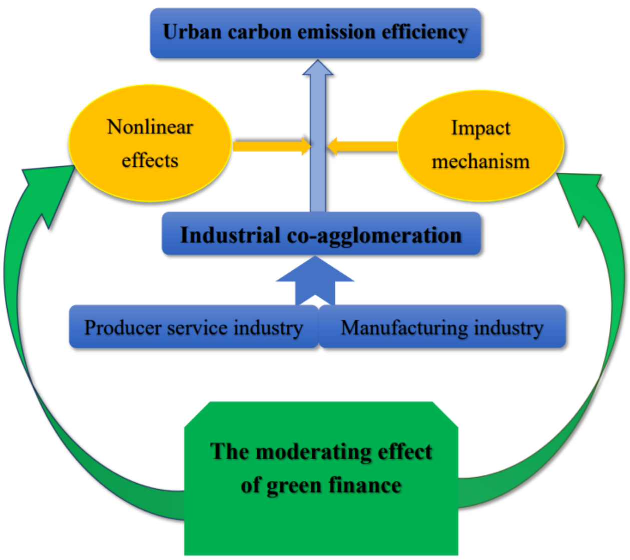
Global NEST Journal, Vol 26, No 7, 05949

Industrial co-agglomeration, green finance and urban carbon emission efficiency: empirical evidence from shandong province in China

Fang S.[1], Li W.*[1], Xu J.[1], Li Q.[1], Zhang Y.[1], Wang C.[1], Gong W.[1] and Zhang R.[2]
[1]School of Economics, Qufu Normal University, Rizhao276800, China
[2]Experimental School Affiliated to Qufu Normal University in Rizhao of Shandong Province, Rizhao276800, China
Received: 22/03/2024, Accepted: 28/06/2024, Available online: 10/07/2024
*to whom all correspondence should be addressed: e-mail: a-liwenwen@163.com
https://doi.org/10.55555/gnj.05949

Graphical abstract



Abstract

This study explores the impact of industrial co-agglomeration on urban carbon emission efficiency in Shandong Province from China during 2007 to 2020. The moderating effect model is constructed to explore the role green finance in the impact of industrial co-agglomeration on urban carbon emission efficiency. We explore the influence mechanism of industrial co-agglomeration on urban carbon emission efficiency. Through conditional process analysis, we investigate the moderating effect of green finance in the mechanism of industrial co-agglomeration on urban carbon emission efficiency. Empirical results indicate that: (1) The impact of industrial co-agglomeration on urban carbon emission efficiency is inverted U-shaped. (2) Green finance has a positive moderating effect in the impact of industrial co-agglomeration on urban carbon emission efficiency. (3) Industrial co-agglomeration affects urban carbon emission efficiency through scale effect, technological effect and structural effect. (4) Green finance plays a moderating role in the impact pathways of industrial co-agglomeration on urban carbon emission efficiency. Therefore, this paper proposes targeted recommendations to improve urban carbon emission efficiency according to industrial co-agglomeration and green finance development.

Keywords: Urban carbon emission efficiency; industrial co-agglomeration; green finance; moderating effect; conditional process analysis

1. Introduction

To alleviate climate change, Chinese government proposed the “dual carbon” goal at 75th General Assembly of the United Nations in 2020. Meanwhile, China’s economic growth has slowed down. The environmental pressure faced by economic development is increasing. How to achieve coordination between urban economic growth and environmental protection is an urgent problem that needs to be addressed. The improvement of urban carbon emission efficiency (UCEE) can not only promote the achievement of the "dual carbon" goal, but also alleviate the environmental pressure on economic growth. According to Zhou *et al.* (2012), We define UCEE as the ratio of the possible optimal carbon emission intensity to the actual carbon emission intensity. The transformation of industrial development models and the support of financial factors are important forces for the improvement of UCEE. Industrial co-agglomeration differs from a single industry development model and has complex externalities on the environment (Zhang *et al.* 2023). In the process of industrial co-agglomeration, green finance not only guides fund allocation, but also has the characteristics of promoting green development and energy conservation and emission reduction (Huang and Gao, 2024). Therefore, clarifying the inherent relationship between UCEE, green finance, and industrial co-agglomeration is of great significance for alleviating the contradiction between urban economic growth and environmental protection.

Shandong Province is a major economic province in northern China, with a relatively developed financial market. However, it is also the province with the highest carbon emissions. The contradiction between economic development and ecological environment is more prominent in Shandong Province. According to the data released in the Statistical Bulletin of Shandong Province, the gross domestic product (GDP) of Shandong Province ranks third in China in 2023, and the development of green finance is relatively fast. However, due to the industrial structure characterized by high carbon, Shandong Province is also the province with the highest carbon emissions. Therefore, this paper takes 16 cities in Shandong Province as an example to study the impact of industrial co-agglomeration on UCEE, as well as the role of green finance in the relationship between the two, which provides empirical experience for the coordinated development of urban economic growth and environmental protection in China.

Industrial co-agglomeration (ICA) may have an impact on UCEE (Hou *et al.* 2023). ICA is a spatial agglomeration phenomenon in which different industries exhibit interdependence and correlation (Wang *et al.* 2023). ICA can contribute to the optimization of resource allocation. Furthermore, ICA also encourages enterprise technological innovation and improves energy efficiency. Ultimately, UCEE can be improved (Zhu and Li, 2021). However, excessive ICA produces crowding effect, which in turn leads to lower labor production efficiency and reduces UCEE (Zhao *et al.* 2024).

