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Measuring green development level at a regional scale: framework, model, and application

Xia Pan · Jianguo Li · Jing Wei · Yapeng Yue · Lili Liu

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Abstract In this study, we propose and construct a novel model that measures regional green development level based on the "three-circle" conceptual framework for green development. Using Jiangsu Province in eastern China as a case study, the spatial–temporal characteristics and dynamics of the green development level from 2000 to 2020 were evaluated using a multi-source dataset at the grid-cell level. Our results show that (1) the analytical hierarchy process-based model proposed herein has higher reliability in terms of the development level measurement than principal component analysis and the entropy weight method. In addition, the average score of green development in the study area was approximately 0.53. Spatially, the green development level in the eastern coastal areas of the study area was found to be generally higher than in other regions, while that in southwestern regions is relatively low. In terms of sub-regions, the green development level scores of the study area have been ranked as follows: middle Jiangsu > southern Jiangsu > northern Jiangsu. (2) It was observed that the gravity center of the green development level can be divided into three stages during the study, with a whole had shifted to the north. (3) For most cities in Jiangsu, the green development level initially increased at first, then declined, and then increased again. (4) In the future, the green development level of Jiangsu Province should pay more attention to promoting regional coordinated development and relationships between society and the environment under rapid economic development.

Keywords Green development level · "Three-circle" conceptual framework · Measurement model · Spatiotemporal characteristics · Jiangsu Province

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X. Pan · J. Li (✉) · Y. Yue · L. Liu
School of Geography, Geomatics, and Planning, Jiangsu Normal University, Xuzhou 221116, Jiangsu, China
e-mail: lijianguo@jsnu.edu.cn

X. Pan
e-mail: panxiajssf@163.com

Y. Yue
e-mail: yyp88668@163.com

L. Liu
e-mail: huanyin728@126.com

J. Wei
Department of Atmospheric and Oceanic Science, Earth System Science Interdisciplinary Center, University of Maryland, College Park, MD, USA
e-mail: weijing_rs@163.com

Introduction

With the rapid development of the global economy, the world is facing unprecedented problems and challenges (Li & Pan, 2012; Wang & Feng, 2021a; Wang et al., 2021c). These have resulted in inevitable changes in our production and lifestyle (Feng et al., 2020; Yu et al., 2020); conventional practices are being increasingly replaced by green and ecological ones (Masoomi et al., 2022). In recent years, green development has become a common and effective pathway to achieving regionally sustainable and scientific development in many countries (Hu, 2011; Li et al., 2020c; Liu & Dong, 2021; Long et al., 2021; Perry, 2020). In developing countries, China has successfully become a pioneer of green economy (Xue et al., 2021). China currently has a vulnerable ecosystem and environment, which is burdened with supporting the largest population in the world and its rapid economic development (Guo et al., 2020d; Wu et al., 2020). Under these circumstances, President Xi has identified that green development is a fundamental policy that is inevitably required to reduce environmental pollution and construct a high-quality modern economic system (Jin et al., 2019).

The term green development was originally derived from the theory of "spaceship economics" proposed by Boulding in the 1960s (Boulding, 1966). Since then, some concepts related to green development have been raised, such as steady state (Daly, 1973), green economies (Pearce, 1989), and green cities (Grossman & Krueger, 1996). Additionally, Green Index was constructed and published in 1990 (Hall & Kerr, 1991). However, there is no universal discipline on green development was developed up to now (Zhong et al., 2021). The combination of green and development represents a new development pattern that is better able to protect or increase the total amount of natural capital during the development process (Liu et al., 2021). This is in contrast to the previous pattern in development where resources were continuously consumed (Li et al., 2021). Green development places emphasis on the harmonious relationship between human beings and ecology (Li et al., 2018). Green development is able to guide modern economic operations and production means for all of society (e.g., politics, culture, science, technology, values, and behavior) (Weng et al., 2020). This effort seeks to increase the ecological capital and achieve comprehensive development of people and ecosystems (Fang et al., 2020). The purpose of green development is to attain earth-system-oriented sustainable development, as opposed to human-oriented sustainable development.

With the increase in the concepts and practices pertaining to green development, increasing attention has been paid to green development level (GDL) measurement models and their applications (Devuyst et al., 2001; Shi et al., 2016; Xian et al., 2020; Yang et al., 2015). Composite index model is the main evaluation method in the existing GDL evaluation research (Pan et al., 2020), for example, the green development performance index (Feng et al., 2017), the human green development index (Li et al., 2014b), the urban green development index (Wang et al., 2018), and the industrial and agricultural green development index (Chen et al., 2021; Wang et al., 2021b). Few studies have focused on the framework and measurement accuracy of the GDL based on the constantly updated cognition and knowledge of it (Li et al., 2018c). For instance, different index systems have been adopted in different studies, usually based on researchers' own practice and experience. Yu et al. (2019) established an index system consisting of economic, population, coastal, and terrestrial pollution. Sun et al. (2018) constructed an index system based on a three-dimensional framework involving social, economic, and ecological environments, including two kinds of subsystems: the natural ecological environmental subsystem and socioeconomic subsystem. The index system proposed by Deng et al. (2018) was based on economic development growth and green environment protection. Guo et al. (2020a) constructed an economic greening index, social greening index, environmental greening index, and government support level to evaluate the GDL. In general, most index systems used in previous studies were derived from preliminary cognition and knowledge on sustainable development and environmental quality assessment (Guo et al., 2020c); these failed to fully clarify and advance the framework, model, and its corresponding index system of the GDL based on the concept of green development itself. The structure of the previous index system generally attempted to measure the speed and level of economic development and the consumption of resources and environment (Hák et al., 2016). In general, this system was based on the perspective of "anthropocentrism." Furthermore, most of the index systems employed generally consider the socioeconomic development levels and environmental quality that are represented using their respective statistical datasets (Guo et al., 2020b; Pan et al., 2020; Yang et al., 2019) while ignoring the importance of social governance and regional ecosystem structure and function; this may lead to greater uncertainty in the evaluation results (Huang et al., 2021). In addition, combining observation data with statistical data can significantly improve the precision of GDL evaluations. However, the GDL measurements in most previous studies were conducted within administrative regions based on social statistical datasets, such as at the country, province, or city level (Cheng & Ge, 2020; Meng et al., 2019; Wang et al., 2021b; Wang et al., 2021a; Yin et al., 2020); high-accuracy GDL measurement is limited.

Simultaneously, extensive studies have been conducted on the GDL measurement methods (Chen et al., 2022; Dai et al., 2021), for example, entropy method (Sun et al., 2018), interval Malmquist-Luenberger productivity analysis method (Huang et al., 2021), and analytic hierarchy process (AHP) (Naseer et al., 2022). However, there are few studies were conducted to improve the assessment accuracy of different GDL assessment methods based on a uniform framework. In this study, we innovatively propose a GDL measurement framework (model) emphasizing the harmonious coexistence and mutuality of the three systems: society, economy, and nature. This framework enables the assessment of regional development from a more inclusive perspective. In this study, Jiangsu Province in eastern China has been selected as a case study, and then three data types were used herein to measure the regional GDL based on the conceptual "three-circle" framework; the data types included the following: observation data obtained via remote sensing observations, simulation data that was retrieved using a model, and statistical data obtained from the statistical yearbook. The main purposes of this study were to (1) propose a novel GDL conceptual framework and its measurement model, (2) explore the spatiotemporal characteristics of the GDL evolution in Jiangsu over a span of 20 years (2000–2020), and (3) provide a series of policies and management strategies to cope with the existing problems identified during this study and promote future GDL.

Materials and methods

Measurement model of regional GDL

Green development is a new type of harmonious development mode that can achieve sustainable and scientific development via changing economic development modes, rational utilization of resources, and building a harmonious society under the constraints of the ecological environment capacity and resource carrying capacity (Yang et al., 2019). Compared with green development, conventional sustainable development emphasizes the coordination of human capital investment, poverty reduction, and economic development from the perspective of resource utilization carrying capacity. In summary, it emphasizes development with a focus on economy (Griggs et al., 2013). The concept of sustainable development is a passive revision of the traditional development concept. It is still people-oriented. In contrast, green development is more inclusive; it pays more attention to the coordinated development of man-land relationships, which emphasizes the symbiosis of economic, social, and natural systems, as well as the diversification of development goals (Hu & Zhou, 2014). Sustainable development emphasizes on the relationship between resources, the environment, and the interests between generations of people. Socio-economic development requires a supply of natural resources. Sustainable development ensures that resources are fully able to support the development of society and economy under specific conditions. With resource depletion, the development of the society would be greatly restricted, which will adversely affect the health, safety, and quality of life of humans (Barrera-Roldán & Saldívar-Valdés, 2002). It may be said that sustainable development is a result of the passive self-examination of the future development of generations. Since the 1980s, sustainable development has become prevalent across the world, although this has occurred alongside an increasing intensity and extension of human development and the consequent utilization of natural resources. Sustainable development has generated a new development pattern, industrial civilization, based on the "anthropocentrism" ideology (Hu, 2014). In addition, sustainable development typically ignores ecological fairness across different nationalities and regions, leading to the transference of environmental pollution and ecological damage to underdeveloped areas. However, green development is a concept that emphasizes on developing an ecological civilization with coordinated relationships between humans and nature; these relationships aim to be more inclusive, harmonious, and symbiotic (Hu & Zhou, 2014). Green development is a new development pattern compared to conventional industrial civilization, and it aims to form a new development culture that may span various regions and societies. It is capable of enhancing the coexistence of humans and the biosphere. Hence, green development can be regarded as a superior, advanced, and a more inclusive form of the concept of sustainable development.

