the Taihu Lake plains. Lower level coupling areas ($C \le 0.3$) are widely distributed in the south of Xuhuai Plain, and the north of Coastal Plain. The regions with a higher coupling ($0.5 < C \le 0.8$) are mainly distributed in central and southern Jiangsu, and constitute the main coupling type of interaction among land use sub-systems.

Table 5
Discriminating standards of coupling coordination degree.

Coupling degree (C)	Coupling type	Coupling coordination degree (D)	Type of coupling coordination
$0 < C \le 0.30$	Lower level coupling	$0 < D \le 0.45$	Lower coordination coupling
$0.30 < C \le 0.50$	Medium coupling level	$0.45 < D \le 0.65$	Medium coordination coupling
$0.50 < C \le 0.80$	Higher coupling level	$0.65 < D \le 0.80$	Higher coordination coupling
$0.80 < C \le 1$	Benign level coupling	$0.80 < D \le 1$	Optimal coordination coupling

Table 6
The average value of fractal dimension LUE in Jiangsu.

Region	Food production efficiency	Socio-economic development efficiency	Ecological maintenance efficiency
Jiangsu Province	54.15%	85.56%	54.95%
Northern Jiangsu	67.03%	66.06%	56.40%
Central Jiangsu	56.05%	92.43%	50.20%
Southern Jiangsu	40.50%	100.74%	56.21%

The coupling coordination degree (D) among land use sub-category efficiencies generally shows the spatial pattern characteristics similar to the C, but with obvious differences in local areas (Fig. 6(b)). Generally, the overall provincial degree of D is mostly at a medium level with an average value of 0.474. Spatially, the D presents a spatial pattern that gradually increases from north to south, which is represented by the low-value agglomeration areas of D in the north and high-value agglomeration areas in the south. Furthermore, the proportion of regions with the lower, medium, higher, and optimal levels of D is 37.50%, 40.38%, 18.27%, and 3.85%, respectively.

As a whole, the coupling degree and the coupling coordination degree are synchronized of the same geographical unit among food production, economic and ecological sub-category efficiencies, accounting for 65.34% of the province's area, of which 75.00% are in lower-coupling & lower-coordination, medium-coupling & medium-coordination.

4.3. Impact factors of coupling coordination status among land use sub-category efficiencies

The adjusted R^2 of the multivariate linear regression analysis is 0.767. Only cultivated land quality (X_{11}) failed significance test in the t-test, while the other variables were significant at the 1% or 5% level. The multivariable linear regression results of the factors affecting the coupling coordination status among land use sub-category efficiencies are shown in Table 7.

As indicated in Table 7, the results of the *Beta* analysis of the linear regression standardized coefficient featured the importance of indicators with significantly positive and negative correlations with coupling coordination degree. The order of impact factors in Table 7 (ranked in descending order of absolute values of *Beta*) is the following: X_{23} (Proportion of industry and service industry) > X_{22} (Population density) > X_{13} (Multiple cropping index) > X_{21} (Average GDP per km^2) > X_{32} (Water conservation index) > X_{12} (Grain output) > X_{33} (Soil retention index) > X_{34} (Carbon sequestration index) > X_{31} (Vegetation cover index) > X_{11} (Cultivated land quality). In general, economic and agricultural factors demonstrate a larger magnitude of correlation compared to ecological factors, especially the X_{23} (Proportion of industry and service industry), X_{22} (Population density) and X_{13} (Multiple cropping index).

From the perspective of the impacts of sub-systems on the coupling coordination degree (D) among land use sub-category efficiencies, X_{13} (Multiple cropping index) and X_{12} (Grain output) in food production system have significant roles in the coordinated development of land use sub-systems, especially the X_{13} (Multiple cropping index), which ranks third among all indicators. In addition, X_{12} (Grain output) is negatively correlated with D. In socio-economic development system, X_{23} (Proportion of industry and service industry) has a significant positive correlation with D and a top rank among indicators, while significant negative correlation exists between X_{22} (Population density) and D, X_{21} (Average GDP per km^2) and D. In ecological maintenance system, X_{31} (Vegetation cover index), X_{32} (Water conservation index), X_{33} (Soil retention index) and X_{34} (Carbon sequestration index) have a significant positive correlation with the coordinated development of land use sub-systems.