The impact of ICA on UCEE may be influenced by green finance (GF) (Wang *et al.* 2024). According to the *Guidelines for Establishing the Green Financial System*, GF is a financial service used to advocate environmental protection, combat climate deterioration and improve resource efficiency. Therefore, GF can ease the financing constraints of green industries and provide more green products and services. Green industries engage in energy saving and technological innovation, which reduces UCEE (Bai *et al.* 2022). This paper takes Shandong Province as an example and incorporates ICA, GF, and UCEE into the same research framework to study the effect and impact mechanism of ICA on UCEE, as well as the moderating role of GF in this relationship.

There are diverse opinions of studies on the correlation between ICA and UCEE, which can be generally generalized into three views. Firstly, ICA intensifies the damage to the environment and reduces UCEE. Co-agglomeration increases energy demand and the total emissions of the region (Shen and Peng, 2021). The continued expansion of ICA has led to vicious competition and reduces UCEE (Liu and Zhang, 2021). Secondly, the majority of scholars believe ICA can improve UCEE (Wang *et al.* 2021b). Agglomeration can break down the barriers of industry development, which can promote mutual exchanges and cooperation between different departments (Tang *et al.* 2022). Thirdly, some studies find that ICA has non-linear effects on UCEE (Du *et al.* 2024). Liu and Zhang (2021) found that ICA had an inverted U-shaped on UCEE, and technological innovation was a key factor affecting "inflection point". Li and Liu (2022) concluded ICA may have an inverted U-shaped impact on UCEE and can improve UCEE through technical factors.

With the increase of climate change and ecological pressure, GF, which focuses on green development, attracts the widespread attention. GF can influence UCEE by guiding capital allocation and accelerating technical innovation (Li and Fan, 2023). Firstly, by channeling social funds, GF enable more resources to be allocated to the emission reduction and environmental protection field (Ren *et al.* 2020b). Enterprises can save resources by following ecological principles, which can reduce ecological pollution and improve UCEE (Lyu *et al.* 2022). Then, low-carbon technology is a key to low-carbon development (Pan *et al.* 2024). GF can provide financial support for technical research and improve UCEE (Zhang and Liu, 2022). GF can take ecology as the entry point to improve UCEE. Therefore, GF has a clear role in improving UCEE (Wang *et al.* 2021).

In summary, existing literature has provided research basis for us, but there are no uniform research conclusions about ICA on UCEE. In addition, few studies have included GF in the process of the impact of ICA on UCEE to explore the role of GF on the relationship between the two. The marginal contribution in this paper are as follows:

Firstly, we investigated the nonlinear impact of ICA between producer services and manufacturing industry on UCEE. Producer services and manufacturing industry are interdependent, which should be analyzed as a whole. Therefore, this paper transcends the single perspective of ICA and starts from the perspective of co-agglomeration of producer services and manufacturing industry to study the impact of ICA on UCEE.

Secondly, GF, ICA and UCEE are included in the unified analytical framework. Previous studies have investigated the effects of ICA on UCEE or GF on UCEE. But there are few studies that include GF, ICA and UCEE together. GF may intervene in the impact of ICA on UCEE by guiding capital flow. Therefore, we analyzed GF, ICA and UCEE together to explore the moderating effect of GF on the relationship between ICA and UCEE.

Thirdly, through conditional process analysis, we explore the moderating mediating effect of GF on the relationship between ICA and UCEE based on the mechanism of scale, technology and structure. Few studies have analyzed the moderating effects of GF on these three mechanism, and most have focused on studying them from a single mechanism perspective. ICA has complex externalities on the environment, which leads to differential moderating of GF in the impact of ICA on UCEE. Clarifying the moderating role of GF on the three mechanism is conducive for fully leveraging the positive externality impact of ICA on UCEE. Therefore, we investigate the moderating effect of GF on the three mechanism of ICA affecting UCEE.

2. Materials and methods

2.1. Theoretical analysis

2.1.1. Impact of ICA on UCEE

The ICA has a positive influence on UCEE, but higher degree of ICA doesn't always mean better. When ICA is above the optimal scale, this positive effect gradually turns to be negative (Hoover, 1937). In the first place, ICA achieves the sharing of resources, which improves the resource utilization and UCEE. It is reflected in the following two main ways:

Firstly, technology spillover effect. The exchange of science, technology and knowledge can run through the whole process of co-agglomeration. Producer services can introduce a large amount of knowledge and technology into the manufacturing industries through factor sharing in the process of co-agglomeration. This exchange can also promote the dissemination of green technology and generate technology spillover effects between industries, gradually forming a circular path of innovation, dissemination, imitation and re-innovation, thus improving UCEE.

Secondly, competition effect. In the process of ICA, the market scale expands, and the competition among enterprises is becoming increasingly fierce. In order to maintain the current position and seize the market, enterprises use resources more efficiently, which in turn can improve production efficiency and UCEE.

When excessive agglomeration occurs, ICA is not conducive to the improvement of UCEE. The negative "crowding effect" and "rebound effect" generated by excessive agglomeration will lead to a positive to negative impact of ICA on UCEE.

On the on hand, the excessive ICA produces “crowding effect”, which causes an increase in the density of economic activities within a unit area. “Crowding effect” leads to a weakening of factor allocation and the production efficiency of enterprises in the agglomeration area has decreased. Intensive economic activities have also led to increased environmental pressure.

On the other hand, excessive ICA produces “rebound effect”. The improvement of energy efficiency has stimulated enterprises and consumers to use more energy, which in turn brings about a decrease in UCEE. Therefore, hypothesis 1 is as follows:

Hypothesis 1. The impact of ICA on UCEE is an inverted U-shape.