Green development focuses on the effective combination of economic growth, environmental protection, and social governance (development). Its theoretical premise is the harmonious coexistence of the economic, natural, and social systems. In the present study, a comprehensive evaluation method was used to quantitatively measure the level of regional green development by promoting the "three-circle" conceptual framework of green development; the said framework can be expressed as a coordinated economic, natural, and social system and emphasizes the coordination, wholeness, and systematic nature of the three systems. The three systems coexist to form a coupling relationship between green growth, green wealth, and green welfare (Fig. 1). Among them, green wealth is the foundation of the natural system, carrier of green welfare, and foundation of green growth; it includes natural capital, human capital, physical capital, and social capital. Green growth is the basis of the economic system and the means of green wealth accumulation and green welfare promotion, including green production and green consumption. Green welfare is the foundation of the social system and the goal of green development. It can promote green wealth and green growth, including space welfare, environmental welfare, cultural welfare, and health welfare.

Construction and evaluation method of index system

Construction of index system

Based on the above understanding, a regional green development index system is developed from the three aspects of green wealth, green growth, and green welfare. All indicators chosen were discriminated based on the availability and representativeness of the three aspects mentioned above. Among them, green wealth mainly reflects the natural and social resource endowment and capacity required for regional green development. Green wealth includes natural capital, human capital, physical capital, and social capital. Natural capital includes all kinds of wealth provided by natural ecosystems (it mainly refers to the resources, ecosystems, biodiversity, etc.) that can be utilized by human beings in green development. Natural capital was represented herein using the soil sensitivity index (SS), land degradation sensitivity index (DS), and net primary productivity (NPP). The SS and DS are comprehensive indicators which were developed using indicators recommended in the Annex C of the "Interim regulations on ecological function zoning" advanced by the Chinese Academy of Sciences and State Environmental Protection Administration (Wang et al., 2015) and combining with the actual situation of Jiangsu's natural environment. These two indicators can truly reflect ecological sensitivity and represent the status of regional ecosystem health. NPP is an important factor measuring carbon sink function of ecosystem, estimating environmental supporting capacity and referring to sustainability of terrestrial ecosystem, which is a significant indicator of natural capital (Yang et al., 2021). Human capital is the wealth of the labor force in green development, including both the quantity and quality of the labor force; it was represented herein by employees and students. Physical capital refers to the man-made objects and the infrastructure involved in their manufacture that can provide value and service for green development. The growth rate of gross output value of industrial enterprises above a designated size can reflect the production efficiency of physical industrial enterprises and reflect the transformation of economic growth mode from resource-input-dominated to productivity improvement (Li & Zhao, 2016), which can meet the requirement of physical capital. In addition, technology is a major part of green economy (Zhao et al., 2019). High technology can promote the upgrade and transformation of traditional physical capital industries and resource productivity improvement. The contribution of new and high-technology industries to the GDP of industrial enterprises above a designated size is a proper representative of green physical capital. Social capital refers to the social resources in a specific area of a certain region in the process of green development. Usually, the increasing regional GDP is an important social resource, which can be used for infrastructure construction. Traffic can produce serious energy consumption and environmental pollution in specific region (Guo et al., 2014). Amount of passenger traffic refers to the passenger

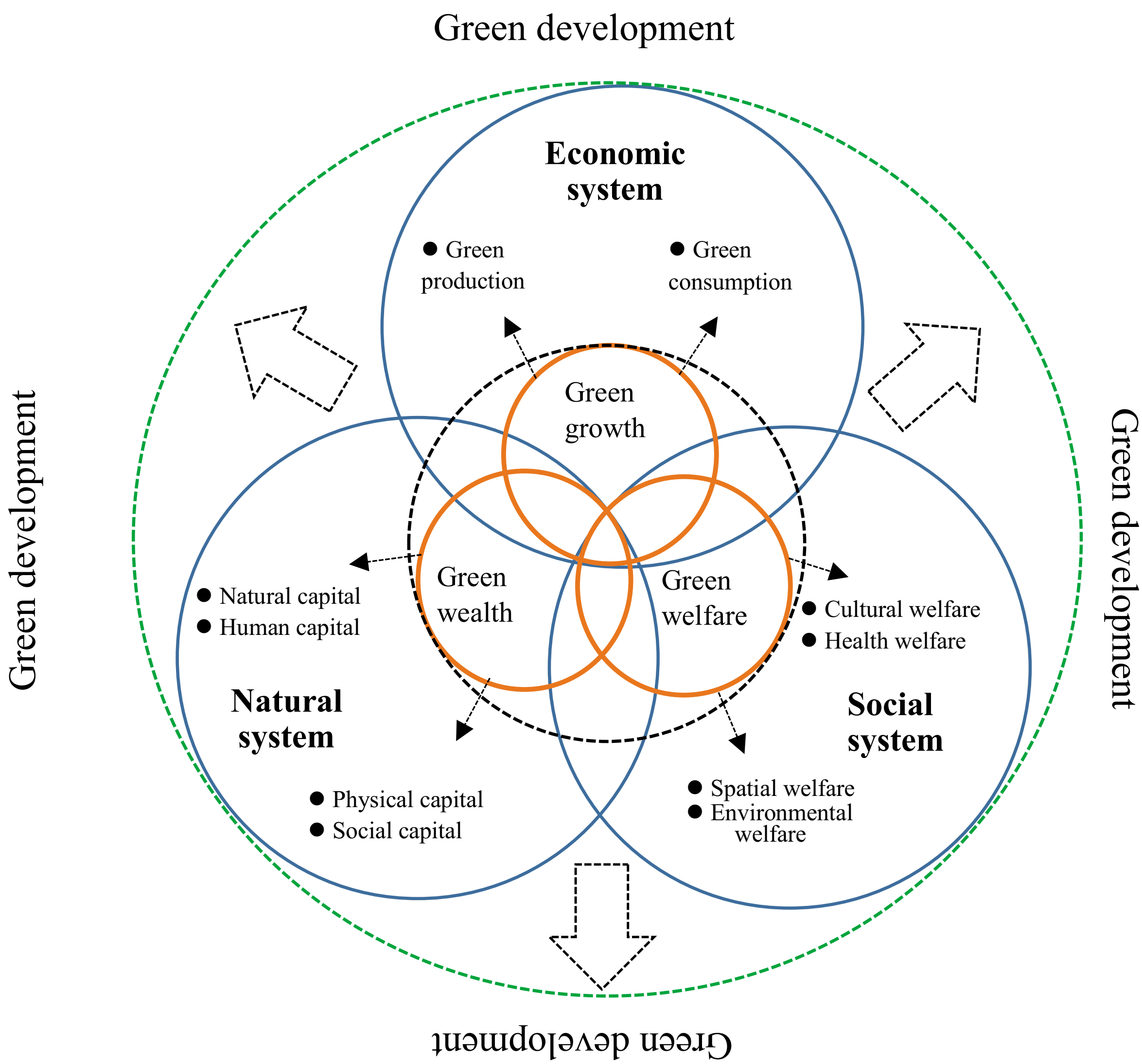


Fig. 1 "Three-circle" conceptual framework of the green development level

volume of public transport based on passenger tickets. The increase of this indicator is conducive to the reduction of private cars, so as to achieve the purpose of energy conservation and emission reduction. Therefore, regional GDP and amount of passenger traffic can reasonably represent social capital.

Green growth mainly reflects the economic system operation process of regional green development, including green production and green consumption. Green production refers to production processes that can achieve reduced consumption of energy and materials, low emissions, and high yield (productivity). Chemical fertilizers consumption, gross product of tertiary industries, and per capita disposable income can overall reflect the processes and achievement of green production in different aspects. Green consumption refers to behavior activities wherein people follow the concept of green development through energy conservation and reduced consumption levels in the industrial and social sectors. This index was represented by the daily per capita residential tap water consumption and per unit comprehensive energy consumption to GDP. The reduction of tap water and energy consumption in life and production can benefit to the reduction of excessive usage of natural resources.