In addition, geographical detectors were used to identify the impact factors in Table 1 (X_{11}~X_{34}) on coupling coordination degree, and the influence power is 0.136, 0.151, 0.263, 0.286, 0.363, 0.383, 0.121, 0.195, 0.034 and 0.060, respectively. The order of influence power is as follows: X_{23} (Proportion of industry and service industry) > X_{22} (Population density) > X_{21} (Average GDP per km^2) > X_{13} (Multiple cropping index) > X_{32} (Water conservation index) > X_{12} (Grain output) > X_{11} (Cultivated land quality) > X_{31} (Vegetation cover index) > X_{34} (Carbon sequestration index) > X_{33} (Soil retention index). The results of multivariable linear regression and geographical detectors indicate that among all measured indicators for coupling coordination degree in Jiangsu Province, these five indicators (ranked in descending order of absolute values of *Beta*), including X_{23} (Proportion of industry and service industry), X_{22} (Population density), X_{13} (Multiple cropping index), X_{21} (Average GDP per km^2), and X_{32} (Water conservation index), are the dominant factors affecting the geographical differentiation of the coordinated development of land use sub-systems in Jiangsu Province.

5. Discussion

5.1. Analysis of the spatial pattern of coupling coordination degree

The results of this study revealed that the areas with higher coordination coupling ($0.65 < D \le 0.80$) and optimal coordination coupling ($0.8 < D \le 0.94$) are mainly concentrated in southern Jiangsu, and the spatial diffusion effect of high-value areas of D (coupling coordination degree) has been produced (Fig. 6(b) in Section 4.2). This is mainly due to the favourable geographic location (e.g., adjacent to the Yangtze River and the Shanghai metropolitan area with international features), abundant economic basis, perfect infrastructure, and great approval from the government (e.g., development strategies and policies). Specifically, most of these areas rely on large cities or urban agglomerations to establish a more mature urban hierarchy and industrial system, and gradually grow into the core regions leading to regional independent innovation, promoting the transformation and upgrading of industrial structure, and driving the national economic development with their higher levels of socio-economic development and superior resources. Meanwhile, southern Jiangsu has become a pioneer area for the country to promote the construction of ecological civilization. Major regional development strategies and policies (e.g., returning farmland to forests and lakes, agricultural land consolidation, ecological compensation, and rehabilitation) implemented by the government in succession have made a significant practical impact on the coordinated development of regional economy, society, resources, environment and ecology, therefore effectively balancing the operational environment of land use sub-systems (Zhou et al., 2017).

In comparison, the areas with lower coordination coupling ($0 < D \le 0.45$) and medium coordination coupling ($0.45 < D \le 0.65$) are mainly distributed in northern Jiangsu (Fig. 6(b)). This is primarily due to constraints on poor geographic location, market environment, scientific and technological levels, and human resourcing, the level of regional socio-economic development and the efficiency of environmental protection are relatively low, resulting in the low degree of coupling and coordination among the sub-systems. Therefore, policies could be designed to intervene in the coupling and coordination process of land use sub-systems through effective implementation of measures of environmental protection and public awareness (Lu and Ke, 2018; Cao et al., 2019).