2.1.2. The moderating effect of GF

GF plays a moderating role in the impact of ICA on UCEE by guiding the allocation of funds needed for ICA. This allocation of funds is guided mainly through incentive mechanism and forced mechanism in the process of ICA. On the one hand, GF guides funds to green enterprises in agglomeration area and provides funds to sectors engaged in green innovation. Under the guidance of GF, enterprises that adopt cleaner production technologies and complete the expected emission reduction missions are rewarded. With the increase of rewarded enterprises, UCEE can be improved eventually. On the other hand, GF can force the energy-intensive industries in agglomeration area to transform and upgrade. GF emphasizes green development, so it can inevitably limit the funds to the high-emission enterprises, forcing them to reduce emissions. The new high-emission investments of enterprises in agglomeration area are reduced. Therefore, the UCEE can be improved.

At different stages of the GF, its moderating effect in the impact of ICA on UCEE is different. When GF is underdeveloped, the moderating effect is limited. The carbon reduction effect brought by GF is weak. There is a shortage of green financial tools in the market and the resource allocation efficiency of GF is inefficient. So, the insufficient funding required for clean production and green technology progress has resulted in insignificant positive externalities of ICA on UCEE. Furthermore, there is a lack of financial support for enterprises to achieve their emission reduction targets and engage green activities. The improvement effect of UCEE is not significant. When GF is developed, the moderating effect become more significantly. At this stage, there are abundant GF tools. So, ICA can achieve effective resource allocation through various green financial tools. Similarly, a developed green finance mark*et al*so provides ICA with sufficient funds to carry out clean production and green technology research and innovation, ultimately achieving the improvement of UCEE. Enterprises can realize the optimal allocation of resources through various GF tools. These GF tools can make enterprises have sufficient funds for green transformation and technology research. Enterprises can carry out green technical activities and achieve emission reduction targets. Then the UCEE can be improved. Therefore, the hypothesis 2 is as follows:

Hypothesis 2. GF plays a positive moderating role in the impact of ICA on UCEE.

2.1.3. The influence mechanism of ICA on UCEE

Grossman and Krueger (1992) categorized the ways in which economic activity affects environmental quality into three main areas: scale, technology and structure.

(1) Scale effect. ICA affects UCEE through changes in economic scale. ICA enables various resources to be centralized and information to be shared. The waste of resources has been reduced, thereby alleviating the pressure on the environment. ICA can further minimize the loss of raw materials in production, which effectively decreases average production and transaction costs. The decrease in production costs has reduced the difficulty of decentralized governance for individual enterprises, which helps them concentrate on improving UCEE. ICA can also bring numerous employment opportunities and improve employment levels and incomes. As income levels rise, people begin to concentrate on environmental issues and create a demand for high environmental quality. People are not only willing to buy environmentally friendly products, but also continue to intensify the pressure to improve UCEE, so as to slow down the deterioration of the environment.

Hypothesis 3a. ICA affects UCEE by scale effect.

(2) Technological effect. ICA affects UCEE through green technology progress. Through sharing elements such as technology and knowledge, ICA can accelerate inter-industry exchange of technology and knowledge, thus giving rise to the generation of new technologies. ICA provides more opportunities for technological exchanges and cooperation among industries, which can promote innovation and environmental-friendly technologies. For instance, ICA can reduce energy consumption and pollution through joint research and development of environmental-friendly technologies. Other industries can benefit from the flow of technology and inter-industry cooperation, which in turn can promote the green technology progress and UCEE of the entire region. ICA may also lead to technological competition. Competition prompts enterprises to increase investment in green innovation, which continuously help enterprises gain technology competitive advantages and improve UCEE.

Hypothesis 3b. ICA affects UCEE by green technology progress.

(3) Structural effect. ICA affects UCEE through industrial structure optimization. The formation of ICA promotes the coupling of production factors and accelerates technological exchanges. Meanwhile, ICA also improves the resource allocation efficiency, which achieves the optimization of industrial structure. ICA effectively breaks down industry barriers and generate multi-dimensional interactions among technology, industry, and economy. Ineffective investment and pollution control costs are reduced, thereby promoting the improvement of UCEE. The continuous growth of similar industries in the agglomeration area means that the homogeneous competition between industries becomes increasingly fierce. The homogenization of products caused by the easy availability of technology "force" enterprises to continuously improve technology and upgrade production equipment, thereby promoting the further industrial structure optimization.

Hypothesis 3c. ICA affects UCEE through industrial structure optimization.

2.1.4. Conditional process analysis of GF

GF guides more funds to low-carbon production and low-carbon consumption to enable the green development of industries in the agglomeration area. Therefore, the scale effect, technological effect and structural effect of ICA are inevitably moderated by GF, which in turn affects the UCEE. Firstly, GF moderates the scale effect of ICA on UCEE. The essence of GF is to provide differentiated exogenous financing for enterprises based on environmental constraints (He *et al.* 2018). GF guides capital to support green projects by relaxing quota restrictions and increasing financial leverage. GF makes green products have a competitive price advantage through the support of preferential interest rates in the field of green consumption. The expansion of green consumption scale has been driven by the increasing awareness of green consumption among consumers, which also improves the UCEE. Secondly, GF moderates the technological effect of ICA on UCEE. Green technology innovation requires long-term and sustained financial support. GF tends to support green technology innovation, which can meet the financing needs of green technology innovation (Hu and Wang, 2018). Finally, GF moderates the structural effect of ICA on UCEE. GF directs more funds to promote rapid development of environmental-friendly industries, thus promoting the industrial structure optimization. GF also strengthens financing constraints on highly polluting industries, forcing them to optimize industrial structures. Therefore, under the influence of GF, the industrial structure shifts to low-carbon development, which improves UCEE (Tian *et al.* 2022).