Green welfare reflects the environmental and welfare social support of public utilities needed for regional green development, including spatial welfare, environmental welfare, cultural welfare, and health welfare. The change of landscape pattern can significantly affect the structure and function of regional ecosystem (Hao et al., 2017). Natural landscape patch density index (PD), natural Shannon diversity index (SHDI), and green coverage ratio involved with spatial welfare generally are used to reflect the degree of fragmentation of natural landscape patches during green development and further measure damage degree of the original natural ecosystem. In environmental welfare, industrial wastewater discharge compliance rate, $PM_{2.5}$, and percentage of industrial solid wastes used comprehensively are three important indices, which can generally represent environmental pollution level in water, air, and soil environment, respectively. In cultural welfare, expenditure for education is significant index can be used to refer to cultural level of the local people. In health welfare, the increase in the number of hospital beds means the expansion and upgrading of medical resource, which can reflect the improvement of medical and health level and represent the meaning of the health welfare. Finally, we constructed an evaluation system that comprised of 10 s-level indicators and 22 third-level indicators (Table 1).

All indicators were selected following the principles of data availability, representativeness, and validity. We combined site interpolation data, remote sensing image and its model fitting process data, and social statistical data indicators, comprehensively considering all aspects of nature, economy, and society. Furthermore, we added ecological, cultural, and health factors to the traditional green development assessment index system to make it more comprehensive. Finally, a comprehensive green development evaluation index system was developed (Table 1). Based on the actual operation of the indicators, the third-grade indexes were divided into two parts: data indexes obtained from remote sensing image estimation and inversion (including SS, DS, PD, SHDI, NPP, and $PM_{2.5}$) and other indicators obtained from the Institute of Social and Economic Statistics. Finally, the two parts were comprehensively calculated and analyzed to evaluate the GDL of the region. The specific process is shown in the technology roadmap (Figs. 2 and 3).

Data sources

In this study, meteorological station data, remote sensing image data, intermediate model data, and social and economic statistics data were combined to evaluate the spatial–temporal evolution characteristics of the GDL in the study area. The monthly mean precipitation and air temperature data were interpolated according to the observation data of the Jiangsu station, recorded at the National Meteorological Data Center (http://data.cma.cn/), by inverse distance interpolation method. NPP was obtained by the CASA method (Li et al., 2018a, 2019, 2020a, b; Li & Liu, 2020). Digital elevation model (DEM) data adopted ARSTER DEM with a spatial resolution of 30 m × 30 m. Normalized difference vegetation index (NDVI) data were studied using MOD13A2 data (data source: https://modis.gsfc.nasa.gov/). Land use data were obtained from the Yangtze River Delta Science Data Center (http://nnu.geodata.cn:8008/), based on Landsat image data visual interpretation and a spatial resolution of 30 m. $PM_{2.5}$ data were derived from the inversion data of a space–time random forest (STRF) model (Wei et al., 2019). Socioeconomic statistics were obtained mainly from county statistical yearbooks and bulletins in the year of assessment; we used data from similar years or districts to fill in the gaps in the data for which the original data were unavailable. We spatialized all acquired data to ensure the consistency in their projection and spatial resolution. In this study, data interpolation and rasterization were unified as 1000-m spatial resolution and projection coordinates Krasovsky_1940_Albers.

Evaluation methods

Soil sensitivity index (SS)

The constructed SS was based on the universal soil loss equation and calculated as the weighted sum of the rainfall erosivity (R), slope and aspect (LS), and land cover (C).

1. Rainfall erodibility (R)
   R is used to evaluate the influence of regional precipitation on soil sensitivity by using precipitation as

Table 1 Green development evaluation index system

First-grade index	Second-grade index	Third-grade index	Unit	Data sources	Indicator direction
Green wealth	Natural capital	Soil sensitivity index (SS)	-	Formula (1–2)	-
		Land degradation sensitivity index (DS)	-	Formula (3–5)	-
		Net primary productivity (NPP)	g C/m^2/yr	CASA	+
	Human capital	Number of employees	10,000 persons	Statistics	+
		Number of students	10,000 persons	Statistics	+
	Physical capital	Growth rate of gross output value of industrial enterprises above a designated size	%	Statistics	+
		The contribution of new and high-technology industries to the GDP of industrial enterprises above a designated size	%	Statistics	+
	Social capital	Regional GDP	RMB 10,000	Statistics	+
		Amount of passenger traffic	10,000 persons	Statistics	+
Green growth	Green production	Per capita disposable income	RMB	Statistics	+
		Consumption of chemical fertilizer	10,000 ton	Statistics	-
		Gross product of the tertiary industry	RMB 10,000	Statistics	+
	Green consumption	Daily per capita residential tap water consumption	Liter	Statistics	-
		Per unit comprehensive energy consumption to GDP	RMB tce/10000	Statistics	-
Green welfare	Space welfare	Natural landscape patch density index (PD)	Number of patches /100 ha	Formula (6)	-
		Natural Shannon diversity index (SHDI)	-	Formula (7)	-
		Green coverage ratio	%	Statistics	+
	Environmental welfare	Industrial wastewater discharge compliance rate	%	Statistics	+
		$PM_{2.5}$	μg/m^3	STRF model (Wei et al., 2019)	-
		Percentage of industrial solid wastes used in a comprehensive way	%	Statistics	+
	Cultural welfare	Expenditure for education	RMB 100 million	Statistics	+
	Health welfare	Number of hospital beds	unit	Statistics	+

a measurement standard. According to the existing precipitation erosion model in Jiangsu Province, the calculation formula for the rainfall erosion force is obtained:

$$R = \sum_{i=1}^{12}(0.3046P_i - 2.6398) \quad (1)$$

where R is the annual rainfall erosivity (J cm/(hm^{2}h)) and P_i is the average monthly rainfall in the month i (mm).

2. Slope and aspect (LS)
The slope length factor is an index used to evaluate the influence of regional terrain on soil sensitiv-

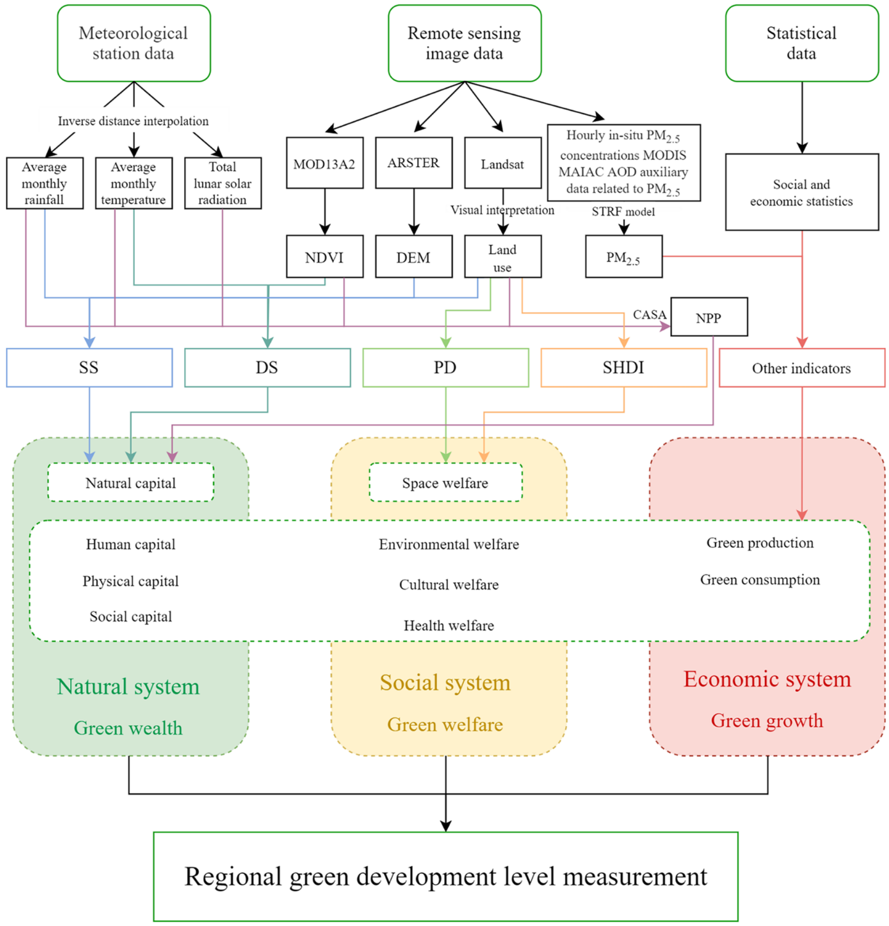


Fig. 2 Technology road map

ity using terrain as a measurement standard. DEM data of the region were used as the LS score.

3. Land cover (C)
   Land cover is the use of land cover status to assess the impact on soil sensitivity in the given area, as indicated by the land use interpretation data.