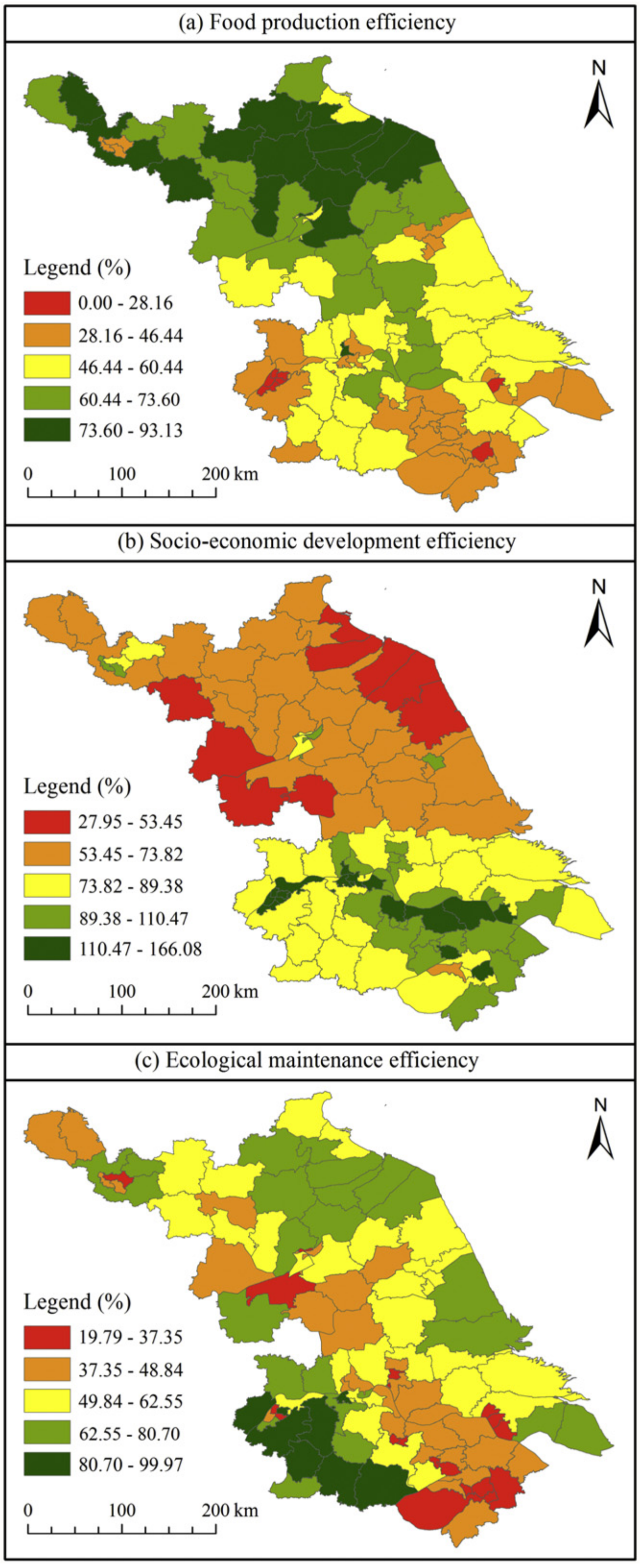

Fig. 5. Spatial differentiation characteristics of LUE in Jiangsu. The difference between red to green characterizes the increasing trend of LUE in each fractal dimension.

5.2. Driving mechanisms of coordinated development of land use sub-systems

This work shows that socio-economic development has a significant impact on the coupling and coordinated development of land use sub-systems (Table 7), whether based on the results of multivariable linear regression or geographical detectors. Specifically, the X_{23} (Proportion of industry and service industry) has a significant positive effect on coupling coordination degree, while both X_{22} (Population density) and X_{21} (Average GDP per km^2) have significant negative effects. These findings indicate that economic aggregates and population size are not the necessary conditions to promote the coordinated development of land use sub-systems. Instead, their growth may also lead to excessive consumption of resources, disorderly development of space, and environmental damage. These results are consistent with previous empirical findings that the unilateral pursuit of industrial GDP and the booming increase of industrial labor force have led to a decrease in the efficiency of China's industrial land use and resulted in serious industrial pollution (Xie et al., 2018a, 2019). Meanwhile, for every 1% increase in population, urban LUE will be reduced by 0.012% (Lu et al., 2016).