Hypothesis 4. GF plays a moderating role in the mechanism of ICA on UCEE.

Overall, there is a nonlinear impact of ICA on UCEE, which GF has a moderating effect in this process. ICA affects UCEE through scale effect, technological effect and structural effect, and GF also has a moderating effect on these three effects. The specific analysis is as follows (see Figure 1).

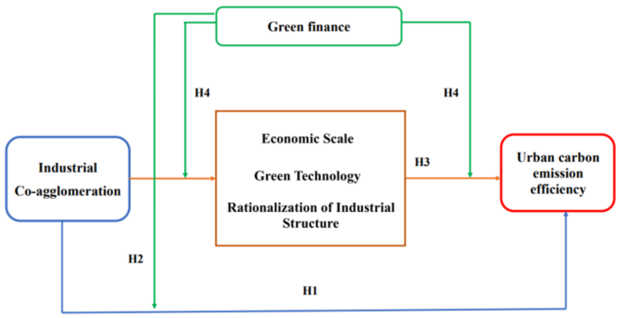


Figure 1. Theoretical analysis framework

2.2. Model, variables and data

2.2.1. Model

(1) Baseline regression model

Based on Edwards and lambert (2007), we construct the moderating effect model to explore the impact of ICA on UCEE and the role of GF, as shown in Eq.(1) to Eq. (3):

$$UCEE_{it} = \alpha_1 ICA_{it} + \alpha_2 ICA_{it}^2 + \alpha_3 Controls_{it} + \delta_t + \mu_i + \varepsilon_{it} \quad (1)$$

$$UCEE_{it} = \alpha_1 ICA_{it} + \alpha_2 ICA_{it}^2 + \alpha_3 GF_{it} + \alpha_4 Controls_{it} + \delta_t + \mu_i + \varepsilon_{it} \quad (2)$$

$$UCEE_{it} = \alpha_1 ICA_{it} + \alpha_2 ICA_{it}^2 + \alpha_3 GF_{it} + \alpha_4 ICA_{it} \times GF_{it} + \alpha_5 Controls_{it} + \delta_t + \mu_i + \varepsilon_{it} \quad (3)$$

where *i* and *t* represent city and year respectively. *UCEE* is the urban carbon emission efficiency. *ICA* is producer services and manufacturing co-agglomeration. ICA^2 is the quadratic term of the *ICA*. *GF* represents green finance. $ICA \times GF$ is the interaction term between the *ICA* and *GF*. *Controls* are the control variables. Eq. (1) is used to examine the impact of the ICA on UCEE. *GF* is added to Eq. (2) to examine the impact of *GF* on *UCEE*. With the addition of $ICA \times GF$, Eq. (3) is used to examine the effect of *GF* on the impact of the *ICA* on *UCEE*. δ_t is a time fixed effect μ_i is an urban fixed effect. ε_{it} is a random disturbance term.

(2) Mechanism model

To explore the mechanism of ICA on UCEE, we construct the following mediating effect model referring to the methods of Ren *et al*. (2020).

$$UCEE_{it} = \beta_0 + \beta_1 ICA_{it} + \beta_2 ICA^2_{it} + \beta_3 Controls_{it} + \delta_t + \mu_i + \varepsilon_{it} \quad (4)$$

$$M_{it} = \beta_0 + \beta_1 ICA_{it} + \beta_2 Controls_{it} + \delta_t + \mu_i + \varepsilon_{it} \quad (5)$$

$$UCEE_{it} = \beta_0 + \beta_1 ICA_{it} + \beta_2 ICA^2_{it} + \beta_3 M_{it} + \beta_4 Controls_{it} + \delta_t + \mu_i + \varepsilon_{it} \quad (6)$$

where *M* represent mechanism variables, including *ES*, *GT* and *RIS*. Eq. (5) examines the relationship between mechanism variables and independent variable. Eq. (6) examines the effect of *ICA* on *UCEE* with the addition of mechanism variables.

2.2.2. Variable

(1) Urban carbon emission efficiency (UCEE).

According to Zhou *et al*. (2012), the Non-radial Directional Distance Function model (NDDF) is constructed in this paper. The input variables are chosen as labor, energy consumption and capital stock. Desired output is gross regional product (GRP). Undesired output is carbon dioxide emissions.

(2) Industrial co-agglomeration (ICA).

The producer services originate from within the manufacturing industry, and there is a clustering trend of mutual attraction and common site selection with the manufacturing industry. The mutual promotion and interactive integration of producer services and manufacturing industry in the future development process will have a more profound impact on China's economic growth (Liu *et al.* 2024). Therefore, in order to achieve the synergistic development of economic growth and environmental protection, it is necessary to study the impact of the industrial co-agglomeration represented by the producer services and the manufacturing industry on the urban carbon emission efficiency.

Agglomeration index of producer services and manufacturing is calculated through location entropy respectively (Shao *et al.* 2017). The ICA is calculated according to Yang *et al*. (2021). There is no unified standard for the definition of producer services. Based on Zhong and Yan (2008) we define producer services as "transportation, storage and postal industry", "scientific research, technical services and geological exploration industry", "information transmission, computer services and software industry", "financial industry" and "leasing and business service industry".

(3) Green finance (GF).

Based on the *Guidelines for Establishing the Green Financial System*, and referring to Yin *et al*. (2021), GF is calculated through entropy method, including green securities, carbon finance, green insurance, green credit, and green investment.