4. Comprehensive calculation of SS

This was achieved using Annex C of the "Interim regulations on ecological function zoning." It has been revised based on the actual situation (Table 2).

The SS is calculated by the weighted synthesis of Eq. (2). We used the AHP method to obtain the weight of SSs: 16.4% (R), 53.9% (LS), and 29.7% (C):

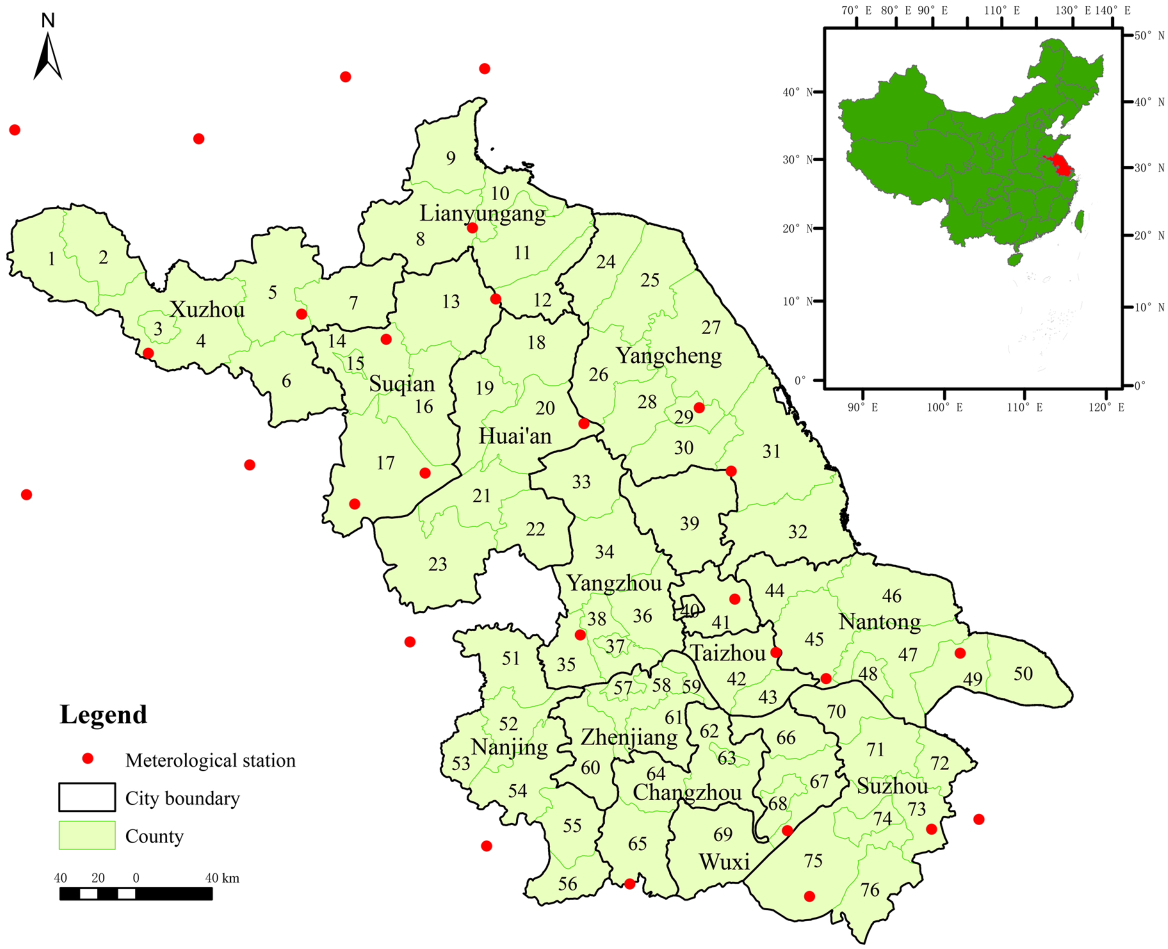
$$SS = \sum_{i=1}^{n} C_i W_i \quad (2)$$

where SS is the soil sensitivity index, C_i is the sensitivity grade value of index i, and W_i is the weight of index i.

Land degradation sensitivity index (DS)

We selected the moisture index (I) and vegetation cover (VC) as indicators to evaluate the sensitivity of land degradation in the study area.

1. Moisture index (I)
   The dry and wet conditions in this area of a specific region can be effectively represented by I. It is closely related to precipitation and temperature.



Name of prefecture level	Names of counties and county-level cities								
Xuzhou	Fengxian(1)	Peixian(2)	Xuzhou(3)	Tongshan(4)	Pizhou(5)	Suning(6)	Xinyi(7)		
Lianyungang	Donghai(8)	Ganyu(9)	Lianyungang(10)	Guanyun(11)	Guannan(12)				
Suqian	Shuyang(13)	Suyu(14)	Suqian(15)	Siyang(16)	Sihong(17)				
Huaian	Lianshui(18)	Huaiyin(19)	Huaian(20)	Hongze(21)	Jinhu(22)	Xuyi(23)			
Yancheng	Xiangshui(24)	Binhai(25)	Funing(26)	Sheyang(27)	Jianhu(28)	Yancheng(29)	Yandu(30)	Dafeng(31)	Dongtai(32)
Yangzhou	Baoying(33)	Gaoyou(34)	Yizheng(35)	Jiangdu(36)	Yangzhou(37)	Ganjiang(38)			
Taizhou	Xinghua(39)	Taizhou(40)	Jiangyan(41)	Taixing(42)	Jingjiang(43)				
Nantong	Huaian(44)	Rugao(45)	Rudong(46)	Tongzhou(47)	Nantong(48)	Haimen(49)	Qidong(50)		
Nanjing	Luhe(51)	Nanjing(52)	Jiangpu(53)	Jiangning(54)	Lishui(55)	Gaochun(56)			
Zhenjiang	Zhenjiang(57)	Dantu(58)	Yangzhou(59)	Jurong(60)	Danyang(61）				
Changzhou	Wujin(62)	Changzhou(63)	Jintan(64)	Liyang(65)					
Wuxi	Jiangyin(66)	Xishan(67)	Wuxi(68)	Yixing(69)					
Suzhou	Zhangjiagang(70)	Changshu(71)	Taicang(72)	Kunshan(73)	Suzhou(74)	Wuxian(75)	Wujiang(76)		

Fig. 3 Map of counties, cities, and meteorological stations in Jiangsu (2000)

The I is the reciprocal of dryness (K). We used ArcGIS 10.4 to identify the month with the average monthly temperature ≥ 10 °C in this region and calculate its cumulative annual temperature. Then, we used the reciprocal of K to obtain the wettability index.

Table 2 Soil sensitivity index categories

Index	Slight sensitivity	Light sensitivity	Medium sensitivity	Heavy sensitivity	Extreme sensitivity
R	< 250	250–300	300–350	350–400	> 400
LS	0–20	20–50	50–100	100–300	> 300
C	Water	Forest	Grass	Farmland	Constructed/unused land
Value	1	3	5	7	9

Constructed land: industrial land, rural settlement, and transportation land

$$K = \frac{0.16 \times \sum t}{r} \tag{3}$$

where K is the dryness, $\sum t$ is ≥ 10 °C cumulative annual temperature (°C), and r is total precipitation (mm).

2. Vegetation cover (VC)
VC is the representative of the vegetation coverage in the area and, thus, an indicator of land degradation. The NDVI is used to calculate the VC:

$$VC = \frac{NDVI - NDVI_{min}}{NDVI_{max} - NDVI_{min}} \tag{4}$$

where VC is the vegetation cover, $NDVI$ is the normalized difference vegetation index, and $NDVI_{max}$ and $NDVI_{max}$ are the maximum and minimum values of $NDVI$, respectively.

3. Comprehensive calculation of land degradation sensitivity

As before, this was revised according to Annex C of "Interim regulations on ecological function zoning" and modified according to the actual situation (Table 3). Indexes are classified and assigned as shown in Table 3.

As the contributions of the I and VC to land degradation sensitivity are similar, the weight of each index is set as 50.0%. The formula for the DS is as follows:

$$DS = \sum_{i=1}^{n} C_i W_i \tag{5}$$

where DS is the land degradation sensitivity index, C_i is the sensitivity grade value of index i, and W_i is the weight of index i.

Natural landscape patch density index (PD)

The PD reflects the degree of natural landscape fragmentation. The land use type map of the study area was used for the calculation in ArcGIS 10.4 and Excel using the grid analysis method. A 1000 m × 1000 m fishing net was created, taking each grid as a landscape unit and counting the number of patches in it. During the calculation process, only natural landscape patches (grassland, woodland, and water), were extracted; the other areas were assigned a value of zero. The PD value was calculated using formula (6):

$$PD = \frac{N}{A} \tag{6}$$

where PD is the natural landscape patch density index (patch number/100 ha), N is the patch number in each grid, and A is the landscape unit area (100 ha).