In food production system, X_{11} (Cultivated land quality) and X_{13} (Multiple cropping index) have significant positive effects on the coupling and coordinated development of land use sub-systems, while X_{12} (Grain output) has a significant negative effect. Particularly, higher X_{13} (Multiple cropping index) of cultivated land represents the higher level of intensive utilization of regional cultivated land resources, which provides effective support for coordinating regional economic development and environmental protection. X_{12} (Grain output) inhibits coordinated development of land use sub-systems, because higher grain production capacity usually implies the dominance of regional agricultural production activities and the relatively homogenous type of land use, which to some extent results in a weak interaction among different land use sub-systems. A recent study also demonstrated that the improvement of cultivated land multiple cropping index and cultivated land quality can fully stimulate the potential of cultivated land use, improve LUE, inhibit ecological and environmental damage such as soil erosion, so as to achieve orderly and sustainable development of land space and win-win of food security and ecological security (Jiang et al., 2019).

All indicators in ecological maintenance system have a significant positive effect on coupling coordination degree. Specifically, ecological processes such as water conservation, soil conservation, and gas regulation, have provided a variety of ecosystem services, such as support, supply, and regulation for the stable and orderly operation of land use system. In this case, the optimization of ecosystem structure and the improvement of the ecological environment can effectively promote the coordinated development of land use sub-systems. These findings are similar to Cao et al. (2019), that is, the improvement and construction of ecological environment has led to an increase in LUE. In other words, the capacity of food production and economic development per unit area can be enhanced through the management and optimization of ecosystems, and the synergistic effect on a larger scale can be realized (Qian et al., 2018).

In short, the driving mechanisms of coordinated development of land use sub-systems indicate that promoting the optimization of economic structure and improving the level of intensive utilization of resources may be more beneficial to improve the coordinated development of land use sub-systems. Policies targeting green economy development and food security may contribute to the orderly development of food production, economy, and ecology.

5.3. Implications for land use planning and management

5.3.1. LUE should be embedded in land use planning

This study shows that land use sub-category efficiency and fractal dimension PHEI in Jiangsu Province possess different characteristics at the

