The dynamic coupling nexus among inclusive green growth: a case study in Anhui province, China

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Abstract

Inclusive green growth (IGG) offers an effective alternative to pursue sustainable development. The core of the IGG system lies in the coordination of inclusive, green, and growth subsystems. However, there is little quantitative assessment on IGG based on subsystem collaboration. This study proposes a holistic scheme of inclusive-green-growth nexus in Anhui province from 2009 to 2018 by using an integrated approach, namely, the entropy weight approach (EWA), coupling coordination degree model (CCDM), grey prediction model (GPM), and obstacle factor diagnostic model (OFDM). The results show that: (1) The proposed integrated approach could be viable to measure the synergistic interactions among internal IGG subsystems; (2) At the provincial level, a relatively high IGG performance but a low coupling coordination degree (CCD) of the IGG nexus are seen. Although the predicted value of CCD will show an upward trend, it will not be able to cross the start stage. The obstacle factors on the coordinated development of IGG can be divided into two stages: (3) At the prefectural level, the cities in which CCD is rising outnumber those it is falling. However, the CCD is also low, and the gap between cities is getting wider. The obstacles that affect the CCD of cities see a dynamic evolution trend from “inclusive obstacle type” to “inclusive and growth obstacle type” then to “green obstacle type” over the decade.

Keywords Inclusive green growth · Coupling coordination degree · Entropy weight · Obstacle factor · Grey prediction model

Introduction

The term “inclusive green growth (IGG)” was first put forward at the Rio + 20 summit in 2012 (Zhu and Ye 2018; Chen et al. 2020a). It is a continuation and extension of the concept of sustainable development (Sun et al. 2020), emphasizing the symbiosis of inclusive, green, and growth subsystems. As an organic combination of green growth and inclusive growth, this novel development mode enables more countries and regions to embark on the path toward more effective sustainable development (Ojha et al. 2020; Li et al. 2021; Zhang et al. 2022). The performance improvement of

a regional IGG system depends on the organic synergy of each subsystem. Therefore, the coordinated development of the three subsystems, namely, inclusive, green, and growth, is a significant prerequisite for achieving the goals of IGG. This idea not only guides countries to explore a new path of sustainable development, especially developing countries that need to solve the problem of imbalanced development, but also attracts wide attention from academia and local governments (Ojha et al. 2020; Sun et al. 2020; He and Du 2021; Zhang et al. 2022). It is urgent and necessary to improve the coordinated development of the IGG subsystems.

China is now at a crucial point in its developmental history. Its economy has accomplished remarkable achievements at the expense of enormous social and environmental costs (Sun et al. 2020; He and Du 2021). On the one hand, the extensive development pattern has resulted in natural resource depletion and ecological damage (Gu et al. 2021b); on the other hand, the rapid economic growth has also brought about social problems, such as education inequality, insufficient housing security, disproportionate urbanization, poor food safety, leading to a widening income gap

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and inequitable sharing of the prosperity (Liu et al. 2021; Wu and Zhou 2021). Economic growth has become inseparable from social development and environmental quality in China. Hence, it is crucial for governments, academia, and individuals to maintain balance among inclusive, green, and growth and promoting IGG.

There is an increasing concern around the world on the inclusive growth (Ge and Li 2020; Ge et al. 2020), green development (Albert et al. 2020; Zhu et al. 2020), and IGG development level. However, the following three aspects of IGG should be further studied. First, in terms of evaluation content, existing research primarily focuses on exploring the overall level (Zhu and Ye 2018; Chen et al. 2020a; Liu et al. 2021; He and Du 2021), or each single-dimensional level, of IGG (Li et al. 2021) and the factors that affect IGG. Early literature has achieved rich studies on external factors affecting IGG from the perspective of foreign direct investment (Zhu and Ye 2018), carbon tax (Ojha et al. 2020), land resource misallocation (He and Du 2021), economic policy uncertainty (Gu et al. 2021b), and fiscal expenditure (Wu and Zhou 2021). However, research regarding the internal coupling nexus and interactive effects among the inclusive, green, and growth subsystems, as well as an analysis on the prediction and obstacles of its evolution has largely been neglected. Thus, the dynamic coupling nexus of IGG based on internal subsystem collaborations must be quantitatively scrutinized.

Second, in terms of research scale, scholars have evaluated, analyzed, and compared the overall IGG performance at the national, provincial, and city-group levels (Liu et al. 2021; Li et al. 2021; Zhang et al. 2022). To the best of my knowledge, only two studies have been conducted on IGG evaluation at the city level in which IGG levels were measured by a single index evaluation (SIE) of input–output efficiency (Chen et al. 2020a; Sun et al. 2020). IGG is a complex and dynamic system; thus, it is more effective to calculate it by designing a multidimensional comprehensive evaluation index system (Wu and Zhou 2021). Therefore, it is necessary to conduct an IGG evaluation at the city level or at the microscale by adopting multidimensional evaluation approach.

Finally, in terms of evaluation method, existing studies mainly use a single evaluation method to explore IGG (Zhu and Ye 2018; He and Du 2021; Zhang et al. 2022). However, given the complex characteristics of the IGG system, it is challenging to discuss by applying a single method. In recent years, some researchers attempted to employ the combination of two or three methods (Sun et al. 2020; Li et al. 2021). In this context, it has great significance to comprehensively capture the holistic information of IGG from the evaluation results to the coupling nexus to the future prediction, and then to the obstacle factors. Consequently, this paper aims to provide a detailed and informative view of IGG by using

an integrated approach, namely, the entropy weight approach (EWA), coupling coordination degree model (CCDM), grey prediction model (GPM), and obstacle factor diagnostic model (OFDM).

Compared with earlier literature, the contribution of this study is threefold. First, from a research perspective, the focus of this study is neither the overall IGG nor its subsystem level, but rather the nexus among the internal subsystems of IGG. This paper assesses IGG based on subsystem collaboration to explore the coupling nexus and interactive effects; this not only characterizes the operation law of the subsystem relationships quantitatively but also enriches the current understanding of IGG. Second, owing to the complex dynamic characteristics of the IGG system, using an integrated approach, this study comprehensively captures the detailed information of IGG, which not only evaluates the IGG development level, its coupling nexus, and obstacle factors based on historical data but also scientifically predicts the development trend of the IGG coupling nexus in the future. Such empirical evidence can provide more profound insights into internal IGG subsystems. Third, this paper explores the spatiotemporal evolution of IGG coupling nexus under different scenarios and identifies the main obstacle factors that affect the disharmonious nexus among IGG. Such investigation will assist us formulating targeted policies for sustainable development in various city types.

The remainder of the article is organized as follows. In the next section, a brief review of literature on IGG will be elaborated. Section 3 presents the study area and data sources of this study. Section 4 outlines the construction of evaluation index system, EWA, CCDM, GPM, and OFDM. Section 5 reports the findings and discussions. Section 6 provides a conclusion on coupling nexus of IGG improvement in Anhui province of China.

Literature review

Researchers working on IGG focus mainly on three aspects. First, in the context of the definition of IGG, the World Bank (2012) defined IGG as a sustainable economic growth pattern of social equity, environment friendly, and economic sustainability. The Organization for Economic Cooperation and Development (OECD) believed that IGG provided a realistic pathway to countries in pursuit of the economic growth going inclusive and green (OECD 2012). The United Nations Environment Programme (UNEP) argued that IGG consisted of three pillars: the sustainability of society, environment, and economy (UNEP 2012). Most scholars suggested that IGG should balance three subsystems of inclusive, green, and growth (World Bank 2012; Wu and Zhou 2019; Sun et al. 2020; Liu et al. 2021).

Second, the evaluation on IGG. At the national level, scholars have assessed the overall IGG index on a single country of China (Wu and Zhou 2019), G20 countries (Yang 2014), and 37 countries in the Asia–Pacific region (Li et al. 2021). At the provincial level, there are fruitful studies on the 30 provinces within China (Zhu and Ye 2018; He and Du 2021; Gu et al. 2021b; Wu and Zhou 2021; Wang et al. 2021; Zhang et al. 2022). At the city-group level, Chen et al. (2020a) and Liu et al. (2021) conducted comparative analysis of IGG development levels among three city groups within the Yangtze River basin and Yangtze River Economic Belt, respectively. Ji and Zhang (2022) compared the different characteristics of sustainable growth between the Yangtze River and the Yellow River Economic Belt regions. Based on previous research, it is clear that further analysis must be conducted on microscale governance.