Natural Shannon diversity index (SHDI)

The SHDI can quantify the composition of the natural landscape structure. The same method, as that described for PD, was used to create a 1000 m × 1000 m fishing net. Each grid was taken as the landscape unit, and the proportion of patch area in the grid was counted. Similarly, only natural landscape patches were extracted. The SHDI value was calculated using formula (7):

$$SHDI = -\sum_{i=1}^{n} P_k \ln (P_k) \tag{7}$$

Table 3 Land degradation sensitivity index categories

Index	Slight sensitivity	Light sensitivity	Medium sensitivity	Heavy sensitivity	Extreme sensitivity
I	> 0.65	0.5–0.65	0.2–0.5	0.05–0.2	< 0.05
C	> 0.7	0.5–0.7	0.3–0.5	0.1–0.3	< 0.1
Value	1	3	5	7	9

where *SHDI* is the natural Shannon diversity index, P_k is the area ratio of patch type k in the landscape unit, and n is the total number of patch types.

In addition to the above indexes, the NPP and $PM_{2.5}$, as well as the other third grade indexes, can be directly or indirectly obtained and classified as statistical data indicators. Statistical data indicators were mainly operated upon in Excel. These statistical index data, obtained from the counties and cities of Jiangsu, were highly accurate.

GDL composite index

There are different dimensions among the indicators. Therefore, before calculating the GDL index, it is necessary to standardize the data so that the results fall between 0 and 1 to eliminate the differences between different indicator units. Equations (8) and (9) are standardized formulas for the positive and negative impact indicators, respectively.

$$P_i = \frac{E_i - E_{min}}{E_{max} - E_{min}} \tag{8}$$

$$P_j = \frac{E_{max} - E_i}{E_{max} - E_{min}} \tag{9}$$

where P_i and P_j are the normalized values of the positive and negative impact indicators, E_i is the original value of each index, and E_{min} and E_{max} are the minimum and maximum values of each index, respectively.

Three methods were adopted to determine the weight of each index in the GDL assessment index system (detailed information on algorithm and data processing in Supplementary sections S1–S3), namely, the AHP method, entropy weight method (EWM), and principal component analysis method (PCA). In the AHP method, we divided the proposed index system into three grades and then determined the relative importance between two indices under each grade, creating the judgment matrix; grades with fewer than three indices were not used in this method (see Supplementary Section S1 for more details). For the EWM method, the index system was divided into three grades, as per the AHP method, and the weight of each index was calculated using the entropy method (see Supplementary Section S2 for more details). For the PCA method, SPSS software was used to extract the principal components to obtain the weight of each index (see Supplementary Section S3 for more details).

Using the weighted synthesis method, the GDL score of Jiangsu is obtained using formula (10):

$$G = \sum_{i=1}^{n} M_i N_i \tag{10}$$

where G is the score of the GDL, M_i is the weight of index I, and N_i is the standardized value of index i.

Study area

Our study was carried out in Jiangsu Province, eastern China, which is located at 30° 45’ N–35° 20’ N and 116° 18’ E–121° 57’ E, and has a total area of approximately 107,200 km^2. Jiangsu lies in the East Asia monsoon climate zone, which is a transitional climate zone from south to north. The study area is coastal, the land is mostly plain with low hills, and the terrain is relatively flat. Jiangsu has 13 cities under its jurisdiction and has a high level of economic development. It is the only province in China where all the prefectures and cities have entered the national top 100 when considering GDP, forming the Yangtze River Delta city cluster together with Shanghai, Anhui, and Zhejiang. Jiangsu is a populous province with 80.7 million permanent residents. The province takes an active part in green development and continuously promotes the green transformation of its economy. The “three lines and one single” list (the bottom line of environmental quality, the red line of ecological protection, the line of resource utilization, and the ecological environment access list) has been compiled for this area. The province has made great progress in the fields of energy conservation, environmental protection, and green construction. In addition, from 2000 to 2020, Jiangsu has implemented the policy of withdrawing counties and dividing districts many times, changing the counties or county-level cities under the jurisdiction of prefecture-level cities into municipal districts. For example, in April 2002, Wujin withdrew the city of Changzhou and divided it into districts. In March 2004, Suyu County was abolished, and the Suyu District of Suqian city was established. In 2016, Hongze County was abolished, and the Hongze District of Huai’an was set up.

Results and discussion

Reliability of regional green development measurement model

To verify the reliability of the method model and its framework, this study also used PCA and the EWM to measure the GDL of Jiangsu, using the kernel density estimation method (KDE). The KDE is a nonparametric method for estimating the probability density function of random variables; the normality of its results can be observed from the perspective of numerical distribution (Zhang et al., 2012). We plotted grid scores of the GDL obtained by the three methods as a KDE chart and compared them. It can be seen from Fig. 4 that the regional green development scores obtained by the three methods have a large gap. The curve distributions also show a large difference, mainly manifested in the curve distribution symmetry (normal) difference. For objects affected by various factors, the normality of the distribution of the evaluation results can reflect their reliability to a certain extent. This is mutually confirmed by the first law of geography: the closer the distance, the greater the correlation between objects. Therefore, the normality of grid scores derived from the three methods was measured using skewness coefficient method described by Brown (1997). The results revealed that the skewness coefficient of the AHP method is 0.15, that of the EWM method is 2.21, and that of the PCA method is 2.03. Compared with PCA and EWM, the AHP method has better normality in evaluating grid scores of the GDL; that is, both the absolute value of the skewness coefficient and the deviation degree of the numerical distribution are the smallest. Therefore, the results of the AHP evaluation were reliable and were further used for analysis in this study.

Most studies usually adopted a single and specific method to evaluate the GDL, which can't reflect the relative precision of results derived from different methods. For example, Sun et al. (2018) used the information entropy model to evaluate the evolution process of green development in China. Cui et al. (2021) evaluated the green development performance of city in the Yangtze River Delta based on the entropy weight method. The assessment results mentioned above were all untested and unreliable, and the

