Impacts and influencing pathways of urbanization on carbon–water-energy-food nexus across Chinese cities

Chenggang Li[1,2] · Yong Liu[1] · Zhenci Xu[3,4] · Gang Zhao[1] · Youhui Bao[1] · Chengcheng Cai[5] · Yu Lu[6] · Yufeng Mao[1] · Alexander Boxuan Wang[7] · Liang Wu[8]

Abstract

Food, water, energy and carbon (F-W-E-C), as important factors of urban development, have synergistic effects and trade-off effects with each other. Scientifically assessing the impact of urbanization on the F-W-E-C nexus is beneficial to optimize the urban development layout and achieve the sustainable urban development. Nevertheless, extant studies have not evaluated the impact and influencing pathways of urbanization on the F-W-E-C nexus. In this study, the Coupling Coordination Degree Model is used to explore the F-W-E-C nexus of 252 prefecture-level cities in China. The panel data model and mediating effect model are utilized to study the impact of urbanization on the F-W-E-C nexus and the impact pathways. This study finds that the F-W-E-C nexus across Chinese cities is weak trade-off. The urbanization promotes the synergy of F-W-E-C. The positive impact is greater in the central cities than in the eastern and western cities, and is greater in medium-sized cities than in small cities, large cities and above. The technological progress is an important pathway of urbanization impacting the F-W-E-C nexus, and assists urbanization to generate a positive influence on the F-W-E-C nexus. This research has implications for promoting a systematic, orderly, and rational coordination development of F-W-E-C and for sustainable urbanization development in China and the world.

Keywords Urbanization · Food-water-energy-carbon nexus · Coupling coordination degree · Pathways

1 Introduction

The world experiences further urbanization with an increasing global urbanization rate from 56.2% in 2020 to 60.4% in 2030. Some underdeveloped regions in East Asia, South Asia, and Africa are the primary regions for urban growth. However, urbanization has led to frequent occurrences of "urban diseases", for instance, cultivated land reduction, water shortage, excessive water consumption, and disproportionate greenhouse gas emissions. Urbanization, as a product of economic development to a certain stage, is inseparably interconnected with the system of food, water, energy, climate, and environment, and also plays a fundamental role in accelerating the resource allocation and flow. If the

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urbanization coordinates with them, it will positively impact the economy, society and environment, and vice versa. Food, water, energy, and carbon (F-W-E-C) nexus is very important in the process of urbanization. Evaluating the coordination degree between the urbanization and F-W-E-C nexus is conducive to establishing the coordinated relationship between the urban and F-W-E-C nexus, and achieving the goal of sustainable cities and communities (SDG11) set by the United Nations. Meanwhile, there are many developing and underdeveloped countries still face many challenges caused by low-quality urbanization, for instance, urban food crises, water shortages, high energy consumption, and high carbon emissions. This study helps these countries to solve these problems in the process of urbanization, better take targeted policy actions to achieve sustainable development of the urbanization and balance the F-W-E-C nexus.

There is a relationship of mutual promotion and constraint among the food system, water system, energy system, and carbon system (Jalilov et al.,2015; Chang et al., 2016; Hamiche et al., 2016; Sanders & Masri, 2016; Chhipi-Shrestha et al., 2017; Liu et al., 2017; Mabhaudhi et al., 2018; Hamidov & Helming, 2020), which is called the F-W-E-C nexus. On one hand, a tremendous amount of water and energy is indispensable in the food production, which generates considerable quantities of carbon emissions (Appiah et al., 2018; Zhao et al., 2018; Xu et al., 2020a, 2020b). Meanwhile, the green, organic and sustainable food production provides certain ecological security and carbon sink functions (Martin-Gorriz et al., 2021; Yu et al., 2022). On the other hand, climate warming and the increase of renewable energy consumption affect the food production and lead to the changes in water consumption (Chopra et al., 2022). Because the water, carbon, clean energy and food security are key goals of the United Nations 2030 Agenda for Sustainable Development, maintaining a balanced relationship between the F-W-E-C system is essential for sustainable socio-economic development (Jin et al., 2023). In this research, the correlation coefficients between urbanization and the agricultural system, the water system, the energy system and the carbon system were calculated based on the data over the period 2003–2017, shown in Fig. 1. Figure 1 shows the urbanization is correlated with F-W-E-C, with a strong correlation with urban water use, energy consumption, and carbon emission subsystems.