IGG evaluation methods can be divided into two groups. The first group is to measure the input–output efficiency based on a SIE by applying the slacks-based model (SBM) (Zhu and Ye 2018), the Malmquist–Luenberger (ML) index (Wang et al. 2021), and Global ML index (He and Du 2021; Liu et al. 2022). This method has been extended from traditional total factor productivity (TFP) to green TFP and inclusive TFP, and then to inclusive green TFP. However, using SIE cannot reveal the multidimensional and comprehensive characteristics of IGG. The second group is to establish a multidimensional indicator evaluation (MIE) by employing EWA (Gu et al. 2021a; Wu and Zhou 2021; Zhang et al. 2022), entropy-TOPSIS method (Chen et al. 2020a), and factor analysis method (Li et al. 2021). Additionally, using a single method is difficult to successfully provide the all-sided characteristics of IGG. Therefore, scholars have sought to use integrated evaluation methods, such as the following: the directional distance function and SBM model (Sun et al. 2020); the SBM model and ML index (Chen et al. 2020a); factor analysis, clustering method, and EWA (Li et al. 2021); EWA, kernel density method, and Gini coefficient (Liu et al. 2021). In addition, most researchers mainly focused on one aspect of IGG; a holistic scheme of inclusive-green-growth nexus still needs to be proposed based on integrated method. Table 1 provides a comparison on the representative the studies (Yang 2014; Zhu and Ye 2018; Chen et al. 2020a; Gu et al. 2021b; Wu and Zhou 2021; Liu et al. 2021).

To comprehensively capture the information of IGG, an integrated approach is adopted in this study. First, EWA, widely employed in studies on the progress of indicator assessment, is an objective weighting method, which can determine the weight value of indicators objectively and reveal the real information of indicators (Wang et al. 2020; Wu and Zhou 2021). Second, CCDM can effectively measure the interactions between and mutual influences among multiple systems, rather than one-way impacts (Ren and Yu 2021). Therefore, this study used CCDM to explore the

pairwise relationships and three subsystem interlinks within IGG. Thirdly, GPM is based on the principle of “least information” and has been successfully and effectively applied to small-sample predicting (Wu et al. 2013). Thus, this paper builds GPM to forecast the development trend of the future coupling nexus. Finally, the OFDM can scientifically investigate the key factors that restrict the development of a system and provide future direction for policy formulation (Chen et al. 2020a).

The third perspective of extant studies concerns the factors that affect regional IGG. Zhu and Ye (2018) established an IGG index by utilizing the SBM and concluded that foreign direct investment was a positive factor in inclusive green TFP. Ojha et al. (2020) searched for a triple dividend in IGG of using carbon tax revenue by employing a dynamic CGE model. He and Du (2021) measured IGG levels in 30 provinces of China from 2009 to 2018 and proved that the misallocation of urban land resources negatively affected the improvement of IGG. Gu et al. (2021b) calculated the IGG index of 30 provinces in China from 2006 to 2016 by employing EWA and explored the impact of economic policy uncertainty on IGG. Consequently, the extant research on the IGG was focused mainly on the peripheral nexus. The core nexus and multisystem interactivity is yet to receive adequate attention.

Therefore, using an integrated approach—namely, EWA, CCDM, GPM, and OFDM—this paper explores the interaction and spatiotemporal dynamic coupling nexus among subsystems of IGG based on the panel data for Anhui province, China over the decade spanning 2009–2018. The purpose of the study is threefold: (1) to construct an evaluation index system and assess the performance of IGG at the provincial and prefectural level, respectively; (2) to identify the types and stages of coupling coordination degree (CCD) during 2019–2018 and to predict the trend in the future; (3) to diagnose the obstacle factors of CCD for proposing targeted recommendations of regional policy making.

Study area and data sources

Study area

Anhui province is located in the central mainland of China, which belongs to the western Yangtze River Delta (YRD) urban agglomeration and consists of 16 cities. Its development is under the guidance of two strategic policies. One is the Regional Integration Development Planning of YRD, one of the world-class urban agglomerations. The other is the Rising of Central China Strategy, which is a major plan of the state to promote the rise of the six central provinces (the remaining five provinces are marked in orange), another regional coordinated development strategy promoted from a

Table 1 Measurement and assessment of inclusive green growth (IGG)

Authors	Publication year	Study area and span	Indicators	Assessment method
Zhu and Ye	2018	30 provinces of China (2000–2015)	Input–output efficiency indicator including 6 aspects (labor; capital; energy; GDP; income disparity; environment pollution)	Super-efficiency slack-based measure model (SIE)
Chen et al	2020	Yangtze River economic belt 108 cities (2003–2016)	Input–output efficiency indicator including 8 aspects (capital; labor; land; energy; GDP per capita; afforestation; air pollution; waste pollution)	Super-efficiency slack-based measure model and MML index (SIE)
Yang	2014	G20 countries (2010)	6 indicators (per capita CO ₂ emissions; Gini coefficient; per capita GNP; net ecological footprint; savings rate; investment in clean energy)	Average weight method (MIE)
Gu et al	2021	30 provinces of China (2006–2016)	4 dimensions, 33 indicators (GDP per capita; secondary sector ratio; energy consumption per unit; green space per capita; per capita income ratio of urban–rural residents; urban unemployment rate, etc.)	Entropy method (MIE)
Wu and Zhou	2021	30 provinces of China (2007–2018)	3 dimensions, 30 indicators (per capita income ratio of rural residents; number of beds per 10,000 people; SO ₂ emission per unit; water consumption per capita; solid waste production; urban unemployment, etc.)	Entropy method (MIE)
Liu et al	2021	3 city clusters in Yangtze River Basin (2004–2017)	4 dimensions of economy, society, environment, and green consumption, each including 2–5 secondary indicators	Entropy method, kernel density, and Gini coefficient (MIE)

high position following Western Development Strategy and Revitalization of Northeast China Strategy. The locations of the cities are graphically illustrated in Fig. 1, and Table 2 shows the brief profiles of the 16 cities.

This paper takes Anhui province of China as a case study for the following two reasons. First, the YRD plays a leading role in China's IGG development. The Regional Integration Development Planning of the YRD has attracted an increasing attention because this plan has become an important Chinese national strategy (Zhou et al. 2020; Deng et al. 2022). However, based on the evaluation results of the IGG performance in 30 provinces of China in previous literature (Zhu and Ye 2018; Gu et al. 2021b), Anhui province is the most backward among the three provinces and one municipality in the YRD, and its inclusive development and green growth face more severe challenges than other provinces and municipality. Second, as one of the six provinces, Anhui province plays a vital role in the Rising of Central China Strategy. Because of its geographical conditions and economic foundation, the region has experienced a growth dilemma in which it is “not east, not west.” Consequently, whether Anhui province can achieve an IGG path will vitally affect the realization of integration development in YRD and the vision of the rise of the central region.

Anhui province covers an area of 140,139 km² (National Bureau of Statistics 2019), which comprises one capital city, namely Hefei, and 15 prefecture-level cities, namely Huaibei, Bozhou, Suzhou, Bengbu, Fuyang, Huainan, Chuzhou, Liuan, Ma'anshan, Wuhu, Xuancheng, Tongling, Chizhou, Anqing, and Huangshan. In 2018, Anhui province had approximately 63.24 million people;

Table 2 Specifications of the 16 cities in Anhui province of China in 2018

Cities	Areas (km ²)	Resident population (10,000 people)	Urbanization rate (%)	Per-capita GDP (yuan)
Hefei	11,445	808.74	74.97	96,730
Huaibei	2741	225.41	65.11	43,707
Bozhou	8521	523.72	41.01	24,387
Suzhou	9939	568.14	42.74	28,694
Bengbu	5951	339.20	57.22	50,550
Fuyang	10,118	820.72	43.29	21,439
Huainan	5532	348.95	64.11	32,478
Chuzhou	13,516	411.42	53.42	43,793
Liuan	15,451	483.74	46.08	26,627
Ma'anshan	4049	233.71	68.25	82,072
Wuhu	6026	374.82	65.54	87,469
Xuancheng	12,313	264.83	55.21	49,738
Tongling	2923	162.91	55.99	75,033
Chizhou	8399	147.45	54.10	46,452
Anqing	13,538	469.13	49.22	40,875
Huangshan	9678	140.71	51.46	48,178

GDP exceeded 3 trillion yuan for the first time, with an annual rate of 8.02%, and the output value of high-tech enterprises exceeded 1 trillion yuan for the first time. Over a 15-year period, Anhui's GDP increased from 481.27 billion yuan in 2004 to 3000.682 billion yuan in 2018, with a total growth rate of 523.49% and an average annual growth rate of 34.9%. Besides, the percentage of forest coverage accounted for 28.7% (National Bureau of Statistics 2019).