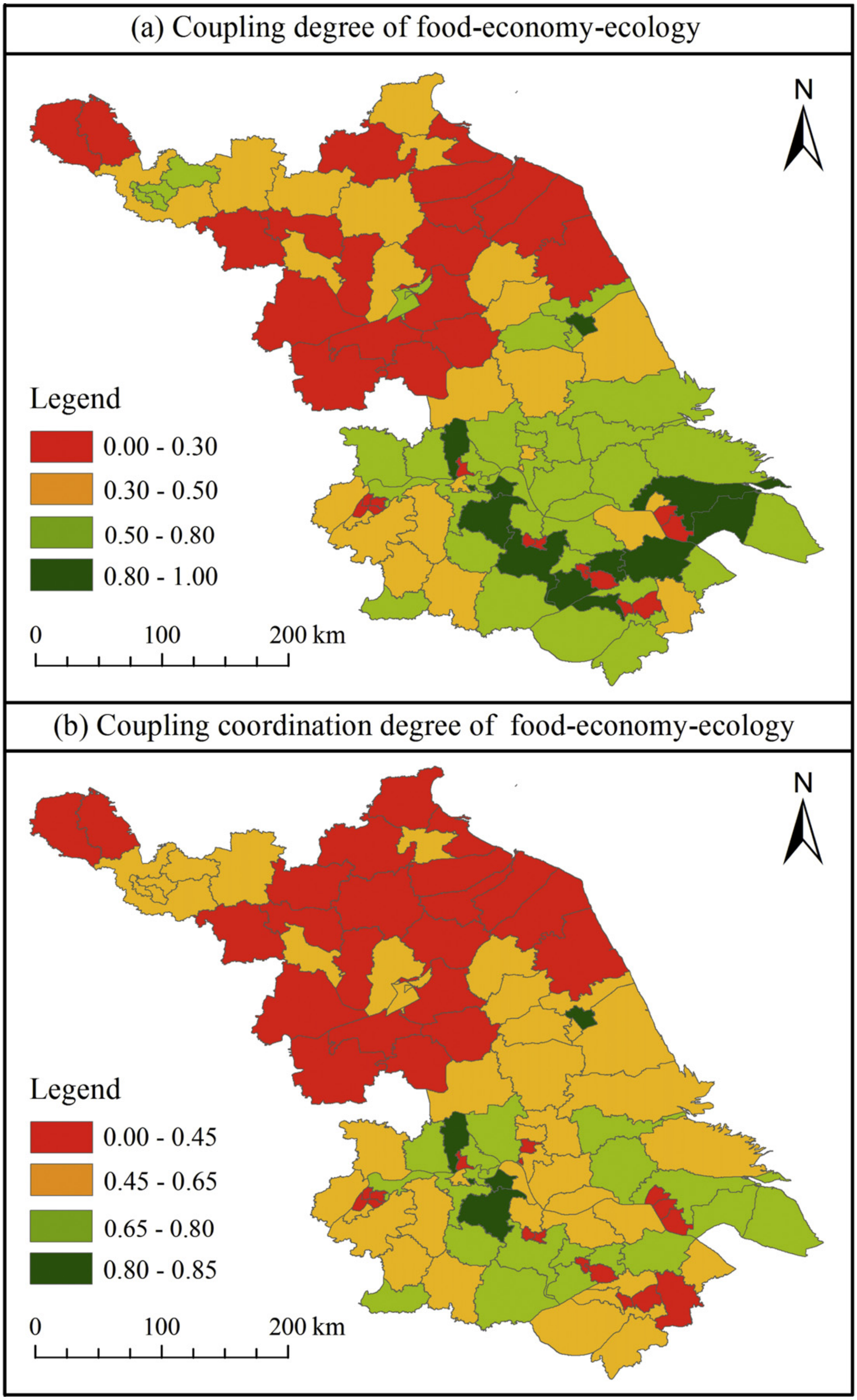

Fig. 6. Spatial coupling and coordination of land use sub-category efficiencies in Jiangsu.

Table 7
Results of the multivariable linear regression of the factors affecting the coupling coordination status among land use sub-category efficiencies.

Targets (*A*)	Indicators (*X*)	Unstandardized *B*	Std. Error	*t*	*Sig.*	Standardized *Beta*
A_1	X_{11}	0.095	0.400	0.238	0.813	0.019
	X_{12}	-0.574^{***}	0.213	−2.691	0.008	−0.246
	X_{13}	1.318^{***}	0.489	2.697	0.000	0.374
A_2	X_{21}	-0.471^{***}	0.205	−2.297	0.005	−0.288
	X_{22}	-1.655^{***}	0.440	−3.759	0.000	−0.475
	X_{23}	2.315^{***}	0.321	7.203	0.000	0.648
A_3	X_{31}	0.249^{**}	0.479	0.520	0.045	0.048
	X_{32}	3.450^{**}	1.636	2.109	0.024	0.258
	X_{33}	0.904^{**}	0.585	1.546	0.038	0.183
	X_{34}	0.661^{**}	0.364	1.818	0.040	0.168
Constant		-2.317^{***}	0.469	−4.490	0.000	

*** Denotes significance level at 1%.
** Denotes significance level at 5%.

provincial and regional levels. The sub-category efficiency and PHEI of land use at the regional-level show the significant spatial variation, such as food production in northern Jiangsu and economic development in southern Jiangsu. In particular, the PHEI of economic development in southern Jiangsu is only −0.74%, while the PHEI in the province is 14.44%, indicating that the potential headroom for efficiency improvements at the regional level may be insufficient. Besides, the phenomenon that the areas with lowest- or lower-level food production efficiency are mainly located in urban planning areas may be due to factors such as the occupation of the surrounding arable land and the abandonment of farmland for urban development. In these cases, optimizing the allocation of land resources through government behaviors is the core issue for sustainable development, because the government plays an important role in promoting the effective utilization of land resources through policies, planning regulations, and schemes (Lu and Ke, 2018), which can effectively coordinate the spatial mismatch between land use sub-category efficiency and fractal dimension PHEI at the provincial and regional levels, and achieve a balance of LUE in a larger area.