There is a growing body research has measure the level food system, water system, energy system, and carbon system, respectively (Behera & Dash, 2017; Liu et al., 2021a, 2021b; Yue et al., 2021; Margenny & Francoj, 2022). Some studies discussed the impact of urbanization on food, water, energy and carbon (Wang et al., 2019; Zhong et al., 2020; Majeed & Tauqir, 2020; Liu et al., 2021a, 2021b). However, there is a lack of systematic analysis and quantitative analysis of the F-W-E-C nexus under the conditions of environmental degradation and socio-economic complexity. Moreover, few studies have explored the pathway of the urbanization impacting on the F-W-E-C nexus with quantitative methods. To fill the gap of existing research, this research expands the existing binary and ternary coupling coordination degree model, construct a multi coupling coordination degree model, and bring the F-W-E-C system into a unified framework to analyze the coordinated development of the F-W-E-C system. The temporal and spatial characteristics of the F-W-E-C nexus are explored. Different from the previous research, in this research, the perspective is partial first, then systematic, and in turn partial. This kind of transformation is achieved by applying a comprehensive evaluation index and coupling coordination degree model. Coupling coordination degree is usually defined as the ability to coordinate and work together between different components in a system. The concept has applications in a variety of fields, including engineering, management, ecology, and so on. The coupled coordination degree approach covers a wide range of aspects such as system modelling and analysis, coordination strategies and control methods, information interaction and
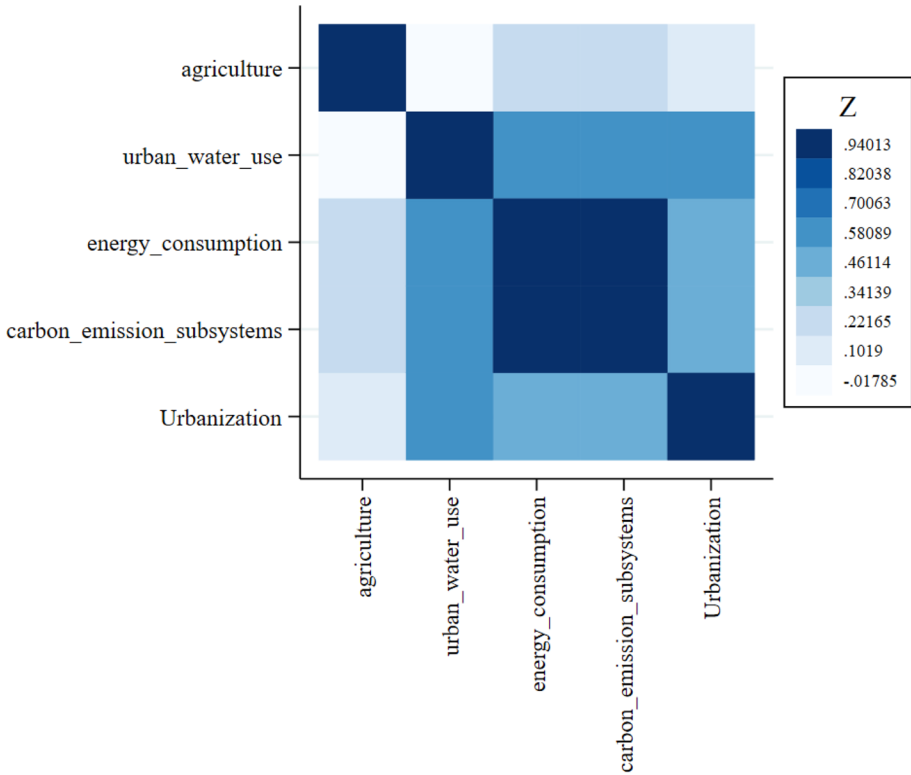
Fig. 1 Heat map of correlation coefficient matrix

communication, optimization and scheduling, as well as real-time monitoring and feedback, aiming to ensure that the different components of a system work in tandem with each other in order to optimise the overall performance of the system.

The purpose of this study is to access the impact of urbanization on the F-W-E-C nexus and the influence pathways. Firstly, the comprehensive level of F-W-E-C nexus is measured. Then, the coupling coordination type of the F-W-E-C system is identified. Third, this study evaluates the impact of urbanization on the coupling coordination degree of F-W-E-C and makes a heterogeneous analysis of the impact in terms of region, city size, and period. Finally, the pathway of the urbanization affecting the coupling coordination degree of F-W-E-C system is explored.