Fig. 1 Location of the 16 cities of Anhui province, China: (a) China; (b) location of Anhui province in central China and the YRD; (c) the 16 cities of Anhui province

Data sources

The data is retrieved from China Statistical Yearbook (2010–2019), Anhui Statistical Yearbook (2010–2019). Evaluation indicators are selected composite indicators that are calculated, such as: selecting fixed asset investment per unit of GDP rather than fixed asset investment and selecting the number of books in the library per 100 people rather than the library stock, which are more accurate for expressing the index considering the factors of regional population difference.

Methodology

Construction of evaluation index system

The IGG evaluation index system, made up of 27 indicators from three dimensions of inclusive, green, and growth, is established and listed in Table 3. In the construction of

evaluation, I first draw on the conceptual framework of IGG reported by World Bank (2012) and OECD (2012), the inclusive, green economy indicators launched by UNEP (2012), the typical assessment indicator systems for green development or green growth, such as the Green Growth Knowledge Platform (2013). I then combine an in-depth analysis of the green development of Chinese institutions such as Chinese Academy of Sciences (Sustainable Development Strategy Study Group 2012) and relevant scholars (Wu and Zhou 2019; Gu et al. 2021b; Liu et al. 2021; Zhang et al. 2022). Meanwhile, the index system also considers the respective aspects of comprehensiveness, availability, and representativeness of data and the practice of IGG in Anhui province and the 16 cities (Reid et al. 2010).

The goal of IGG is to seek overall social equality and inclusion, including not only achieving the equality of education and medical condition, as well as shared cultural resources, but also increasing the equality of opportunity in employment and narrowing the income gap. IGG should not only improve people's living space and quality of life, but

Table 3 Indicator system of inclusive green growth

Subsystems	[Code]Criteria (unit)	Property
Inclusive subsystem (<i>Inc</i>)	[C ₁]Library books per 100 persons (ben/100 persons)	Benefit
	[C ₂]10,000 people with college degrees or above (per 10,000 persons)	Benefit
	[C ₃]Number of beds per 1000 persons (per 1000 persons)	Benefit
	[C ₄]Registered urban unemployment rate (%)	Cost
	[C ₅]Disposable income per capita between urban and rural residents (%)	Cost
	[C ₆]Urban population density (person/km ²)	Cost
	[C ₇]Per capita housing gross leasable area (m ²)	Benefit
	[C ₈]Amount of fertilizer per unit cultivated area (kg/hm ²)	Cost
	[C ₉]Incidence of population fires (1 in 100,000)	Cost
Green subsystem (<i>Gre</i>)	[C ₁₀]Industrial solid waste production (million tons)	Cost
	[C ₁₁]Discharge of COD in industrial wastewater (tons)	Cost
	[C ₁₂]Industrial SO ₂ emissions (tons)	Cost
	[C ₁₃]Proportion of air quality reaching or better than grade 2 weather (%)	Benefit
	[C ₁₄]Per capita green area of parks (m ²)	Benefit
	[C ₁₅]Average traffic volume (car/hour)	Cost
	[C ₁₆]Central processing rate of sewage treatment plant in urban areas (%)	Benefit
	[C ₁₇]Popularity rate of sanitation toilet in rural areas (%)	Benefit
	[C ₁₈]Per capita afforestation area (m ² /person)	Benefit
Growth subsystem (<i>Gro</i>)	[C ₁₉]Fixed asset investment per unit of GDP (yuan)	Cost
	[C ₂₀]Secondary sector land yield (yuan/m ²)	Benefit
	[C ₂₁]Tertiary sector labor productivity (10,000 yuan/person)	Benefit
	[C ₂₂]Water consumption per unit of GDP (m ³ /1,000 yuan)	Cost
	[C ₂₃]Power consumption per unit of GDP (watt yuan)	Cost
	[C ₂₄]Energy consumption per unit of industrial added value (ton standard coal/10,000 yuan)	Cost
	[C ₂₅]Industrial waste water discharge per unit of GDP (ton/10,000 yuan)	Cost
	[C ₂₆]Industrial waste gas emission per unit of GDP (m ³ /yuan)	Cost
	[C ₂₇]Solid waste generation per unit of GDP (tons/yuan)	Cost

also enhance food security and social stability. In this study, the inclusive subsystem is described by equality of education and medical condition and sharing culture resources (C_1 , C_2 , and C_3), the status of employment and income gap (C_4 and C_5), living space and quality of life (C_6 and C_7), and food security and social stability (C_8 and C_9).

The selection of indicators of the green subsystem is based on the classic framework of the PSR model (pressure-state-response) (Liu and Suk 2021). C_{10} , C_{11} , and C_{12} indicate the pressure on the ecological environment from the aspects of solid, liquid, and gas, respectively; C_{13} , C_{14} , and C_{15} signify the state of the ecological environment; C_{16} , C_{17} , and C_{18} are selected to reflect the response to the environment. Furthermore, the green subsystem covers as many kinds of environment-related forms as possible such as solid, liquid, gas, and noise, and is complete in covering not only urban but also rural areas.

Both resource conservation and environmental friendliness together constitute the growth subsystem. C_{19} , C_{20} , C_{21} , C_{22} , C_{23} , and C_{24} symbolize the resources consumption and costs of creating GDP. C_{25} , C_{26} , and C_{27} are chosen as cost indicators for pollutant emission.

Entropy weight approach (EWA)

The accuracy of measurement of IGG is strongly linked to the objectivity of the weight selection approach. Entropy first originated from a physical concept of thermodynamics and was subsequently applied into information theory (Fei et al. 2021). The advantage of EWA is that it can overcome the overlap of information among multidimensional variables, therefore describing objectively the nature of the indicators (Li et al. 2021). Compared with the subjective weighting methods—Analytic Hierarchy Process and Delphi method—the accuracy and reliability of the assessment can be improved. Furthermore, EWA is not limited by the number of indicators. Research progress is as follows:

Step 1: Construct the standardized evaluation matrix.

Set the initial evaluation matrix of Anhui IGG as:

$$y = (p_{ij})_{mn}, i = 1, 2, \dots, m, j = 1, 2, \dots, n \quad (1)$$

Step 2: Normalize the initial matrix (dimensionless), and get the new matrix (Grimm et al. 2008):

$$y' = (p'_{ij})_{mn} \quad (2)$$

Among all the improved EWA, the extremum entropy weight method is the best (Zhang et al. 2022). Consequently, this paper uses this method to normalize the initial matrix. The formula is as follows:

For the benefit (positive) indicator (the larger the indicator, the better):

$$p'_{ij} = \frac{p_{ij} - \min(p_{ij})}{\max(p_{ij}) - \min(p_{ij})}. \quad (3)$$

For the cost (negative) indicator (the smaller the indicator, the better):

$$p'_{ij} = \frac{\max(p_{ij}) - p_{ij}}{\max(p_{ij}) - \min(p_{ij})}. \quad (4)$$

Among the formula, $\max(p_{ij})$ and $\min(p_{ij})$ are the maximum and minimum of each indicator, respectively. p_{ij} is the original indicator, and p'_{ij} is the normalized indicator.

Step 3: Calculate the information entropy and the weight of each index.

Calculate the information entropy of each index (Wu and Zhou 2021):

$$e_i = -\frac{1}{\ln n} \sum_{j=1}^n p'_{ij} \ln p'_{ij}. \quad (5)$$

Calculate the weight of each index:

$$\omega_i = \frac{1 - e_i}{m - \sum_{i=1}^m e_i}, \text{ and } e_i \geq 0 \quad (6)$$

Step 4: Construct the evaluation matrix based on the entropy weights.