Recent studies have also advocated government or land use management to embrace more integrated and comprehensive planning to maintain effective and sustainable land use (Zhou et al., 2017; Herzig et al., 2018). Therefore, it is necessary to improve the national land spatial planning system and incorporate the LUE into the planning and decision-making of policies for sustainable land use (Herzig et al., 2018). Firstly, governments should regard a region's LUE as the scientific basis of planning during socio-economic development and improve its enforcement (Lu et al., 2018). Meanwhile, regional differences in LUE, especially the PHEI, should be taken as guidance for the allocation of land indicators (e.g., construction land, newly-increased cultivated land) and decision-making of regional development strategies during the adjustment, revision or redesign of relevant planning. Secondly, the government should scientifically understand the spatial patterns, key issues, and savings potential of LUE in different regions. On this basis, differentiated land use policies should be embraced to narrow regional development gaps and tap into the potential land uses, such as macroeconomic layout policy, industrial development policy, and investment or financing policy (Lu et al., 2018). Thirdly, the government should pay more attention to the spatial differences and correlations of regional LUE to gradually eliminate administrative barriers and optimize the spatial linkage environment for LUE. Specifically, the spatial spillover effects of high-value clusters of LUE should be enhanced to promote the improvement of LUE in adjacent areas. Low-value clusters of LUE should be encouraged and supported to improve regional openness and actively accept radiation from high-value clusters relying on its resource endowment.

5.3.2. Implications for land use management

Our results show that all research objects in Jiangsu have LUE < 1 in food production and ecological maintenance. For economic development efficiency, the objects of LUE < 1 are mainly concentrated in the southwest, central and north of Jiangsu Province, while the objects of LUE ≥ 1 are generally distributed along the Yangtze River and around Taihu Lake (Fig. 5). As we explained in Section 2.2.2, the relative relationship between current land use performance and expectations in food production, economic development, and ecological maintenance also implies the implementation of different land use management strategies.

5.3.2.1. For the case of LUE < 1. For the situation of LUE < 1, such as the efficiency of food production and ecological maintenance in the whole province, and the socio-economic development efficiency in central and northern Jiangsu (Fig. 5), it means that the current land use performance in these regions has not reached the expected level of resource utilization, and there is great potential for land utilization. The realization of these potentials may require joint action by all stakeholders, such as governments and local authorities (Lu and Ke, 2018). For governments, it is necessary to strengthen the supports for regional food production, socio-economic development and ecological maintenance, including policy support, financial support, and technical support, etc. For example, the government could further stimulate regional food production potential and improve the quality of farmland utilization by: 1) encouraging the orderly circulation of cultivated land management rights to raise the level of intensive use of cultivated land and develop moderate scale of agriculture with multiple management models and cooperative management (Liu et al., 2019); 2) guiding farmers to control the use of chemical fertilizers, pesticides, plastic sheeting and other chemicals in agricultural production to reduce farmland pollution and improve the quality of cultivated land. Because recent researches have confirmed that due to the improper use of chemical fertilizers and pesticides, the ecological environment around the cultivated land is more serious, greatly reducing the production capacity of cultivated land and the quality of agricultural products (Skevas et al., 2014; Xie et al., 2018b); and 3) exploring the incentive mechanism of grain production scale to stimulate farmers' enthusiasm for agricultural production.