This study takes the rapid development of China's urbanization as the background and deeply explores the impact and its pathways of urbanization on the food-water-energy-carbon nexus. China, as a developing country with rapid urbanization, has made brilliant achievements in the economy development, urban infrastructure, residents' living conditions, etc., while faces many challenges such as incomplete urbanization and low-quality urbanization (Guan et al., 2018). Different from the urbanization path of developed countries such as Europe and the United States, China has taken the traditional urbanization path. The irrational expansion of cities has brought great pressure on the food production and water resources (Dos Santos et al., 2017; Rashid et al., 2018; Abd Elmabod et al., 2019; Oueslati et al., 2019), as well as a large amount of energy consumption and carbon

emissions (Wang et al., 2014; Wang et al., 2016). This causes the deterioration of ecological and environmental quality (Luo et al., 2018; Liu et al., 2020), which in turn affects the sustainable development of cities. Therefore, clarifying the coupling coordination degree of F-W-E-C system, and evaluating the impact of urbanization on the coupling coordination degree of F-W-E-C system and its impact pathways can implement the effective sustainable management of food production, water consumption, energy consumption and carbon emissions in China's future urbanization process. It also provides the solutions and experiences for the problems that may arise in the process of urbanization, which is conducive to the sustainable urban development around the world.

This article focuses on the following questions. (1) How does the coupling coordination degree of F-W-E-C system (named F-W-E-C nexus) evolve in time and space? (2) How does the urbanization affect the coupling coordination degree of F-W-E-C system? (3) What are the pathways of urbanization that affect the coupling coordination degree of F-W-E-C system? To answers these questions, this study uses the panel data of 252 prefecture-level cities in China from 2003 to 2017 to evaluate the coupling coordination degree of F-W-E-C system and study the impact and its pathways of the urbanization on the F-W-E-C nexus. This study employs the following framework, which is shown in Fig. 2. First, this study constructs an evaluation index system of F-W-E-C nexus and comprehensively measure the F-W-E-C nexus. This study calculates the coupling degree and coupling coordination degree based on the four subsystems evaluation index, and explore the temporal and spatial evolution trend of the coordination degree. Second, this study studies the linear and nonlinear impact of urbanization on the coordination degree of F-W-E-C system based on the whole sample. The heterogeneity is analyzed according to the sub samples in different regions, city scales and periods, respectively. Third, this study utilizes the intermediary effect model to analyze the pathways of urbanization that affect the coupling coordination degree of F-W-E-C system. It is worth mentioning that this study classifies technological progress into two categories, namely, input-oriented and output-oriented technological progress. Based on the results, this study also discusses the effective sustainable management of food, water, energy, and carbon emissions, which could help to achieve the goal of sustainable cities and communities, and also a harmonious coexistence between the urban and sustainable development.
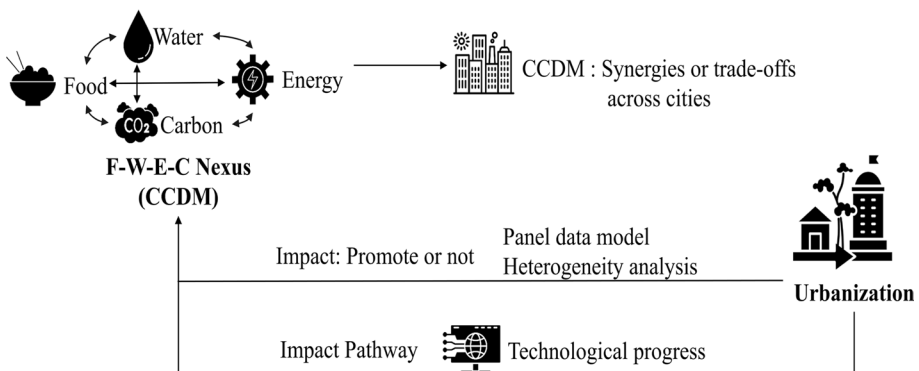

Fig. 2 Research framework. All icons are from The Noun Project (https://thenounproject.com). *Note*: **1** CCDM denotes the Coupling coordination model; **2** F-W-E-C nexus denotes synergies or trade-offs between food, water, energy and carbon

2 Literature review

2.1 The measurement of food system, water system, energy system, and carbon system

Some studies adopted an isolated framework to measure the level of the food system, water system, energy system, and carbon system. The food system is measured from the perspective of the demand and supply of various types of food, and the degree of waste (Grafton et al., 2017; Rosa et al., 2021). Dufour (2021) introduce a short history of methods used to measure bathing beach water quality, including membrane filter, quanti-tray method, proprietary multi-well tray and molecular methods. The water system contains the supply, consumption, and waste of various types of water (Stanchev & Ribarova, 2016; Guan et al., 2020; Rosa et al. 2021; Hua et al., 2022). The energy system can be estimated by the amount, resources, and efficiency of all types of energy extraction (Hua et al., 2022). Carbon emissions contains the sum of carbon emissions from all types of energy consumption and the intensity of carbon emissions (Lin & Jia, 2019; Yang et al., 2019a, 2019b).