Use the entropy weight to construct the weighted standardized evaluation matrix. The specific formula is as follows (Gu et al. 2021b):

$$V = v_{ij} = \omega_i (p'_{ij})_{mn}. \quad (7)$$

Coupling coordination degree model (CCDM)

CCDM can be applied to measure the coupling degree between two or more systems, which is based on the concept and principle of coupling in physics and reflects the relationship between coordination and benign cycle. The coupling degree is a measurement of the strength of the interactions among the subsystems. Inspired by the dispersion coefficient, this method was initially proposed between two systems (Fan et al. 2019) and then was improved and extended to three or more systems (Li and Yi 2020; Wang et al. 2020; Fei et al. 2021). This paper introduces inclusive, green, and growth subsystems to measure the interaction and CCD among three subsystems in IGG. CCDM includes coupling degree and CCD. This paper considers the comprehensive level index of inclusive, green, and growth subsystems as *Inc*, *Gre*, and *Gro*, respectively. The specific calculation steps are as follows:

Step 1: Build a coupling model:

$$C = \sqrt[3]{\frac{Inc \times Gre \times Gro}{((Inc + Gre + Gro)/3)^3}} \quad (8)$$

Step 2: Calculate compatibility index:

$$T = \alpha Inc + \beta Gre + \gamma Gro \quad (9)$$

Step 3: Calculate the CDD:

$$D = \sqrt{C \times T} \quad (10)$$

In the equation, D is the coordination degree, C is the coupling degree, and α , β , and γ are the undetermined coefficients. Because the three monomial subsystems are of equal importance, α , β , and γ are all assigned as $1/3$. For coupling degree $C = 0$, the coupling degree among the subsystems is the smallest, which indicates that the cooperation among the elements of the systems is disordered and in a maladjusted or irrelevant state. For coupling degree $C = 1$, the coupling degree among the systems is the largest, which points to all the elements of the systems being harmonious and orderly, reaching the optimal state of benign interaction (Deng et al. 2022).

Inc , Gre , and Gro represent the level indices of the inclusive, green, and growth subsystem, respectively. Table 4 shows the coordination types and level classes of CCD to clearly demonstrate the coordination among the subsystems of IGG, based on previous research (Fan et al. 2019; Chen and Zhang 2021; Fei et al. 2021).

The grey prediction model (GPM)

The GPM, based on small-sample predicting, has been widely employed in various disciplines. The fractional order-accumulated grey forecasting model (FGM (1,1)) that Wu et al. (2013) proposed avoids the disadvantage of the traditional cumulative generation operator

against the new information priority principle. Therefore, the FGM (1,1) has higher stability, better model fitting, and more accurate predictions than traditional GPMs.

The specific process is as follows: (1) perform the new data set (fractional order accumulation data sequence) based on the original data sequence (Zhou et al. 2020); (2) construct a first-order differential equation for the new data set, and solve for the feature solution coefficients; (3) establish the grey coefficient matrix based on the feature solution coefficients, and use the least square approach to calculate it; (4) measure the fitted and predicted values; and (5) calculate the forecasting error. In this study, I use the mean absolute percentage error (MAPE) to examine the prediction accuracy (Wu et al. 2015; Li and Lu 2021).

The obstacle factor diagnostic model (OFDM)

To further clarify the focal point and the policy adjustment direction of the future development of Anhui IGG, the OFDM is applied to diagnose and analyze the impact factors. The structure of the model is as follows:

$$O_i = D_i \times C_i = D_i \times \omega_i = \frac{(1 - p'_{ij}) \times \omega_i \times 100\%}{\sum_{i=1}^m (1 - p'_{ij}) \times \omega_i} \quad (11)$$

In the formula, I introduce three main variables: obstacle degree, index deviation degree, and factor contribution degree (Ou et al. 2017). Obstacle degree (O_i) denotes the obstacle degree of the subsystem indexes or an individual index to the CCD of the regional IGG, which highlights the impact degree of a subsystem or an individual index on the coupling coordination level of the regional IGG (Chen et al. 2020b). Index deviation degree (D_i) represents the gap

Table 4 Evaluation criteria for coordination types and level classes of CCD

Serial number	Coupling coordination Index interval	Coordination type	Level class
1	$0.0 \leq D < 0.1$	Extreme imbalance (F_1)	Germination stage (S_1)
2	$0.1 \leq D < 0.2$	Severe imbalance (F_2)	
3	$0.2 \leq D < 0.3$	Moderate imbalance (F_3)	
4	$0.3 \leq D < 0.4$	Mild imbalance (F_4)	
5	$0.4 \leq D < 0.5$	Little imbalance (F_5)	Start stage (S_2)
6	$0.5 \leq D < 0.6$	Barely coordination (F_6)	Steady stage (S_3)
7	$0.6 \leq D < 0.7$	Primary coordination (F_7)	
8	$0.7 \leq D < 0.8$	Intermediate coordination (F_8)	
9	$0.8 \leq D < 0.9$	Good coordination (F_9)	Maturity stage (S_4)
10	$0.9 \leq D < 1.0$	Excellent coordination (F_{10})	

between the actual value and the optimal target value, which is expressed by the difference value between the evaluation standardized value of each index (p'_{ij}) and the optimal target value (100%). Factor contribution degree (C_i) signifies the contribution value of an individual factor (P_i) to the overall target, which can usually be expressed by the indicator weight (ω_i).

Results and discussions

Dynamic coupling of IGG nexus at provincial level

This part focuses on three key areas: (1) the performance of IGG and inclusive, green, and growth subsystems; (2) the CCD and types/stages of IGG nexus; (3) obstacle factors of IGG nexus; (4) prediction on CCD of IGG nexus.

The evolution of the IGG performance

Based on the assessment index system and measurement model of regional IGG, Table 5 presents the information entropy and weight values of each index, which are obtained

according to formulas (3) and (4) after normalization of the original data.

As can be seen from the weights for each subsystem at the provincial level, the figure for the inclusive subsystem sees the biggest proportion at 40.29%, followed by the green subsystem, which stands at 32.39%, with the growth subsystem only accounting for 27.32%. This finding furnishes evidence that the inclusive subsystem makes a greater contribution to the IGG, which highlights an important constraint for promoting the development goal of IGG. Additionally, it also lets us conclude that Anhui province made great efforts in social inclusive development but still needs to strengthen its promotion of sustainable economic growth on the premise of saving resources and reducing pollutant emissions. During the analyzed period, China has slowed its economic growth, shifting to a stage of high-quality development and emphasizing on social inclusiveness and ecological balance. Some studies have come to the similar conclusion (Ji and Zhang 2022), arguing that people's well-being and social progress should be given more attention.

Table 6 gives information that the IGG index in Anhui province was generally growing from 2009 to 2018, and the overall performance increased gradually from 0.2909 to 0.7098, with an average annual growth of 10.42%,

Table 5 Entropy values and weights of indicators at the provincial level

Inclusive	C_1	C_2	C_3	C_4	C_5	C_6	C_7	C_8	C_9	Proportion
Entropy	0.876	0.865	0.833	0.891	0.887	0.887	0.913	0.822	0.880	—
Weight	0.044	0.047	0.059	0.038	0.04	0.04	0.031	0.063	0.042	40.29
Green	C_{10}	C_{11}	C_{12}	C_{13}	C_{14}	C_{15}	C_{16}	C_{17}	C_{18}	Proportion
Entropy	0.843	0.890	0.952	0.895	0.940	0.861	0.933	0.873	0.890	—
Weight	0.055	0.039	0.017	0.037	0.021	0.049	0.023	0.044	0.039	32.39
Growth	C_{19}	C_{20}	C_{21}	C_{22}	C_{23}	C_{24}	C_{25}	C_{26}	C_{27}	Proportion
Entropy	0.806	0.907	0.852	0.939	0.945	0.939	0.929	0.954	0.951	—
Weight	0.068	0.033	0.052	0.022	0.019	0.021	0.025	0.016	0.017	27.32

Table 6 Overall and subsystem performances of IGG at provincial level (2009–2018)

Years	<i>Inc</i> performance performance	<i>Gre</i> performance performance	<i>Gro</i> performance performance	Overall performance
2009	0.0979	0.1456	0.0474	0.2909
2010	0.1039	0.1271	0.1026	0.3336
2011	0.1217	0.1453	0.1521	0.4191
2012	0.1470	0.1285	0.1672	0.4427
2013	0.1693	0.1512	0.1272	0.4477
2014	0.1849	0.1605	0.1529	0.4982
2015	0.2334	0.1492	0.1825	0.5651
2016	0.2648	0.1843	0.1681	0.6171
2017	0.2911	0.1978	0.1882	0.6771
2018	0.3109	0.2015	0.1973	0.7098

indicating that IGG had a good momentum of development. Based on the scores of IGG performance, the process of IGG in Anhui province has gone through three stages: the poor performance stage, medium performance stage, and good performance stage; however, it has not achieved the high-quality development stage, demonstrating that there are still great development potential and growth space. In the first stage (2009), the condition was relatively poor. The overall performance was merely 0.29; social inclusion, environmental green, and economic growth were all at low levels.