(4) Mechanism variables

Economic scale (*ES*). We use real GDP per capita in the base year 2006 as an indicator to measure the economic scale.

Green Technology (*GT*). The emission reduction effect of green technology is stronger, so the number of green inventions applied for in the current year is used as an indicator to measure the technology effect.

Rationalization of Industrial Structure (*RIS*). This paper draws on the Theil index to measure the degree of rationalization of the industrial structure of each prefecture-level city

(5) Control variables

There are other factors that may affect UCEE. We select a series of control variables. Based on Shao *et al*. (2019) and Han and Xie (2017), control variables are reported in Table 1.

2.2.3. Data source

In this paper, the data of 16 cities of Shandong Province in China from 2007 to 2020 are selected to study the impact of ICA on UCEE. The raw data are from China Insurance Yearbook, Shandong Statistical Yearbook, China City Statistical Yearbook, and statistical yearbooks of each city. Laiwu was merged into Jinan in 2018, the data of Laiwu from 2007 to 2017 are summed up with Jinan. The sample size of this study is 224 observations.

Table 1. Descriptions of control variables

Variables	Symbols	Definition	Unit
Population size	PS	Number of urban populations	10^7 person
Urbanization level	UR	Ratio of urban built-up land to urban area	Square kilometer
Energy intensity	EI	Ratio of total energy consumption to GRP	Tce/10^8 yuan
Industry Structure	IS	Ratio of secondary industry value added to GRP	10^8 yuan
Technology Progress	Tech	Ratio of R&D Expenditure to GRP	10^8 yuan
Environmental moderating	ER	Ratio of energy conservation and environmental protection expenditure to GRP	10^4 yuan
Government intervention	Gov	Ratio of local fiscal expenditures to GRP	10^8 yuan
Openness to the world	Fdi	Ratio of foreign direct investment to GRP	10^8 yuan

3. Results and discussion

3.1. Analysis of the time-varying characteristics of UCEE in Shandong Province

We calculate the UCEE of cities in Shandong Province based on the Eq. (4). In 2012, President Xi Jinping elaborated on the new development concept, and in 2016, the Ministry of Finance issued guidance on building green finance. Both of these have a certain impact on the changes in urban carbon emission efficiency. Therefore, in order to show the time varying of UCEE more visually, the years 2007, 2011, 2015 and 2020 are selected as samples for analysis in this paper, as shown in Figure 2.

During 2007-2011, the UCEE of cities in Shandong Province increased. During this period, the economic development of Shandong Province grew fast, this made the UCEE increase rapidly. Rapid economic growth led to higher per capita incomes, which improved environment.

During 2012-2015, the average UCEE of Shandong Province showed a short decline. However, some cities had seen an increase in UCEE during this period. In 2012, China thought highly of green development and took it as an aspect that needed to be noted. Therefore, since 2013, the UCEE between cities was beginning to differentiate. For cities with non-resource dependence, high population density and coastal features, green transformation are less constrained because of their rational industrial structure, which makes UCEE improve steadily. However, for cities with long-term dependence on resources, low population density and non-coastal cities, their development has obvious characteristics of resource dependence and high pollution, which makes them face more obstacles in the green transformation. Therefore, these cities will be more constrained by resources and environment, which makes the UCEE show a downward trend.

After 2015, the majority of cities had seen an increase in UCEE. 2016 was the starting point of the transformation of old to new economic growth drivers in Shandong Province. In 2015, the government issued the *Action Plan for Promoting Industrial Transformation*

and Upgrading in Shandong Province (2015-2020), which put forward a series of implementation plans focusing on the innovation, convergence and agglomeration development of producer services. In this period, industry began to transform, and the pace of ICA accelerated. The upgrading of the manufacturing industry was driven through producer services, thereby the UCEE can be improved.

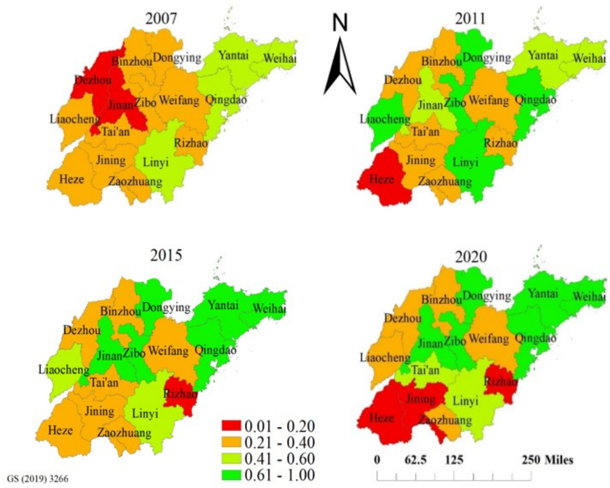


Figure 2. The UCEE of Shandong Province in 2007, 2011, 2015 and 2020

3.2. Baseline regression results

The influence among the ICA, GF and UCEE are regressed separately. The results are reported in Table 2. Second column in Table 2 shows the impact of ICA and ICA^2 on UCEE without adding control variables. Third column shows that ICA significantly influences UCEE with adding control variables, indicating ICA improves UCEE. Economy of scale and technological spillover effect generated by ICA save resources, optimize the allocation of resources, thus improving UCEE (Chang and Oxley, 2009). However, ICA^2 is significantly negative, which means when there is an excessive agglomeration, the "crowding effect" and "rebound effect" will occur and the UCEE can be reduced (Andersson and Lööf, 2011). Therefore, the impact of ICA on UCEE is twofold (Chen *et al.* 2018), that is, the impact of ICA on UCEE is an inverted "U-shaped". Hypothesis 1 holds. The results of third column show that GF significantly affects UCEE, indicating that the GF plays a positive role in UCEE.