In terms of economic development, as discussed in the literature (Xie et al., 2018a), most cities have sufficient room for improvement in LUE in industrial (economic) development due to that the proportion of cities with the average utilization efficiency of industrial land <1 is 84.38%. Our results confirm that 73.08% of county-level cities in Jiangsu have not achieved the expected economic benefits of land use (Fig. 5 (b)), i.e., the LUE in economic development is <1. Therefore, government should take certain administrative measures (e.g., improving the market mechanism and reforming comprehensive supporting facilities) to enhance the spatial agglomeration of population, industry and other economic factors and activate the vitality and potential of economic development. For local authorities, it is necessary to break beyond administrative boundaries and establish the concept of large-scale regional development (Wu et al., 2017). To promote the optimization and upgrading of regional industrial structure, locally superior industries should be actively cultivated, and overall planning and unified investment should be made according to the local resource endowment. Besides, industrial transition and setting up incentive mechanisms for talent introduction and preferential policies for enterprises' residence to create conditions for the flow of production factors (e.g., labor, capital, and technology, etc.) should be actively undertaken (Xie et al., 2019).

As for the potential headroom for ecological protection efficiency increases, while strictly protecting the existing ecological space (e.g., rivers, lakes), it is also necessary to pay attention to the ecological service functions of cultivated land resources in regulating climate, conserving water, maintaining biodiversity and landscape heterogeneity. In addition, a multifunctional and tridimensional greening system in urban and rural areas should also be further constructed and strengthened, such as road greening, courtyard greening, and building greening (Lu et al., 2018).

5.3.2.2. For the case of LUE ≥ 1. It is important to note that although there is no LUE ≥ 1 in food production and ecological maintenance in Jiangsu Province, these situations indicate that the existing resource conditions can provide products or services equal or higher than the regional expectations for human well-being. Therefore, land use management in these cases should focus on improving or at least maintaining the existing land use performance. Specifically, the subjective behavior of stakeholders (e.g., government, enterprise, and citizen, etc.) should be regulated to intervene in the process of regional resource utilization. These actions include the guidance and effective implementation of government policies, the application of environmental technologies, and the enhancement of environmental protection and public awareness, etc. (Cao et al., 2019).

Finally, the results show that the situation with LUE ≥ 1 in economic development is mainly concentrated in the plains along the Yangtze River and around Taihu Lake in southern Jiangsu, accounting for 26.92% of all county-level cities (Fig. 5(b)). Despite the high-level economic development in these regions, to some extent, the above situation may imply the sacrifice of resources and environment, highlighted by the overload of land space, overcrowding and insufficient supply of resource space. Previous studies have also confirmed the development challenges and contradictions between the high-level economic development and the severe resources bearing and shortage in the above regions (Xie et al., 2018a; Liu et al., 2019; Zhang et al., 2019). In this case, promoting the intensive use of land resources and improving LUE through macro-control and internal tapping of potential should be the policy targets for land use management while maintaining or further developing the existing socio-economic achievements (Lu and Ke, 2018; Masini et al., 2018). Government can disperse human economic activities and relieve the carrying pressure of regional resource (e.g., population, industry, etc.) to achieve adjustment and management of orderly land space through certain administrative means, such as space control, planning regulation, and transformation of economic development pattern (Zhu et al., 2017; Herzig et al., 2018). Suggestions on land use management strategies: 1) actively explore intensive land development modes and reasonably control the scale of cities to optimize the structure and layout of construction land based on strictly protecting the ecological environment and cultivated land (Lu and Ke, 2018); 2) accelerate the implementation of innovation-driven strategies to improve and optimize the industrial structure by replacing factor-driven development with innovation-driven development; 3) reduce wasteful practices of over-utilizing developed land and transition toward land use patterns with more efficient and intensive use of stock land, such as the transformation of old cities, and idle and inefficient land redevelopment (Lu et al., 2018); 4) actively promulgate policies of population migration to reduce the burden on local resources and the environment.