In the second stage (2010–2015), the overall performance of IGG in Anhui province was in the medium stage, and the largest score was 0.5651. Two opportunities have effectively promoted the IGG development of Anhui province. One is the active implementation of a national development strategy, “Wanjiang city belt undertaking industrial transfer demonstration zone plan,” since 2010, the only regional development program with the theme of industrial transfer in China. The other is guidelines issued by the State Council to promote the development of the Yangtze River economic belt relying on the golden waterway in 2014, and Anhui is incorporated into the Yangtze River economic belt.

In the third stage (2016–2018), the overall performance was in the good stage, reaching a peak at 0.7098 in 2018. The economy of resources, environmental friendliness, social equality, and sustainable economic growth saw steady increases, indicating the IGG of Anhui province presented a gradually increasing trend toward an ideal situation. This finding is closely related to the development plan for the YRD urban agglomeration adopted by the China State Council executive meeting in 2016, with Anhui being included in the YRD economic zone and participating in the integrated development of the YRD. The plan provides a novel path to advance the transformation of the economic growth mode from high input,

high consumption, high pollution, and low benefit to ecologically prioritized, green-development-oriented, high-quality development.

The performances of subsystems also generally saw an upward trend in the last 10 years, among which the inclusive subsystem had the highest-rising speed and the largest increment, from 0.0979 in 2009 to 0.3109 in 2018, with an increment of more than 0.2. This finding is consistent with the driving role of the inclusive subsystem on the overall improvement of regional IGG in the previous study (Wu and Zhou 2021). Although the growth and green subsystems had slight fluctuations in individual years, the whole tendency in 10 years was increasing, with an increment of approximately 0.15 and 0.056, respectively. This shows that the three subsystems of inclusive, green, and growth in Anhui province are unevenly distributed.

In short, this study reflects that the overall performance of IGG showed an upward trend, which is in accordance with the prior studies (Zhu and Ye 2018; Wu and Zhou 2019, 2021; He and Du 2021; Zhang et al 2022). However, Anhui province must constantly coordinate the nexus among the subsystems of inclusive, green, and growth for the uneven performances.

The CCD of IGG nexus

Table 7 presents the CCD of IGG nexus in Anhui province under different scenarios, and the coordination types are classified according to the classification principle (Table 4). The finding indicates that the CCD is increasing; however, the value is extremely low, approximately clustering between 0.13 and 0.36, and the highest value is merely 0.356, which has not yet crossed the germination stage (S_1).

Figure 2 demonstrates the temporal evolution for the CCD of IGG nexus in Anhui province. The CCD among three subsystems (D_4) is generally less than that between

Table 7 Types/Degrees of the coordinated development among subsystems at the provincial level under different scenarios in 2009–2018

Years	<i>Inc – Gre</i>		<i>Inc – Gro</i>		<i>Gre – Gro</i>		<i>Inc – Gre – Gro</i>	
	D_1	Type	D_2	Type	D_3	Type	D_4	Type
2009	0.2041	F ₃	0.1355	F ₂	0.1607	F ₂	0.1361	F ₂
2010	0.1976	F ₂	0.1821	F ₂	0.1967	F ₂	0.1599	F ₂
2011	0.2204	F ₃	0.2244	F ₃	0.2394	F ₃	0.1935	F ₂
2012	0.2259	F ₃	0.2493	F ₃	0.2374	F ₃	0.2024	F ₃
2013	0.2531	F ₃	0.2377	F ₃	0.2274	F ₃	0.2042	F ₃
2014	0.2675	F ₃	0.2628	F ₃	0.2490	F ₃	0.2236	F ₃
2015	0.2857	F ₃	0.3068	F ₄	0.2592	F ₃	0.2467	F ₃
2016	0.3235	F ₄	0.3133	F ₄	0.2718	F ₃	0.2651	F ₃
2017	0.3444	F ₄	0.3385	F ₄	0.2911	F ₃	0.2864	F ₃
2018	0.3560	F ₄	0.3534	F ₄	0.2984	F ₃	0.2974	F ₃

Fig. 2 The temporal evolution for the CCD of IGG nexus at the provincial level (2009–2018)

two ones (D_1 , D_2 , and D_3), which means the subsystems among the three elements are less harmonious and coherent. The rank of the increment over the decade is Inclusive-Growth (D_2) > Inclusive-Green-Growth (D_4) > Inclusive-Green (D_1) > Green-Growth (D_3). The annual growth rate is $D_2(11.24\%) > D_4(9.07\%) > D_3(7.12\%) > D_1(6.37\%)$. In 2018, the CCD of D_1 and D_2 , D_3 , and D_4 were roughly similar and were maintained at around 0.35 and 0.3 respectively. This shows Anhui province has been facing an increasingly prominent issue on unhealthy interactions of green-growth nexus, which is one of reasons that many studies focus on the economy-environment link (Fan et al. 2019; Faik et al. 2021; Wu and Zhou 2021; Deng et al. 2022; Ji and Zhang 2022).

Prediction of coupling nexus

To promote regional coordination and sustainable growth, the development trends of the coupling nexus among IGG subsystems must be further investigated. Based on the above CCD results, this paper applies the FGM (1.1) method to forecast the CCD of IGG nexus in 2019–2023 by using the MATLAB2018b software.

Table 8 shows the predicted values and the MAPE on CCD of the IGG nexus in Anhui province. As seen, the MAPE is distributed from 1.83 to 3.42%. Accordingly, the prediction accuracy lies between 96.58% and 98.17%. These results indicate that the FGM (1,1) satisfies the error requirements and prediction accuracy and that the model can be used to forecast the coupling nexus among IGG subsystems. Additionally, as can be seen among the types and degrees of coordinated development, the value within inclusive-green nexus is highest, reaching 0.5182 and belonging to the start stage (S_2) in 2023, followed by the inclusive-growth and the inclusive-green-growth nexus, which are 0.4440 and 0.3884 in 2023, respectively. The green-growth nexus has the lowest value of 0.3699. Further, regarding the growth rate of the coupling nexus among IGG subsystems, the rate within the inclusive-green area will be the fastest within the next 5 years, followed by inclusive-growth, and then inclusive-green-growth. The coupling relationship between the green and growth subsystems has the slowest growth, indicating that the disharmony of internal IGG subsystems will alleviate over time. However, compared with the other three nexuses, the contradiction between economic growth and green ecology has been and will continue to be a prominent obstacle to the coupling nexus among IGG in Anhui province, primarily because its economic development is at a much lower level than the other provinces and municipality in the YRD. This economic growth and industrialization are also at the expense of a harmonious ecological balance in the region. Therefore, the government should prioritize the synergistic optimization of the green-growth nexus while improving the overall performance of IGG.

Obstacle factors

According to Eq. (4), the obstacle degrees (ODs) and the obstacle factors (OFs) affecting the coupling nexus of IGG in Anhui Province are obtained, and 5 indicators with the largest ODs are selected and arranged from left to right, as listed in Table 9.