Table 2. Baseline regression results

Variables	UCEE			
	Eq. (1)	Eq. (1)	Eq. (2)	Eq. (3)
ICA	0.384*** (4.030)	1.526*** (7.098)	1.345*** (5.900)	1.298*** (5.636)
ICA^2	-0.076** (-2.512)	-0.295*** (-6.479)	-0.257*** (-5.368)	-0.248*** (-5.113)
GF			0.785*** (3.143)	0.769*** (3.106)
ICA×GF				0.498** (2.019)
Controls	N	Y	Y	Y
Time	Y	Y	Y	Y
City	Y	Y	Y	Y
Obs	224	224	224	224
R^2	0.953	0.969	0.970	0.971

Note: *** p<0.01, ** p<0.05, * p<0.1. The t-statistics in parentheses are the same as below.

3.3. Analysis of the moderating effect of GF

The ICA×GF is added to Eq. (3) to examine the moderating effect of the GF between ICA and UCEE. The result is reported in the fourth column in Table 2. The ICA×GF plays a significant positive role on UCEE, which indicates GF has a significant positive moderating effect. Hypothesis 2 is verified. Therefore, while pursuing the improvement of UCEE, it's necessary to focus on GF to improve the carbon emission reduction effect brought by GF.

3.4. Robustness and endogeneity test

3.4.1. Robustness test

In an effort to demonstrate the dependability of research findings, robustness tests are carried out in the following two ways:

(1) Adding lagged term

The first-order lag of ICA (L. ICA) is added to the regression model to exclude the possible lag effect of the influence of ICA on UCEE in the current period. The significance and sign of ICA, ICA^2, and ICA×GF on UCEE are same with the baseline regression.

(2) Model replacement

Despite replacing the model with the *Tobit* model, the results remain robust. The dependent variable is a finite dependent variable truncated by 0 and 1, which possibly causes biased results if its finite distribution is ignored (Fan *et al.* 2022), so the panel Tobit model is chosen for robustness testing. the significance and sign of ICA, ICA^2, and ICA×GF on UCEE is same with the baseline results.

3.4.2. Endogeneity test

In order to alleviate the endogeneity as much as possible, we adopt the instrumental variable to handle it. According to Fan *et al*. (2023), we select total water supply (TWS) to conduct the endogeneity test. The significance and sign of ICA, ICA^2, and ICA×GF on UCEE do not change, the result is robust.

3.5. Mechanism analysis

3.5.1. Analysis of mediating effect

From the baseline regression results, we can conclude that there is an inverted U-shaped relationship between ICA and UCEE, but the mechanism is not clear. Therefore, according to the previous hypothesis, this section focuses on the verification of the path mechanism of ICA affecting UCEE. Since the consistency between the results of Eq. (4) and Eq (1), only regression results of equations (5) and (6) are presented in Table 3.

ICA promotes the UCEE by expanding the scale of the economy from column 3. As can be seen in column 2, ICA is conducive to the ES. In the column 3, the coefficient of ES on UCEE is significantly positive, indicating that the expansion of economic scale is conducive to improve UCEE. The coefficient of ICA^2 on UCEE decreases, indicating that the scale effect mitigates the negative impact of over-agglomeration on UCEE. ICA concentrates numerous production factors, leading to the expansion of market demand and market size (Wang and Wang, 2023). In order to obtain scale rewards, enterprises in the agglomeration area focus on improving their production efficiency.

Table 3. Mechanism analysis results

Variables	ES	UCEE	GT	UCEE	RIS	UCEE
ICA	1.657*** (11.183)	1.137*** (5.993)	0.324*** (4.527)	0.957*** (5.781)	0.048*** (8.103)	1.429*** (6.582)
ICA^2		-0.214*** (-5.697)		-0.177*** (-5.189)		-0.274*** (-5.921)
ES		0.064*** (6.879)				
GT				0.206*** (9.042)		
RIS						-0.359** (-2.182)
Control	Y	Y	Y	Y	Y	Y
Time	Y	Y	Y	Y	Y	Y
City	Y	Y	Y	Y	Y	Y
Obs	224	224	224	224	224	224
R^2	0.989	0.976	0.807	0.977	0.971	0.970

As shown in column 5, ICA promotes the UCEE by green technology progress. The coefficient of ICA on GT in column 4 of Table 3 is significantly positive, indicating that ICA promotes the green technology progress. ICA produces knowledge spillover effects, thereby promoting the green technology progress. The results in column 5 show that green technology progress contributes to the improvement of UCEE. The narrowing of the ICA^2 coefficient also indicates that the green technology progress alleviates the negative impact of over-agglomeration on the environment (Rasoulinezhad and Taghizadeh-Hesary, 2022). ICA is conducive to the flow of talents, technology, which reduces the cost of information exchange and stimulates the innovation ability of the industry (Wang and Gao, 2023). Therefore, the green technology progress provides technical conditions for the green transformation (VijayaShanthy *et al.* 2023), which reduces pollution emissions and improving UCEE.

ICA promotes the UCEE by promoting the rationalization of the industrial structure from column 7. The coefficient of RIS in column 7 is negative, indicating that there is a negative correlation between RIS (Theil index) and UCEE. Theil index is a negative indicator, which reflects the degree of coordination of the industrial structure. This suggests that China's current stage of ICA is still at a low level. Low-quality and low-level agglomeration tends to make the industrial structure irrational, guiding the industry to transform in the direction of high pollution, thereby increasing the pressure on the environment and reducing UCEE (Wang *et al.* 2021).