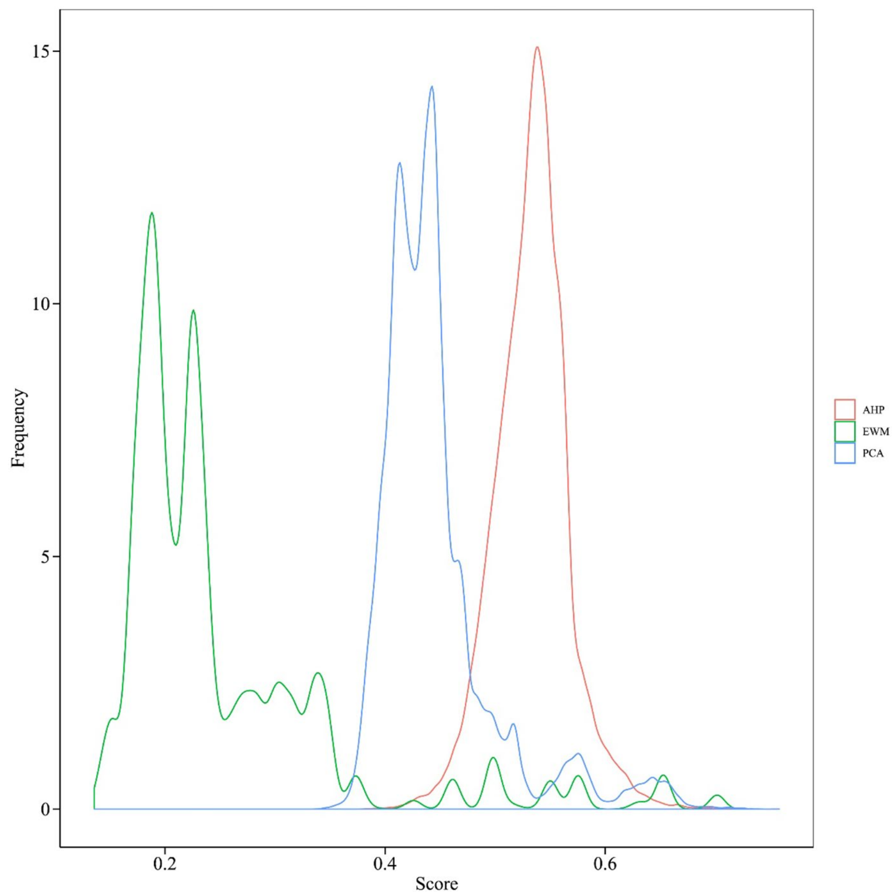


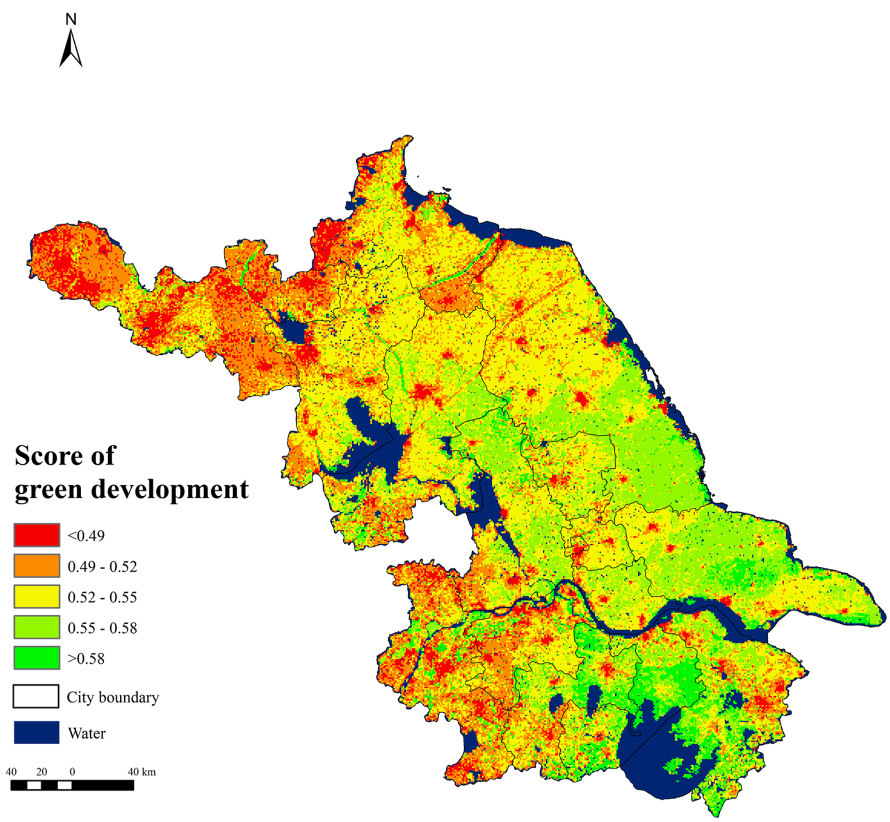
Fig. 4 Kernel density curves of the mean results of the three models

precision of them is relatively low. In this study, the KDE method has been employed to assess the relative precision of the three methods mentioned above, which benefits to obtaining more reliable assessment result of the GDL and then being used to conduct next analysis further.

Spatial characteristics of the GDL in Jiangsu

Through the data and weights of various indicators (see Supplementary Materials), the green development measure model constructed in this study is applied to calculate the GDL of Jiangsu from 2000 to 2020. The GDL scores of Jiangsu in the five-time nodes (2000, 2005, 2010, 2015, and 2020) were averaged to obtain the average score distribution of the GDL of Jiangsu for the study period (Fig. 5). As shown in Fig. 5, the average and standard deviation of the GDL scores of Jiangsu are approximately 0.53 and 0.033, respectively. Additionally, the GDL of most areas of Jiangsu is at a medium–high level (large area of water, represented by blue color in Fig. 5, has been excluded). This is consistent with the findings of Sun et al. (2018). However, the GDL of the study area exhibits a large spatial difference, which is generally manifested as the generally higher GDL score of the eastern coastal areas compared to other regions; in the southwestern regions, the GDL score was relatively low. The main reason for this is that SHDI, DS, PD, NPP, and SS (especially SHDI and DS) in the eastern coastal areas of the study area perform better than those in the inland areas. SHDI mainly reflects the diversity of regional landscape patches, due to the inland areas in Jiangsu's land development history, and is relatively long, and its land development strength is greater than that in coastal areas (the coastal areas generally have a short history of development, and ecosystem in most areas of them is relatively complete and fragile and within ecological protection regions) (Li et al., 2014a). Moreover, inland areas experience stronger disturbance to the regional landscape ecology due to human activities compared to the coastal areas; therefore, these areas are characterized by a higher degree of landscape fragmentation (Li et al., 2019, 2020b). Index DS reflects the degree of potential land degradation. In recent years, because of

Fig. 5 Score distribution of green development level



the occupation of construction land and unreasonable farming habits (excessive fertilization, unreasonable irrigation, etc.), large areas of agricultural farmland have been lost, and farmland soil has tended to degenerate (i.e., acidification and salinization) (Jin et al., 2020), which has further resulted in high soil degradation index scores (Yang et al., 2015; Zhang et al., 2004). However, in the eastern coastal areas, the soil and land quality has generally showed an obvious improvement, especially after reclamation (Li et al., 2018b; Xu et al., 2017).

As seen from Fig. 6, in terms of the specific cities, Wuxi, Nantong, and Changzhou have higher GDL scores of 0.567, 0.551, and 0.549, respectively, compared to the other cities. In contrast, the GDL scores of Lianyungang, Nanjing, and Xuzhou are relatively lower (0.518, 0.517, and 0.501, respectively). From the perspective of different regions, the GDL score in middle Jiangsu is the highest, with a mean value of 0.544, that of southern Jiangsu is 0.539, and that of northern Jiangsu is the lowest (0.526). The order of regional spatial distribution of the GDL in Jiangsu is the following: middle Jiangsu > southern Jiangsu > northern Jiangsu (Fig. 6). Compared to middle Jiangsu, the SS and $PM_{2.5}$ in southern and northern Jiangsu are significantly higher (negative effect), which indicates that ecosystems and living environment in the two regions are more vulnerable to human activities. Consequently, both green wealth and green welfare in the study area are easily subject to human interferences. Among them, DS and PD in southern Jiangsu are very high indicating that the threat of land degradation and the landscape fragmentation effect are more serious in this region, which largely and obviously reduces the overall GDL. In addition, the spatial pattern of GDL is quite different from the traditional spatial pattern of economic development in Jiangsu. In previous studies, it has been reported that the level of economic development in Jiangsu gradually decreases from south to north and is highest in southern Jiangsu (Che et al., 2012). However, this study found that the GDL of southern Jiangsu was not the highest. The main reason for this is that the rapid social and economic development as well as urbanization in southern Jiangsu resulted in the correspondingly rapid disappearance of ecological land in a short period, which further led to a relative decline in regional environmental carrying capacity (Grafakos et al., 2016; Tang et al., 2021). The area of newly added construction lands in southern Jiangsu is large which generally occupied large amounts

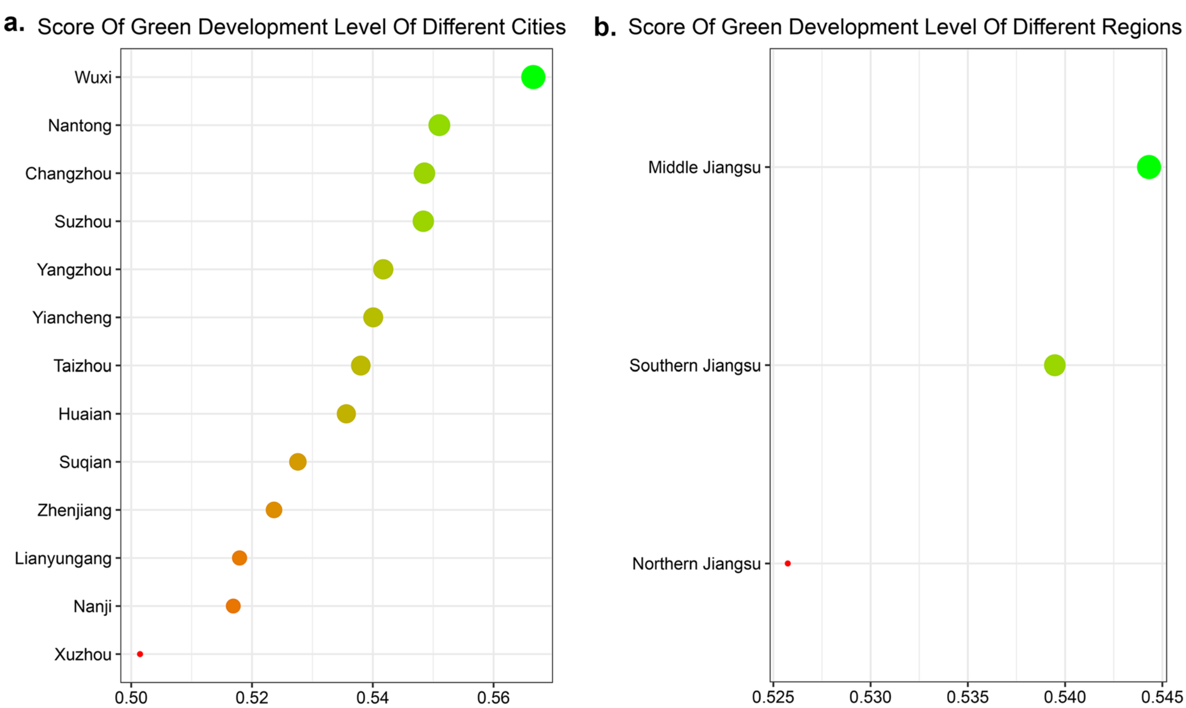


Fig. 6 Mean value of green development level of Jiangsu (**a** score of different cities, **b** score of different regions)

of agricultural lands and ecological lands (Jin et al., 2020). This processes significantly reduced the level of regional green capital and green welfare, especially owing to the rapid loss of land and water resources caused by economic development; this deterioration trend was particularly evident before 2000. However, the study of Weng et al. (2020) has shown that the level of sustainable development in southern Jiangsu is the highest, compared with other regions in Jiangsu based on single statistical dataset. We think that the results are unreliable due to their study overall overlooked the effect of natural landscape and pollutants on the GDL.