Table 8 Predicted results on types/degrees of the coordinated development among subsystems at the provincial level under different scenarios

Years	<i>Inc – Gre</i>		<i>Inc – Gro</i>		<i>Gre – Gro</i>		<i>Inc – Gre – Gro</i>	
	D_1	Type	D_2	Type	D_3	Type	D_4	Type
2019	0.3897	F4	0.3705	F4	0.3115	F4	0.3145	F4
2020	0.4186	F5	0.3886	F4	0.3252	F4	0.3321	F4
2021	0.4495	F5	0.4069	F5	0.3395	F4	0.3502	F4
2022	0.4827	F5	0.4253	F5	0.3544	F4	0.3690	F4
2023	0.5182	F6	0.4440	F5	0.3699	F4	0.3884	F4
MAPE	1.83%	—	3.42%	—	3.11%	—	2.31%	—

Table 9 OFs/ODs of coupling IGG nexus in Anhui province for 2009–2018

Year	Categories	Order					Year	Categories	Order				
		1	2	3	4	5			1	2	3	4	5
2009	ODs /%	8.18	7.26	6.79	6.71	6.61	2014	ODs /%	9.41	8.29	8.15	8.02	7.57
	OFs	C ₃	C ₂₁	C ₈	C ₁₉	C ₂		OFs	C ₁₉	C ₃	C ₁₀	C ₉	C ₂₁
2010	ODs /%	8.19	7.75	6.68	6.48	6.42	2015	ODs /%	14.11	12.26	9.16	7.42	6.30
	OFs	C ₃	C ₈	C ₂₁	C ₁₉	C ₁₅		OFs	C ₁₉	C ₁₀	C ₃	C ₉	C ₆
2011	ODs /%	9.87	9.14	7.77	6.67	6.67	2016	ODs /%	17.56	12.97	10.01	7.90	7.28
	OFs	C ₈	C ₃	C ₂₁	C ₅	C ₂		OFs	C ₁₉	C ₁₀	C ₃	C ₆	C ₉
2012	ODs /%	10.63	8.81	8.23	7.62	7.33	2017	ODs /%	19.67	13.28	11.38	10.71	10.46
	OFs	C ₈	C ₃	C ₁₅	C ₁₀	C ₂₁		OFs	C ₁₉	C ₁₀	C ₁₃	C ₆	C ₃
2013	ODs /%	11.05	8.63	7.44	6.77	6.70	2018	ODs /%	22.35	13.74	13.50	13.15	10.88
	OFs	C ₈	C ₁₅	C ₁₀	C ₉	C ₂		OFs	C ₁₉	C ₆	C ₁₀	C ₃	C ₁₃

The results are as follows: from the top 5 OFs and ODs of each index, in 2013 and earlier, the main obstacles to the coordinated development of IGG are C₃, C₈, and C₂₁. After 2014, the main obstacle indexes of the coordinated development of IGG include C₁₉, C₁₀, and C₃. Therefore, the impact of each index on the coordinated development of IGG can be divided into two stages: the first stage (2009–2013) is dominated by the inclusive subsystem (C₃ and C₈), which is the largest impact factor; in the second stage (2014–2018), the growth subsystem (C₁₉) occupied the first place, and the green subsystem (C₁₀) also began to occupy the main position. Among them, the indicator (C₁₀), which reflects the solid waste generation of cities, has attracted a significant increase in attention in Chinese cities in recent years. Compared to the management of water and air pollution, many urban areas are facing increasingly severe issues regarding solid waste-management (Lee et al. 2021). The Chinese government and Anhui province have prioritized solid waste management, issuing a series of central and local policies (Gu et al. 2021a). The Chinese government proposed a work plan for a pilot construction of the “Zero-waste City.” Tongling city in Anhui province and other 16 pilot cities and regions were selected for pilot projects in 2019 (Meng et al. 2021). Other projects include the “Waste Removal Action 2018” carried out by the Ministry of Ecology and Environment of China and a document establishing a long-term mechanism for solid waste pollution prevention and control issued by the Anhui Provincial People’s Government.

In addition, C₃ has been consistently important in the analyzed years, indicating that health-care equity has always been the primary obstacle factor of IGG in Anhui province and plays a crucial role in livelihood security. Prior studies have found that strengthening basic public services, particularly the equitable distribution of medical

resources, was conducive not only to the promotion of inclusive growth (Saniya et al. 2021) but also to the reduction of CO₂ emissions and, therefore, the promotion of green growth (Faik et al. 2021). Further, unhealthy interactions among IGG subsystems may lead to coronavirus transmission, and the discrepancy between medical demand and expenditure has increased as a result of the COVID-19 pandemic (Zhang 2021). In practice, evidence can also be found. To achieve the vision of universal health, General Secretary Xi Jinping has repeatedly included national fitness and health in widely viewed speeches since October 2016 and implemented “Healthy China 2020 Strategy” and the “Healthy China 2030 Plan Outline.”

According to the ODs of the three subsystems in the analyzed years (Appendix Table 11), the obstacles belonging to the inclusive subsystem and growth subsystem, especially the inclusive subsystem, are generally becoming smaller, while conversely, the ones in the green subsystem are on the top.

Dynamic coupling IGG nexus at prefectural level

This part focuses on three key items: (1) the CCD and types/stages of IGG nexus; (2) the representative cities of the IGG nexus; (3) OFs of IGG nexus.

To examine the dynamic coupling nexus at the prefectural level, I select four cross-sectional years, namely, 2009, 2012, 2015, and 2018, and calculate the entropy and weight of each cross section of the 16 cities (Appendix Table 12); I then calculate the subsystem performances for the 16 cities in the analyzed years (Appendix Table 13). Because the coupling nexus among the three subsystems is worse than the two subsystems, this part only explores the CCD under the scenario of the three subsystems.

Table 10 The CCD and types/stages of IGG nexus in the 16 cities, Anhui province from 2009 to 2018

Cities	2009		2012		2015		2018	
	CCD	Type/Stage	CCD	Type /Stage	CCD	Type/Stage	CCD	Type/Stage
Hefei	0.4661	F ₅ /S ₂	0.4129	F ₅ /S ₂	0.4119	F ₅ /S ₂	0.4357	F ₅ /S ₂
Huaibei	0.3846	F ₄ /S ₁	0.3541	F ₄ /S ₁	0.3521	F ₄ /S ₁	0.3311	F ₄ /S ₁
Bozhou	0.3535	F ₄ /S ₁	0.3612	F ₄ /S ₁	0.3689	F ₄ /S ₁	0.3560	F ₄ /S ₁
Suzhou	0.3258	F ₄ /S ₁	0.3454	F ₄ /S ₁	0.3242	F ₄ /S ₁	0.3459	F ₄ /S ₁
Bengbu	0.3395	F ₄ /S ₁	0.3501	F ₄ /S ₁	0.3679	F ₄ /S ₁	0.3672	F ₄ /S ₁
Fuyang	0.3265	F ₄ /S ₁	0.3426	F ₄ /S ₁	0.3391	F ₄ /S ₁	0.3393	F ₄ /S ₁
Huainan	0.3639	F ₄ /S ₁	0.3194	F ₄ /S ₁	0.2675	F ₃ /S ₁	0.2696	F ₃ /S ₁
Chuzhou	0.3595	F ₄ /S ₁	0.3844	F ₄ /S ₁	0.3604	F ₄ /S ₁	0.3679	F ₄ /S ₁
Liuan	0.3466	F ₄ /S ₁	0.3754	F ₄ /S ₁	0.3441	F ₄ /S ₁	0.3554	F ₄ /S ₁
Ma'anshan	0.3971	F ₄ /S ₁	0.3715	F ₄ /S ₁	0.3729	F ₄ /S ₁	0.3515	F ₄ /S ₁
Wuhu	0.3995	F ₄ /S ₁	0.4000	F ₅ /S ₂	0.4250	F ₅ /S ₂	0.4039	F ₅ /S ₂
Xuancheng	0.3587	F ₄ /S ₁	0.3813	F ₄ /S ₁	0.3645	F ₄ /S ₁	0.3705	F ₄ /S ₁
Tongling	0.4372	F ₅ /S ₂	0.4199	F ₅ /S ₂	0.3754	F ₄ /S ₁	0.3952	F ₄ /S ₁
Chizhou	0.3842	F ₄ /S ₁	0.3943	F ₄ /S ₁	0.3964	F ₄ /S ₁	0.4038	F ₅ /S ₂
Anqing	0.3687	F ₄ /S ₁	0.3703	F ₄ /S ₁	0.4273	F ₅ /S ₂	0.4319	F ₅ /S ₂
Huangshan	0.4281	F ₅ /S ₂	0.4242	F ₅ /S ₂	0.4495	F ₅ /S ₂	0.4693	F ₅ /S ₂

Fig. 3 The spatial evolution for the CCD of IGG nexus at the prefectural level in the analyzed years

The CCD of IGG nexus

Figure 3 shows the CCD spatial dynamics of the IGG nexus in the 16 cities of Anhui province. The CCD ranges roughly between 0.25 and 0.45, which means they rank in moderate, mild, and little imbalance; only Hefei in 2009

and Huangshan in 2018 exceeded 0.45. The number of cities that rose from 2009 to 2012, from 2012 to 2015, and from 2015 to 2018 was 10, 7, and 10, respectively, while the number that fell was 6, 9, and 6, respectively. Hence, there are more cities that had an increase.