3.5.2. Conditional process analysis

We use the mediating effect model to examine the path of ICA on UCEE and further take GF as a moderating variable to explore whether GF has a moderating role in the three influence pathways. Referring to the methods of Wen and Ye (2014) and Hayes and Rockwood (2020), the following model is constructed for conditional process analysis:

$$M = a_0+a_1ICA+a_2GF+a_3GF\times ICA+\varepsilon \quad (11)$$

$$UCEE = b_0+b_1ICA+b_2M+\varepsilon \quad (12)$$

$$M= c_0+c_1ICA+\varepsilon \quad (13)$$

$$UCEE = d_0+d_1ICA+d_2M+d_3GF+d_4GF\times M+\varepsilon \quad (14)$$

In Eq. (11), (12), (13) and (14), *M* include *ES*, *GT*, and *RIS*. Eq. (11) and (12) are the first stage of the conditional process analysis to test whether GF has a moderating effect in the first half of the path in the mediating effect of ICA on UCEE. Eq. (13) and (14) are the second stage conditional process analysis to test whether GF has a moderating effect in the latter half of the path in the mediating effect of ICA on UCEE. Table 4 reports the moderating effect of GF in the impact path of ICA on UCEE. Table 5 reports the moderating effect of GF in the impact path of ICA^2 on UCEE.

Table 4. Conditional process analysis results of ICA

Variables	GT	UCEE	ES	UCEE	RIS	UCEE
	(11)	**(12)**	**(13)**	**(14)**	**(13)**	**(14)**
ICA	3.147*** (7.011)	0.910* (2.430)	2.950*** (5.197)	0.050* 1.711	-0.730** (-3.145)	0.127*** (4.091)
GF	35.011*** (6.919)			0.574** (3.050)		0.949*** (4.645)
ES				0.045*** (13.189)		
GF×ES				0.100** (2.130)		
GT		0.020*** (7.980)				
RIS						-0.880*** (-9.967)
GF×RIS						-6.575*** (-5.068)
ICA×GF	64.292*** (5.666)					
R^2	0.411	0.297	0.109	0.575	0.043	0.488

Table 5. Conditional process analysis results of ICA^2

Variables	GT	UCEE	ES	UCEE	RIS	UCEE
	(11)	**(12)**	**(13)**	**(14)**	**(13)**	**(14)**
ICA^2	1.073***(7.332)	0.015* (2.182)	0.530*** (4.986)	0.009* 1.705	-0.014** (-3.224)	0.023*** (3.397)
GF	35.415***(7.060)			0.580** (3.082)		0.969*** (4.737)
ES				0.045*** (13.236)		
GF×ES				0.099** (2.110)		
GT		0.020*** (8.012)				
RIS						-0.880*** (-9.926)
GF×RIS						-6.535*** (-5.025)
ICA^2×GF	11.835*** (5.727)					
R^2	0.420	0.293	0.101	0.575	0.045	0.485

As can be seen in column 2 of Tables 4 and 5, the coefficients of ICA×GF and ICA^2×GF on GT are significantly positive, indicating that GF positively moderates the first half of the technological effect of ICA on UCEE. The development of ICA and GF has promoted technological progress. As can be seen from the third column of Table 4 and Table 5, GT is conducive to the improvement of UCEE. The coefficients of GF×ES on UCEE in column 5 are all significantly positive, indicating that GF positively moderates the second half of the scale effect of ICA on UCEE. GF guides the flow of capital to clean industries and expand their scale, which improves UCEE. The coefficient of GF×RIS on UCEE in column 7 is significantly negative, indicating that GF negatively moderates the second half of the structural effect of ICA on UCEE. Under the current degree of industrial structure rationalization, the intervention of GF is rather detrimental to the improvement of UCEE.

Further simple slope analysis is shown in Figures 3, 4 and 5, as well as Tables 6, 7, and 8. As shown in Figure 3 and Table 6, At high levels of GF (M+1SD), as ES levels increase, its impact on UCEE is more significant than at low levels of GF (M-1SD). This means that as GF level increases, the scale effects of ICA and ICA^2 on UCEE gradually increase. As can be seen from Figure 4 and Table 7, there are large differences in the effects of ICA and ICA^2 on GT at different GF levels. At high GF levels, the effects of ICA and ICA^2 on GT are more significant. While Figure 5 and Table 8 show that the impact of RIS on UCEE varies slightly at different GF levels. However, since RIS is a negative indicator, this increase is not conducive to the improvement of UCEE.