Dynamics of the GDL in Jiangsu

From 2000 to 2020, the score changes of the GDL in Jiangsu (Fig. 7) showed an upward trend. The lowest GDL score in the study area was found for the year 2000, with a mean value of 0.514, which increased to 0.533 in 2005 and 0.543 in 2010, with a total increase of 5.64%. This observation is consistent with that of Beijing (Wu et al., 2018). Then, the GDL increased to 0.552 in 2020. Despite slight fluctuations in the GDL, there was still an overall upward trend, with a general increase of 3.56% over the past 20 years.

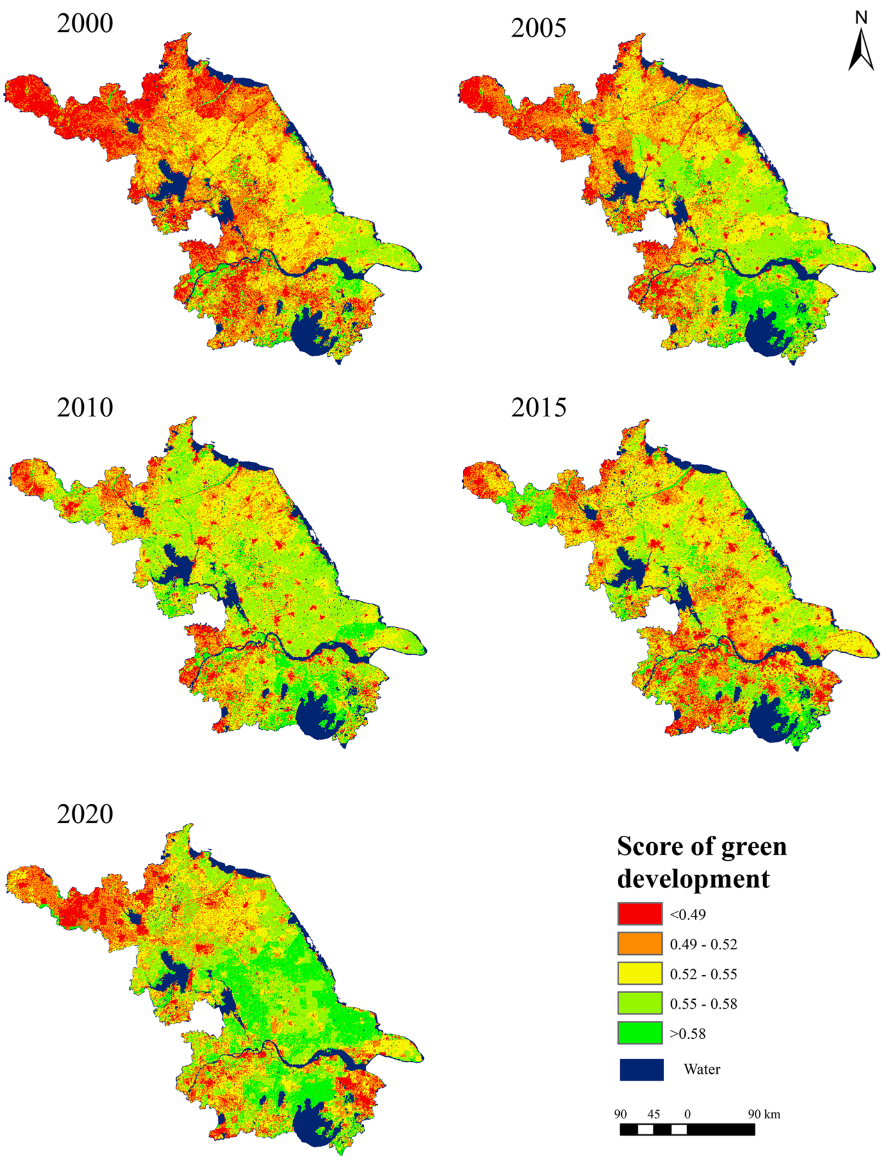


Fig. 7 Score distribution of green development on a temporal scale

The upward trend may indicate that the GDL will continue to increase in the future. Ding and Chen (2021) pointed out that Jiangsu experienced a drastic upward change in the green development with large fluctuation revealed by a proposed water-energy-food-ecology system, which means Jiangsu has achieved a great improvement in resource usage, ecological environment protection in recent years which is consistent with this study.

According to the changes in different cities in Jiangsu over the study period (Fig. 8), the GDL scores of Jiangsu's cities maintained an upward trend; however, the scores for each city differed. Among them, Suzhou had the highest GDL in 2005, while Huaian and Lianyungang scored the highest in 2010. Xuzhou had the highest GDL in 2015, and all other cities had the highest GDL in 2020. In general, before 2010, an adequate homogeneity between the GDL and development of the regional economy was observed. However, after 2010, the level of regional GDL showed a more significant downward trend, which was converse to the economic development. Therefore, the GDL of Jiangsu also showed a more obvious Kuznets curve change trend, which is consistent with the environmental quality change trend (Ekins, 1997); that is, over a certain period (in the initial stage of development), the GDL overall increases with economic growth, which is mainly manifested in the rapid accumulation of green capital and effective improvement of green welfare. However, when the transformation of economic development pattern lags and development speed exceeds a certain critical point, the decreases of the GDL with the development of the economy, and is mainly manifested as the rapid deterioration of the environment (indicated by factors such as the rapid rise in $PM_{2.5}$, decline in water environment quality, and rapid decline in regional terrestrial ecosystem productivity (NPP) (Mohsin et al., 2019). This result also indicated that the core factors affecting the level of regional GDL are the supporting capacity and green capital level of the regional ecological environment, and not the level of economic development. Since 2015, people have increased investments in green development, and the GDL in many cities has shown a rapid improvement in recent years. As Wang and Feng (2021b) advocated, Jiangsu has passed the peak point of Kuznets curves. And consequently, with the continuous development of economy, regional ecological environment and the GDL are expected to continue to rise in the coming years.

Changes in the gravity center of the GDL

The change of the gravity center of green development was plotted (Fig. 9) according to the GDL scores at 5 years (2000, 2005, 2010, 2015, and 2020). The GDL gravity center of the study area was located in Gaoyou (affiliated to Yangzhou City). The gravity center of green development in Jiangsu from 2000 to 2020 overall shifted to the north, but there is a tendency to shift to the south in the future. The gravity center of transfer process can be divided into three