Table 10 presents the CCD and types/stages of the IGG nexus of the 16 cities in the analyzed years. Spatially, the CCD at the prefectural level was generally low. No city achieved the steady stage (S₃), resulting in the uneven development of inclusive, green, and growth subsystems. It seriously impeded the synergetic development of the IGG nexus. The results also clearly show that Hefei has a maximum value of 0.466, while the minimum value was 0.326 for Suzhou in 2009. Meanwhile, Huangshan and Huainan were always the cities with the highest and lowest value of CCD from 2012 to 2018.

Additionally, the standard deviation of CCD was calculated, rising from 0.039 in 2009 to 0.046 in 2018, reflecting an increase in the dispersion of individuals within the study. Compared with the previous research (Liu et al. 2021), this paper provides new evidence that regional disparities and inner imbalances are widening not only reflecting in IGG level across various city clusters but also in the IGG coupling nexus among different cities.

Representative cities of the IGG nexus

(1) Cities with rising CCD

The CCD of some regions are mainly rising. The finding shows that most cities are rich in cultural tourism

resources, including Huangshan, Anqing, and Chizhou. Mount Huangshan, located in the Huangshan City, is the world's natural and cultural heritage. Chizhou has one of the four great Buddhist Shrines, Mount Jiuhua. Anqing is well-known as the home of Huang Mei opera. These cities have been exploring the integrated development of culture and tourism, especially the coordinated development of low-carbon industries, circular economy industries related to tourism. Therefore, the integrated development of resource industries with other industries, and the industrial diversification are effective to embark on the path of IGG.

Other cities with risings are Bengbu and Suzhou. Since the establishment of the National Independent Innovation Zone in 2008, Bengbu has gradually the advantage of innovation, promoting the collaborative development among IGG subsystems. Suzhou is an important city in the northern part of Anhui province. For historical reasons, its geographical location is close to the north, agriculture is dominant, and the economy is relatively underdeveloped. Although the performances of the three subsystems are in the low level, the value difference among the subsystems is not obvious.

(2) Cities with falling CCD

The CCD of some regions are generally getting worse from 2009 to 2018. The finding indicates that most of the cities are resource-exhausted, such as Huainan, Tongling, Ma'anshan, and Huaibei. Both Huainan and Huaibei are rich in coal. Tongling is famous for the copper mines, while Ma'anshan is rich in steel. Especially, Huainan has seen a significant drop in CCD. The disadvantages of resource-exhausted cities are obvious and even lower than Fuyang, Huaibei, and Suzhou, which are in the least developed areas of Anhui province. With the depletion of resources and the large-scale energy consumption, the advantages of these cities have been disappearing. This shows resource-exhausted cities suffers a growing dilemma to synergetic development of IGG. The provincial capital, Hefei's CCD has a falling trend in volatility; however, factors such as a large population base, high urban density, and urban-related problems have led to the fact that although the subsystem performances are in the first place (Chen et al. 2014), the CCD is not in the high position.

Cities' rising or falling CCD may be partially attributed to the resource curse theory, forcing us to revisit whether the natural resource abundance in China is a development gift or resource curse (Wang et al.

2022). Compared with other cities, the four cities with abundant mineral resources, namely, Huainan, Tongling, Ma'anshan, and Huaibei, are likely to form a resource-dependent development path and lack the motivation to develop an innovative economic growth model. Consequently, with the mineral industry falling into recession, natural resources did not promote sustainable economic development, but rather had a "curse effect" on the region's economic growth, hindering the coordinated development of IGG (Wu et al. 2021). Further, if an excessive concentration of the culture or tourism industries has a crowding-out effect on other industries, which will lead to the simplification of industries and products, the cultural tourism cities will also suffer the phenomenon of resource curse and ultimately cause a decline on CCD (Deng and Ma 2016; Xie et al. 2021). Therefore, unlike Li et al. (2021)'s previous study that found that IGG is directly related to stage of regional economic development, this study finds that the IGG performances and CCD are not only closely related to economic development levels but also highly affected by a city's resource abundance and dependence.

Obstacle factors

The factors that exhibit the development of the 16 cities in Anhui province are analyzed in the same way as mentioned before, and the indexes affecting the coordinated development at the prefectural level are diagnosed; finally, targeted countermeasures and recommendations are proposed for the future high-quality development. Based on the OFDM, the OFs and ODs of each index for the 16 cities in 2009, 2012, 2015, and 2018 are obtained. The five top indexes are selected as the key obstacles, whose total obstacle degree is $>$ or $\approx 50\%$ in most cities in the surveyed years, and rank from left to right, as listed in Fig. 4.

C_1 , C_{18} , and C_{20} are belonging to the inclusive, green, and growth subsystems, respectively. They are common factors that restricted the CCD in most cities over four dynamically monitored years, indicating that sharing of cultural resources, the human response to the environment, and the utilization of land resource are the most influential factors of regional CCD level. Figure 4a indicates C_1 (14 times), C_{20} (14 times), C_{21} (13 times), C_{18} (11 times), and C_3 (10 times) in 2009; Fig. 4b shows C_{20} (15 times), C_1 (14 times), C_{18} (12 times), C_3 (11 times), and C_{19} (9 times) in 2012; Fig. 4c illustrates C_{21} (15 times), C_{20}

Fig. 4 Dynamic changes in the top 5 OFs/ODs of coupling IGG nexus from 2009 to 2018 in the 16 cities of Anhui province: (a) OFs/ODs in 2009; (b) OFs/ODs in 2012; (c) OFs /ODs in 2015; (d) OFs /ODs in 2018

(12 times), C_{14} (11 times), C_1 (10 times), and C_2 (9 times) in 2015; Fig. 4d depicts C_{18} (14 times), C_{20} (12 times), C_{13} (12 times), C_1 (12 times), and C_5 (8 times) in 2018 are diagnosed as the key obstacles to the improvement of the coupling nexus among IGG in the 16 cities in Anhui province. The indexes with more occurrences belong to the subsystem, indicating that the common obstacle that restricts the CCD is the existence of a corresponding subsystem (Zhang et al. 2019).

Based on the frequencies of the top 5 factors, cities are classified as “inclusive obstacle type,” “green obstacle type,” “growth obstacle type,” “inclusive and green obstacle

type,” “inclusive and growth obstacle type,” and “green and growth obstacle type,” of which “inclusive obstacle type” refers to those whose five largest obstacle indicators are criteria within the inclusive subsystem and “inclusive and growth obstacle type” are those that include both inclusive subsystem index and green subsystem index among their five largest obstacles. Among the top 5 OFs in the 16 cities, the cumulative frequencies of the inclusive, green, and growth subsystems in the 4 analyzed years were 35, 15, and 30 in 2009; 35, 13, and 32 in 2012; 29, 22, and 29 in 2015; 30, 38, and 12 in 2018, respectively. Hence, the obstacles that affect the CCD of cities saw a dynamic

evolution trend from “inclusive obstacle type” to “inclusive and growth obstacle type” then to “green obstacle type” over the decade. In the implementation of the targeted poverty alleviation strategy, basic public services and other industries have improved in their inclusive development, while green ecology has become increasingly prominent. This can be seen in General Secretary Xi Jinping’s ecological civilization thought, the green development planning of the YRD, and Anhui Province’s development strategy for promoting a comprehensive green transformation of its economy and society.

Conclusions

Based on subsystem collaboration, this paper constructs an evaluation index system of regional IGG. The EWA, CCDM, GPM, and OFDM are used to quantitatively explore the complex and dynamic IGG system. The feasibility of this approach is verified by the empirical study of Anhui province and its cities from 2009 to 2018. The integrated approach not only reveals the operating law of regional IGG but also highlights the coupling of subsystems and the interactions among internal factors, which broadens the understanding of regional IGG evaluation.