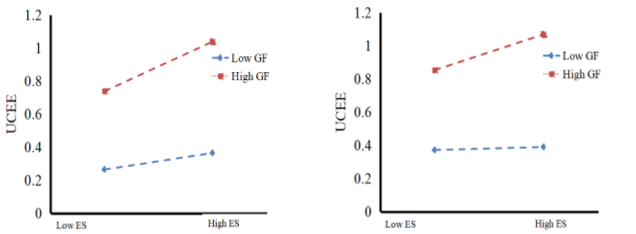


Figure 3. The moderating effect of GF in the scale effect of ICA on UCEE

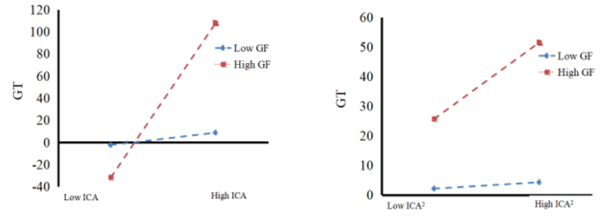


Figure 4. The moderating effect of GF in the technological effect of ICA on UCEE

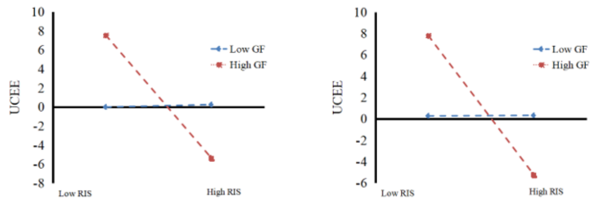


Figure 5. The moderating effect of GF in the structural effect of ICA on UCEE

Table 6. Direct and scale effect at different levels of GF

	GF	Effect	BootSE	BootLLCI	BootUCLT
Direct effect of ICA on UCEE		0.0500	0.0292	-0.0076	0.1075
The scale effect of ICA on UCEE	M-1SD	0.1142	0.0250	0.0652	0.1634
	M	0.1335	0.0248	0.0893	0.1887
	M+1SD	0.1528	0.0288	0.1059	0.2191
Direct effect of ICA^2 on UCEE		0.0092	0.0054	-0.0014	0.0199
The scale effect of ICA^2 on UCEE	M-1SD	0.0206	0.0049	0.0115	0.0308
	M	0.0240	0.0050	0.0152	0.0348
	M+1SD	0.0274	0.0058	0.0180	0.0408

Table 7. Direct and technological effect at different levels of GF

	GF	Effect	BootSE	BootLLCI	BootUCLT
Direct effect of ICA on UCEE		0.0910	0.0375	0.0172	0.1648
The technological effect of ICA on UCEE	M-1SD	0.0273	0.0168	-0.0089	0. 0575
	M	0.1123	0.0225	0.0745	0.1610
	M+1SD	0.1974	0.0408	0.1382	0.2993
Direct effect of ICA^2 on UCEE		0.0153	0.0070	0.0015	0.0291
The technological effect of ICA^2 on UCEE	M-1SD	0.0061	0.0035	-0.0016	0.0121
	M	0.0219	0.0044	0.0144	0.0317
	M+1SD	0.0377	0.0084	0.0265	0.0587

Table 8. Direct and structural effect at different levels of GF

	GF	Effect	BootSE	BootLLCI	BootUCLT
Direct effect of ICA on UCEE		0.1270	0.0310	0.0658	0.1882
The structural effect of ICA on UCEE	M-1SD	0.0329	0.0130	0.0096	0.0604
	M	0.0643	0.0193	0.0271	0.1029
	M+1SD	0.0957	0.0284	0.0413	0.1521
Direct effect of ICA^2 on UCEE		0.0228	0.0058	0.0113	0.0342
The structural effect of ICA^2 on UCEE	M-1SD	0.0063	0.0025	0.0020	0.0114
	M	0.0123	0.0035	0.0056	0.0194
	M+1SD	0.0182	0.0052	0.0086	0.0289

4. Conclusions

We explore the nonlinear impact of the ICA on UCEE in Shandong Province from China during 2007 to 2020. Through the mediating effect model, we further investigate the pathways of ICA affecting UCEE. By using moderating effect model and conditional process analysis, we explore the role of GF in the relationship between ICA and UCEE. The results show that: (1) The impact of ICA on the UCEE is inverted "U-shaped". (2) GF plays a positive moderating role in the relationship between ICA and UCEE. (3) ICA affects UCEE through scale effect, technological effect and structural effect. (4) GF has a moderating effect on the mediating effect of ICA on UCEE.

According to the conclusions, the suggestions are as follows:

(1) Reasonable industrial plans should be formulated. The impact of co-agglomeration on UCEE is various at different phase. Cities with low level of agglomeration should not pursue co-agglomeration blindly, but should first focus on improving the quality of producer services and manufacturing. Industries with relevance should be fully guided and integrated, with corresponding convenient conditions and supportive policies provided. For regions where ICA exceeds the optimal scale, development areas should be reasonably planned. The optimization of regional industrial structure should be promoted through the development of clean industry

(2) GF should be developed vigorously. Firstly, we should develop a uniform GF measurement standard. Evaluating and monitoring the application, approval, release and use of green funds may improve the development level of GF. Furthermore, low-level green financial market may weaken the moderating effect of GF. Green financial products that meet market demand should be extensively developed. Existing green financial products should be optimized. The development of new products that meet market demand should be accelerated

Appendix

Table A.1 Acronyms

UCEE	Urban carbon emission efficiency
GDP	Gross domestic product
NDDF	Non-radial Directional Distance Function
GRP	Gross regional product
ICA	Industrial co-agglomeration
ICA^2	Quadratic term of industrial co-agglomeration
GF	Green finance
ES	Economic scale
GT	Green Technology
RIS	Rationalization of Industrial Structure
PS	Population size
ER	Environmental moderating
UR	Urbanization level
EI	Energy intensity
IS	Industry Structure
Tech	Technology Progress
Gov	Government intervention
Fdi	Openness to the world

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Author contribution

Shuo Fang: Methodology, Conceptualization, Writing — review and editing, Data curation. **Wenwen Li:** Formal analysis, Methodology, Funding acquisition. **Jizu Xu:** Data curation, Formal analysis. **Qian Li:** Methodology, Formal analysis. **Yanyan Zhang:** Writing — review and editing. **Chuanhui Wang:** Investigation. **Weifeng Gong:** Data curation, Supervision. **Rongyan Zhang:** Investigation.

Acknowledgments

The work is supported by Humanities and Social Sciences Youth Foundation, Ministry of Education of the People's Republic of China (22YJCZH087).

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