5.4. Limitations and prospects

Due to the limitations of data acquisition and research methods, this research also has some shortcomings. On the one hand, the regional expectations of some evaluation indicators used in Jiangsu case (Table 4) are based on the understanding of the development stages of the critical regions and related national regulations or average level. However, they are, in fact, not specifically developed for Jiangsu Province by official documents. For example, in the dimension of economic development, the X_{23} (proportion of industry and service industry) of the objects outside the urban planning area refers to the average level of the X_{23} of 30 townships in Jiangsu in China's top 100 townships in 2017; similarly, in the dimension of ecology, the calculation of various indicators in constructive land ecosystem mainly refers to the average level of the national demonstration areas of ecological civilization construction in Jiangsu. Although the determination of regional expectations in the above scenarios is based on areas with leading development level in the corresponding fields, which is convincing to a certain extent. However, objectively, this may also be higher or lower than the regional expectation to some extent, and correspondingly underestimate or overestimate the true level of regional LUE. On the other hand, only representative indicators were selected for LUE assessment. For example, to account for the efficiency of food production, only the indicators of food production capacity and resource endowment on cultivated land are considered, which fails to consider the role of animal husbandry and aquaculture in regional food production to a certain extent.

Despite the shortcomings, we presented a novel approach to evaluate explicitly the LUE in food production, economy and ecology. Unlike other studies of LUE, it links the actual performance of land use with the regional environmental and socio-economic objectives and expectations in a given region, which will enable stakeholders to test whether the specific development objectives are achievable with a given land use system or whether alternative land uses and/or management practices needed to be considered to achieve the objectives (Herzig et al., 2018), thereby informing policy development and spatial planning. In addition, to our knowledge, this study is among the few studies (Ke and Tang, 2018; Wang et al., 2019) that utilize geospatial modeling tools (e.g., InVEST) to integrate socio-economic data to comprehensively assess regional LUE, which makes it possible to seek the coordination and balance among food production, economy and ecology in land use based on quantitative evaluation, instead of paying one-sided attention to the economic benefits of land use.

Of course, the above shortcomings imply that it is necessary to identify more reliable, targeted, and authoritative regional expectations in further studies to assess regional LUE to minimize result errors. Meanwhile, improvements need to be made to refine the conceptual index system. Besides, based on the coupling coordination relationships and its influencing factors, the trade-offs among different dimensions of food production efficiency, economic development efficiency, and ecological maintenance efficiency will be further explored.

6. Conclusion

Taking the Jiangsu Province in eastern China as a case study area, we employed coupling coordination degree model, multivariable linear regression and geographical detectors to assess the LUE and to analyze the spatial differentiation characteristics, coupling relationships, and influencing mechanisms among land use sub-category efficiencies.

The results of this study show that the LUE of Jiangsu in food production, economic development, and ecological protection is 54.15%, 85.56%, and 54.95%, respectively, indicating that Jiangsu has great sustainable land use potential to be improved. The spatial pattern of the efficiency of the three sub-categories varies greatly. In particular, the unbalanced development in socio-economic is still prominent. The coupling coordination degree among land use sub-category efficiencies generally synchronizes with the coupling degree, and the medium coupling and coordination type has dominated in Jiangsu. The coupling coordination degree of land use in Jiangsu show significant spatial agglomeration characteristics; in particular, the spatial diffusion effect is remarkable in areas with a higher or optimal degree of coupling coordination. Economic aggregate and population size are not necessary conditions to promote the coordinated development of food production, economy, and ecology, while the intensive utilization of arable land, optimization of economic structure, and improvement of the ecological environment play an essential role in promoting the sustainable use of land space and the coordinated development. This study suggests that land use and land use management need to formulate rational and diverse land use strategies that serve to (1) tap into the potential of land space, (2) promote the coordinated development of food production, economy and ecology, (3) pay more attention to resource security, economic structure optimization and ecological balance, and (4) provide practical guidance on efficient and sustainable land use to resolve conflicts between humans and nature.

Declaration of competing interest

No conflict of interest exists in the submission of this manuscript, and the manuscript is approved by all authors for publication. I would like to declare on behalf of my co-authors that the manuscript was original research that has not been published previously, and not under consideration for publication elsewhere.

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Appendix A. Supplementary data

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