A relatively high IGG performance but a low CCD of the IGG nexus are seen at the provincial level. Although the predicted value of CCD will show an upward trend, it will not be able to cross the start stage; particularly, the contradiction within green-growth nexus has been and will continue to be in a prominent position. The CCD at the prefectural level is also low. Further, the gap of CCD between the cities is getting wider. Therefore, to improve coordination among subsystems and narrow the gap, we should give high priority to framing synergetic development plans for IGG development.

Policy makers should firmly seize the opportunity of the regional integration of the YRD and the new central 10-year strategy to reform the income distribution system, eliminate the artificial factors of unfair distribution, and promote the universality of development results. They also need to increase investment in education, medical care, social security, culture, and other areas of people’s livelihood in underdeveloped areas. We should attach importance to the coordinated development of economy, resources, and environment; intensify education and publicity; and guide the people to set up a green and low-carbon consumption concept. The transformation and upgrading of the industrial structure should be carried out, especially to increase the labor productivity of the tertiary sector of the economy. Priority will be given to industries that are clean and environmentally friendly.

Table 11 ODs for three subsystems at provincial level from 2009 to 2018

Years	<i>Inc</i> subsystem (%)	<i>Gre</i> subsystem (%)	<i>Gro</i> subsystem (%)	Total (%)
2009	43.64	24.87	31.50	100
2010	45.37	29.26	25.37	100
2011	49.11	30.33	20.56	100
2012	46.78	34.50	18.72	100
2013	43.76	30.47	25.76	100
2014	46.08	31.06	22.86	100
2015	40.88	38.92	20.20	100
2016	36.99	35.95	27.06	100
2017	34.69	39.01	26.29	100
2018	31.69	42.16	26.15	100

Cultural and tourism cities should improve the tourism supply chain, cultivate cultural and creative products, develop sustainable cultural, technological, and creative elements, and ultimately realize the coordinated development of tourism industries, cultural industries, information technology industries, and high-end manufacturing industries. Resource-exhausted cities should explore the path of transformation and development and pay more attention to the concept of sustainable, low-carbon, and green development. Innovative technology cities should give more attention to the innovation-driving effect and lead the regional development to a sustainable model. Agriculture leading cities should develop agricultural modernization and realize the coordinated development of regional economic growth and sustainable development.

Further research is needed on this topic. First, due to the consistency and availability of data, the selection of indicators in this article is not comprehensive enough. For example, the indicator, industrial solid waste production, only considers solid waste in industrial production but fails to include agricultural and domestic solid waste. In subsequent studies, more effective indicators might be supplemented or replaced in the regional IGG evaluation system. Second, because previous studies have focused primarily on national or regional IGG and its impact factors, a future step may be to analyze the impact of IGG on other factors and the measurement of IGG within particular industries, such as the big data industry, the digital cultural industry, or the strategic emerging industries. In the end, this paper contributes on the internal subsystems of IGG, while the prior studies focus on the external factors which affect IGG. If possible, further exploration may combine the internal and external system to give a more detailed view of IGG.

Appendix

Table 12 The weights of the indicators at prefectural level in four analyzed years

Indicator	Weight 2009	Weight 2012	Weight 2015	Weight 2018
[C ₁]Library books per 100 persons	0.125	0.110	0.060	0.062
[C ₂]10,000 people with college degrees or above	0.053	0.043	0.049	0.043
[C ₃] Number of beds per 1000 persons	0.076	0.069	0.043	0.053
[C ₄]Registered urban unemployment rate	0.034	0.043	0.038	0.025
[C ₅]Disposable income per capita between urban and rural residents	0.031	0.035	0.030	0.064
[C ₆]Urban population density	0.034	0.020	0.041	0.041
[C ₇]Per capita housing gross leasable area	0.034	0.045	0.043	0.040
[C ₈]Consumption of fertilizer per cultivated area	0.018	0.017	0.022	0.018
[C ₉]Population fire rate	0.013	0.017	0.031	0.021
[C ₁₀]Industrial solid waste production	0.022	0.022	0.018	0.024
[C ₁₁]Discharge of COD in industrial wastewater	0.014	0.023	0.031	0.019
[C ₁₂]Industrial SO ₂ emissions	0.011	0.029	0.022	0.019
[C ₁₃]Proportion of air quality reaching or better than grade 2 weather	0.015	0.015	0.045	0.063
[C ₁₄]Per capita green area of parks	0.056	0.043	0.058	0.050
[C ₁₅]Average traffic volume	0.020	0.032	0.013	0.030
[C ₁₆]Central processing rate of sewage treatment plant in urban areas	0.026	0.024	0.027	0.049
[C ₁₇]Popularity rate of sanitation toilet in rural areas	0.040	0.024	0.041	0.023
[C ₁₈]Per capita afforestation area	0.073	0.078	0.048	0.097
[C ₁₉]Fixed asset investment per unit of GDP	0.022	0.067	0.030	0.027
[C ₂₀]Secondary sector land yield	0.090	0.088	0.086	0.076
[C ₂₁]Tertiary sector labor productivity	0.062	0.055	0.106	0.041
[C ₂₂]Water consumption per unit of GDP	0.018	0.019	0.016	0.015
[C ₂₃]Power consumption per unit of GDP	0.026	0.023	0.031	0.029
[C ₂₄]Energy consumption per unit of industrial added value	0.016	0.014	0.018	0.015
[C ₂₅]Industrial wastewater discharge per unit of GDP	0.029	0.013	0.016	0.022
[C ₂₆]Industrial waste gas emission per unit of GDP	0.020	0.013	0.025	0.017
[C ₂₇]Solid waste generation per unit of GDP	0.022	0.017	0.014	0.017

Table 13 Subsystem performances of IGG at prefectural level in the four analyzed years

Cities	Inc performance				Gre performance				Gro performance			
	2009	2012	2015	2018	2009	2012	2015	2018	2009	2012	2015	2018
Hefei	0.258	0.195	0.281	0.242	0.194	0.135	0.121	0.157	0.168	0.177	0.176	0.261
Huaibei	0.210	0.151	0.156	0.159	0.205	0.193	0.167	0.145	0.126	0.105	0.083	0.139
Bozhou	0.171	0.169	0.155	0.166	0.235	0.213	0.218	0.157	0.173	0.158	0.156	0.151
Suzhou	0.153	0.169	0.147	0.180	0.193	0.144	0.141	0.178	0.161	0.167	0.139	0.168
Bengbu	0.155	0.149	0.177	0.131	0.187	0.201	0.167	0.184	0.145	0.113	0.142	0.141
Fuyang	0.173	0.190	0.181	0.196	0.181	0.157	0.159	0.122	0.159	0.136	0.135	0.122
Huainan	0.188	0.146	0.096	0.151	0.143	0.109	0.082	0.062	0.119	0.089	0.072	0.121
Chuzhou	0.198	0.197	0.160	0.196	0.200	0.208	0.198	0.168	0.158	0.152	0.156	0.130
Liuan	0.138	0.154	0.153	0.196	0.228	0.217	0.185	0.185	0.170	0.151	0.145	0.143
Ma'anshan	0.215	0.185	0.207	0.187	0.156	0.116	0.152	0.101	0.126	0.095	0.078	0.105
Wuhu	0.223	0.208	0.258	0.191	0.166	0.201	0.192	0.154	0.159	0.165	0.161	0.215
Xuancheng	0.181	0.188	0.162	0.151	0.225	0.176	0.189	0.203	0.137	0.156	0.151	0.115
Tongling	0.282	0.241	0.175	0.255	0.168	0.154	0.180	0.140	0.147	0.141	0.091	0.140
Chizhou	0.210	0.215	0.255	0.228	0.240	0.224	0.213	0.226	0.104	0.127	0.096	0.132
Anqing	0.152	0.152	0.189	0.206	0.202	0.217	0.212	0.201	0.170	0.174	0.209	0.173
Huangshan	0.230	0.204	0.239	0.237	0.269	0.279	0.288	0.277	0.144	0.154	0.157	0.180

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Data availability The datasets used and/or analyzed during the current study are available from the corresponding author on reasonable request.

Declarations

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