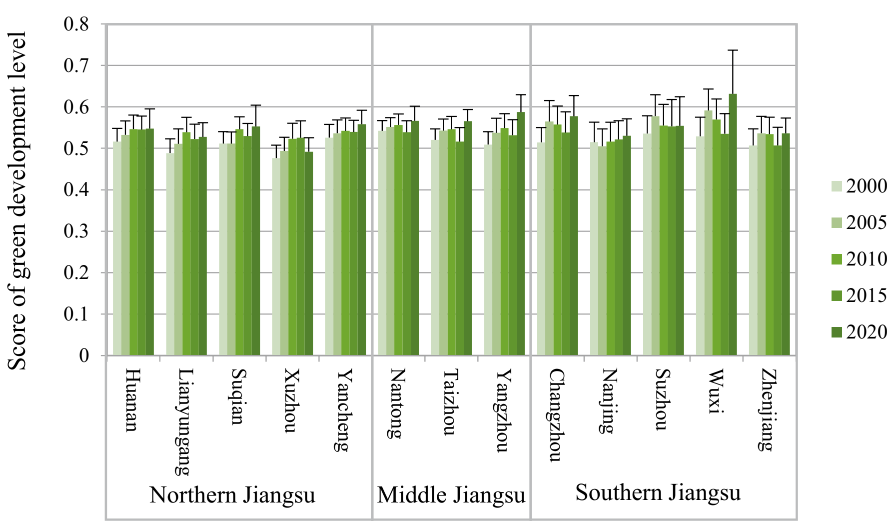


Fig. 8 Time series histogram of the GDL score of the cities in Jiangsu

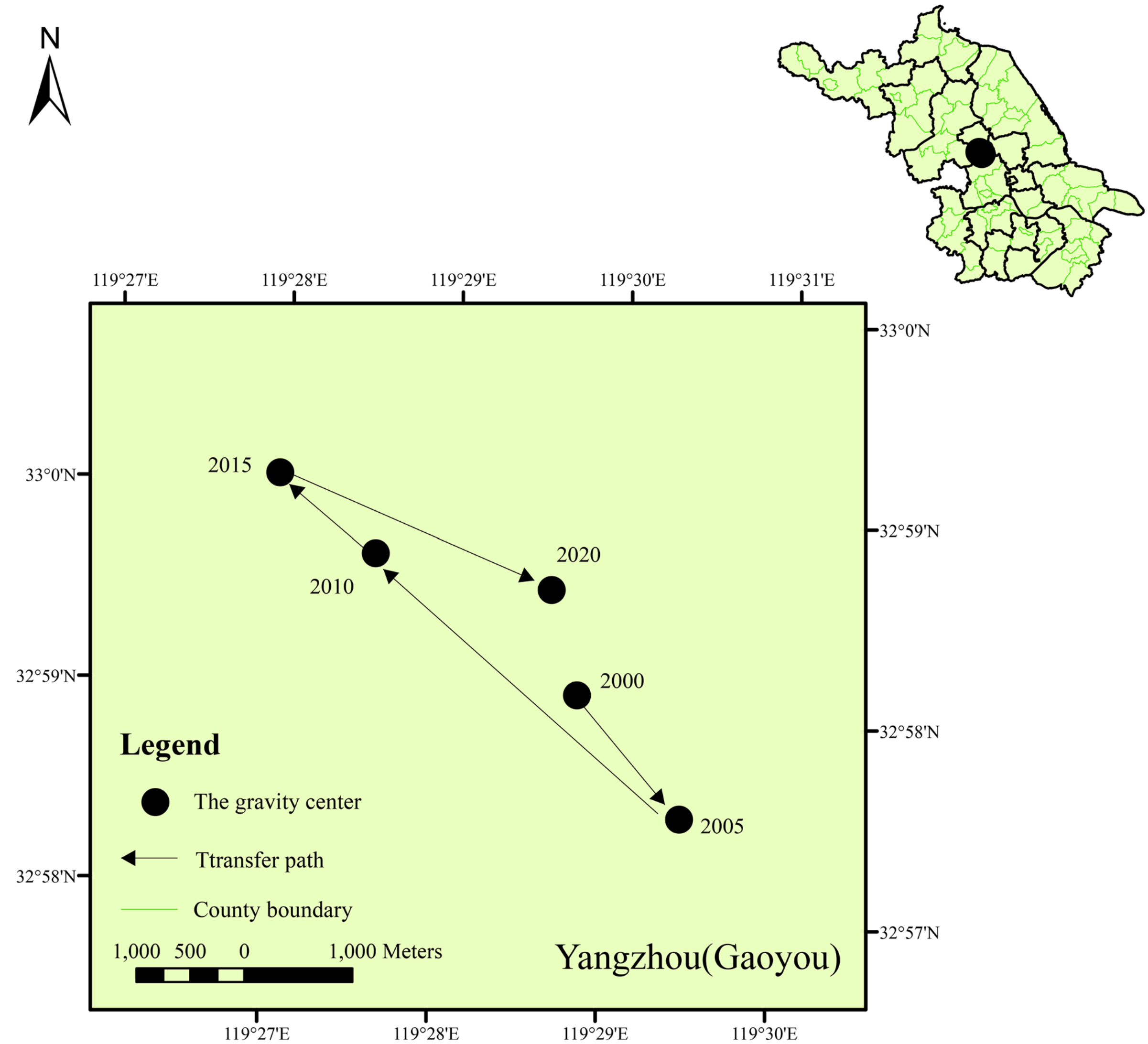


Fig. 9 Changes in the gravity center of the green development level score

stages during the study. Firstly, the gravity center shifted to the south from 2000 to 2005. This is closely related to the rapid social and economic development in the south. Research by Zhang and Han (2014) showed that the economic center of Jiangsu has gradually moved to the south from 1978 to 2012. Secondly, the gravity center shift of the GDL in the study area was opposite to the change of the gravity center of economy from 2005 to 2015. The main reasons for this difference in the change of the two gravity centers are as follows: during this period, northern Jiangsu was still in the initial and middle stages of industrialization and urbanization (Xu, 2014), while southern Jiangsu was in the middle and late stages (Ye et al., 2017). The continuous advancement of industrialization and urbanization inevitably led to ecological damage and environmental pollution, such as the overexploitation of land, large consumption of resources and energy (Chen et al., 2020; Yi et al., 2021), and excessive discharge of the "three wastes" of industry (wastewater, waste residue, and waste gas) (Ge et al., 2018). In addition, the spatial extent of southern Jiangsu was relatively small, resulting in the relatively limited ecosystem and ecological service capacities. Rapid industrial development and urban expansion further reduced these capabilities considerably (Lv et al., 2017). The natural resources in southern Jiangsu are ever short board, which yet is burdened with supporting large population (Yang & Ding, 2018). Therefore, in this stage of development, the GDL in southern Jiangsu was relatively lower compared to that in northern Jiangsu, leading to the overall northward shift of the gravity center of green development in Jiangsu. However, in the long run, once the economic growth pattern transformation in southern Jiangsu is successful, its GDL will also be greatly improved in the future. The last stage is the southward shift of the gravity center from 2015 to 2020, which can illustrate this.

Policy implications

Evaluation results reveal that the GDL in Jiangsu shows an obvious regional imbalance with a possibility of gradual polarization. From the perspective of land development and utilization, Jiangsu needs improvements in its ecological land areas such as agriculture, wetlands, and nature reserves. In the process of urbanization, green urban infrastructure can be improved by building green roofs, sponge cities, and other green urban ecological spaces (Demuzere et al., 2014; Getter & Rowe, 2006) to improve the production and support capacities of its ecosystem and enhance regional ecosystem service capacities. In terms of energy consumption and environmental protection, China should implement a more positive and green energy strategy (Midilli et al., 2006), promote the transformation and upgradation of industrial structure, give priority to the development of energy-saving and circular economy industries, reduce pollutants, and thus improve regional air quality. At the same time, the government should increase publicity regarding green development and improve people's awareness about resource conservation and environmental protection to gradually improve environmental welfare. From a regional scale, northern Jiangsu should pay more attention to ecological environment conservation, improve the quality of economic development, and cultivate new driving forces to further promote regional green wealth. However, southern Jiangsu needs to closely focus on the transformation of the economic development mode as well as efficiency of economic development and actively expand the external positive effect of economic development to improve regional green welfare.

Conclusions

This study advances a novel "three-circle" conceptual framework of regional green development and measures the GDL of Jiangsu in eastern China using multi-source data and further examines its spatial–temporal characteristics and driving forces. The results show that the AHP-based model has relatively high precision in GDL measurements. In Jiangsu, the average score of the GDL is approximately 0.53, with a significant spatial difference, showing an overall rising trend over the study period (2000–2020). Spatially, the mean score of the GDL in the study area has been ranked as follows: middle Jiangsu > southern Jiangsu > northern Jiangsu. Concerning specific cities, Wuxi, Nantong, and Changzhou generally have higher a GDL score, the mean scores being 0.567, 0.551, and 0.549, respectively. Meanwhile, the GDL scores for Lianyungang, Nanjing, and Xuzhou were relatively lower, with mean values of 0.518, 0.517, and 0.501, respectively. In the study area, both in the entire province and specific cities, a general trend of increment in the GDL score, followed by a decline, was identified from 2000 to 2015, with a final rise in 2020; the overall trend was upward. In addition, it was observed that the gravity center of the GDL in Jiangsu can be divided into three stages during the study. The GDL gravity center overall shifted to the north, but there is a tendency to shift to the south in the future. The core aim of Jiangsu's environmental policies in the future is to address the imbalance in regional green development in space. Considering the different regions in Jiangsu, ecological environment conservation, quality and pattern of economic development, and the cultivation of new drivers of economic development should be focus on the region of northern Jiangsu to furthering regional green wealth. However, in southern Jiangsu, the transformation of economic development patterns, efficiency of economic development, and reduction of negative external effects of economic development should be addressed to improve green welfare in the future.

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Author contribution XP: methodology, software, data curation, and writing—original draft preparation. JL: conceptualization and supervision. JW: resources. YY: project administration. LL: project administration.

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Availability of data and material The datasets used and analyzed during the current study are available from the author on reasonable request.

Code availability The code used during the current study is available from the author on reasonable request.

Declarations

Ethics approval Not applicable.

Consent to participate Not applicable.

Consent for publication Not applicable.

Conflict of interest The authors declare no competing interests.

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