2.2 The impacts of urbanization on F-W-E-C

Urbanization has a relationship with the agricultural system, water resources system, energy system and carbon system. Urbanization affects the consumption of water resources in different regions in China (Liu et al., 2022). Abnormal agricultural subsidies may have reduced rural–urban migration, significantly slowing down China's urbanization process (Huang et al., 2020). The impact of energy forms on energy poverty varies across regions with different levels of urbanization (Pereira & Marques, 2022).The impacts of urbanization on food, carbon, energy and water, respectively, are widely discussed (Cai et al., 2018; Barthel et al., 2019; Ridzuan et al., 2020; Niva et al., 2020; Wang et al., 2021a, 2021b; Zhu & Salleh, 2021). The rapid growth of urbanization has a certain impact on the energy use, carbon emissions, water resource pressure, water quality, and economy (Su et al., 2018). Urban expansion have resulted in water conflicts between agriculture and urban sectors, but the issues could be solved by improving the efficiency of water use (Flörke et al., 2018). Although urbanization has improved social welfare by promoting population development and social progress, it has also led to an increase in energy and water consumption and air pollution and resource competition (Fan et al., 2019). Furthermore, the rapid expansion of urban areas threatens the food security since it causes a large loss of agricultural land (Shi et al., 2016), and quickens the regional carbon emissions (Liu et al., 2016). Urbanization can impacts food systems through political, economic, and social pathways (Blekking et al., 2022). Urbanization has a negative impact on carbon emissions (Chen, 2021). Shi et al. (2020) have explored the effects of urbanization on the food-water-land-ecosystem nexus in Shenzhen, China,, and find that urbanization not only leads to a decline in habitat quality, but also causes a decline in urban water supply and food production. Yang et al. (2024) analyzed the impacts of urbanization on the food-water-energy nexus using the Beijing-Tianjin-Hebei urban agglomeration in China as a case study, and found that urbanization caused a decline in habitat quality (HQ) and carbon sequestration (CS).

Overall, much of the existing research has focused on the measurements and linkages between food, water, energy and carbon systems and the impact of urbanization on these systems. However, some studies use an isolated framework to measure the

level of the food system, water system, energy system, and carbon system, while do not measure the relationship of F-W-E-C system. Futhermore, some studies only focused on the impact of urbanization on a single system (Bilgili et al., 2017; Gorrell et al., 2019; Kassouri, 2021; Awan et al., 2022). It is clear from the above studies that F-W-E-C system is a tightly linked system. The study of the impacts of urbanization should no longer be confined to the independent subsystems, but to the whole food-water-energy-carbon system. This study measures the relationship of food, water, energy and carbon systems and explores the impacts of urbanization on F-W-E-C nexus. This study also discusses the impact pathway of urbanization on F-W-E-C nexus.

3 Methods and data

3.1 Data

The data from 2003 to 2017 used in this article are mainly from *the China Urban Statistical Yearbook*, *China Energy Statistical Yearbook*, CEADs database, *China Commerce Ministry* and *China Meteorological Department*. The data on carbon emissions in prefecture-level cities are summarized results and they are adopted from the county-level inventory of CEADs. The energy consumption data are converted into tons of standard coal (Mtce) by the annual urban electricity consumption, total gas supply (artificial and natural gas), and total liquefied petroleum gas supply to form the total energy consumption. The reference coefficients of all kinds of energy discounted standard coal are from *China Energy Statistical Yearbook 2020*. The following are reference coefficients for converting some common energy sources to standard coal:

(1) Standard coal: 1 tonne of standard coal is equal to 1 tonne of standard coal.
(2) Raw coal: 1 tonne of raw coal is usually equal to 1 tonne of standard coal.
(3) Oil: about 0.43 tonnes/tonne, i.e. 1 tonne of oil is equivalent to about 0.43 tonnes of standard coal.
(4) Gasoline: about 0.59 tonnes/tonne, i.e. 1 tonne of gasoline is equivalent to about 0.59 tonnes of standard coal.
(5) Diesel: about 0.54 tonnes/tonne, i.e. 1 tonne of diesel is equivalent to about 0.54 tonnes of standard coal.
(6) Natural gas: about 0.12 m3/tonne, i.e. 1 tonne of natural gas is equivalent to about 0.12 tonnes of standard coal.
(7) Liquefied petroleum gas (LPG): about 0.48 tonnes/tonne, i.e. 1 tonne of LPG is equivalent to about 0.48 tonnes of standard coal.
(8) Biomass: The conversion factor for biomass energy varies depending on the type and moisture content, and usually ranges between 0.3 and 0.5 tonnes/tonne.

In addition, this study uses the total quantity of annual urban water supply to measure the water consumption since the water is provided based on demand. As for the missing data, this study applies the linear interpolation method and moving average method to make up.

3.2 Variable definition

(1) Explained variable: F-W-E-C nexus. The F-W-E-C nexus reflects the interaction relationship of food system, water system, energy system, and carbon system. It is calculated by the coupling coordination degree model.

(2) Explanatory variable: Urbanization level. The urbanization level is the natural logarithm of the built-up area of city i in year t is used to denote the area of the built-up area of city i in year t.

(3) Control variable: ① Development level. It is expressed in per capita GDP, 10,000 yuan/person; ② Industrial structure. It is expressed by the proportion of the secondary industry and the tertiary industry in GDP respectively; ③ Opening level. It is expressed by the actually utilized foreign capital. ④ Urban greening degree. It is expressed by the urban garden green space area. ⑤ Average relative humidity and annual average temperature. It is regarding to control variables for the environment.

(4) Intermediary variable: ① Input-oriented technological progress. This study uses the R&D investment to measure the input-oriented technological progress, which is expressed by the proportion of scientific expenditure in financial expenditure; ② Output-oriented technological progress. It is calculated by the amount of patent authorization, which is the sum of the invention patent, utility model patent, and design patent.

3.3 Index system design

As mentioned in Sect. 1, food, water, energy, and carbon are inseparable. They influence and restrict each other. Based on their interaction features, this study selects the indicators related to the F-W-E-C nexus and design an indicator system from various levels and dimensions (See Table 1), following the principles of systematic, scientific, comparability, and data availability.

3.4 Measurement of the comprehensive evaluation index

Based on the selected indicators, first, this study applies dimensionless processing to the original data. Then, the weight of each indicator is determined by using the entropy method. Finally, with the weighted sum calculation method, this study gets the comprehensive evaluation index of food system $F(f)$, water system $W(w)$, energy system $E(e)$, and carbon system $C(c)$, which is used to evaluate the comprehensive level of F-W-E-C system. The calculation formula of each comprehensive evaluation index is shown in Formula (1):

$$F(f) = \sum_{i=1}^{n_1} \alpha_i f_i; \ W(w) = \sum_{j=1}^{n_2} \beta_j w_j; \ E(e) = \sum_{k=1}^{n_3} \gamma_k e_k; \ C(c) = \sum_{l=1}^{n_4} \delta_l c_l \tag{1}$$

where, n_1, n_2, n_3 and n_4 represent the number of evaluation indicators in the four subsystems. $\alpha_i, \beta_j, \gamma_k$ and δ_l are the weights calculated by the entropy method. f_i, w_j, e_k and c_l are dimensionless values after standardizing the original data of F-W-E-C system using range standardization. The specific calculation procedures of the comprehensive evaluation indexes of the four subsystems are as follows:

Table 1 Evaluation index system and weight of F-W-E-C system

System types	Evaluation index	Index attribute	Weight
Food system	Proportion of primary industry (%)	+	0.1968
	Total power of agricultural machinery (10,000 kWh)	+	0.1729
	Food yield (ton)	+	0.2071
	Sown area of food (1000 hectares)	+	0.1627
	Per capita years of education (years)	+	0.0466
	Technical progress (%)	+	0.2054
	Fertilizer application amount (10,000 tons)	–	0.0086
Water system	Water consumption amount (10,000 tons)	–	0.0032
	Water consumption intensity (ton/10000 yuan)	–	0.0007
	Proportion of secondary industry (%)	–	0.0241
	Technical progress (%)	+	0.2269
	Density of water supply pipeline (km/km2)	+	0.6707
	Annual urban precipitation (mm)	+	0.0745
Energy system	Energy consumption amount (tons of standard coal)	–	0.0110
	Energy consumption intensity (ton of standard coal/10000 yuan)	–	0.0048
	Proportion of secondary industry (%)	–	0.0845
	Proportion of tertiary industry (%)	+	0.1046
	Technical progress (%)	+	0.7950
Carbon system	Carbon emissions (million tons)	–	0.0164
	Carbon intensity (t/10000 yuan)	–	0.0125
	Proportion of secondary industry (%)	–	0.0933
	Technical progress (%)	+	0.8777

"+" represents a positive effect indicator; "-" represents a negative effect indicator

(1) Data standardization. Each indicator of the four subsystems in Table 1 comes from different levels, and their indicator values have significant differences in dimension and magnitude. Therefore, the above indicators need to be standardized to ensure the accuracy of the final results. In this article, the range standardization method is used to standardize the indicators of comprehensive evaluation indexes.

$$X_{ij}\prime = \frac{X_{ij} - \min\{X_j\}}{\max\{X_j\} - \min\{X_j\}} \tag{2}$$

$$X_{ij}\prime = \frac{\max\{X_j\} - X_{ij}}{\max\{X_j\} - \min\{X_j\}} \tag{3}$$

where, X_{ij} and $X_{ij}\prime$ represent the original value and the standardized value of the index $j(j = 1, 2, ..., n)$ in year $i(i = 1, 2, ..., m)$ respectively. Furthermore, $\max\{X_j\}$ and $\min\{X_j\}$ refer to the maximum and minimum index values in all years respectively.

(2) Weight calculation of each indicator (see Table 1 for the final weight calculation results). This study uses the entropy method to calculate the evaluation indicator weights of the evaluation indexes. The following shows the concrete calculation steps.

① Calculation of index proportion. P_{ij} means the proportion of index j in year i, then

$$p_{ij} = X_{ij}' / \sum_{i=1}^{m} X_{ij}' \tag{4}$$

② Calculation of index information entropy. e_j is defined as the information entropy of index j, then

$$e_j = -\left(\frac{1}{lmn}\right) \sum_{i=1}^{m} (P_{ij} \times \ln P_{ij}), 0 \le e_j \le 1 \tag{5}$$

In Formula (4) and Formula (5), m is the number of years to be evaluated.

③ Calculation of index redundancy d_j.

$$d_j = 1 - e_j \tag{6}$$

④ Calculation of the index weight w_j.

$$w_j = d_j / \sum_{j=1}^{n} d_j \tag{7}$$

(3) Calculation of comprehensive evaluation index S_I. The comprehensive evaluation index is calculated by the method of the weighted sum of weight and index.

$$S_I = \sum_{j=1}^{n} w_j \times X_{ij}' \tag{8}$$

In Formula (7) and Formula (8), n is the number of indicators selected in each evaluation indicator system. The weights of the each indicator are shown in Table 1.

3.5 Calculation of coupling coordination degree

3.5.1 Coupling degree model

In physics, coupling mean the phenomenon that two or more systems or motion forms affect each other and even unite through various interrelationships (Gorman et al., 2017; Liu et al., 2018a, 2018b). In this article, the coupling refers to the phenomenon that the food system, water system, energy system, and carbon system are affected by various interactions and external factors. The coupling degree is the degree of interaction (Gan et al., 2020) between the four subsystems, regardless of whether it is good or bad.

Urbanization is a process in which essential productive factors flow from rural areas to urban areas. By nature, it is a transformation process of economic and social structure, which causes a series of impacts on the economy, food production, carbon emissions, agricultural land, energy consumption, and water consumption (Dociu & Dunarintu, 2012; Martínez-Zarzoso & Maruotti, 2011; Deng et al., 2015; Sheng et al., 2017; Wakode et al., 2018). In the context of China's urbanization, there is a coordination development of F-W-E-C system in urban areas. So, this study uses coordination degree to evaluate the F-W-E-C nexus in the urbanization process. Taking Wang et al.'s (2021a, 2021b) practice, this study expands the binary of ternary system to multi system and constructs the coupling degree model as follows:

$$C = \left[\frac{\prod_{i=1}^n U_i}{\left(\frac{1}{n} \sum_{i=1}^n U_i \right)^n} \right]^{\frac{1}{n}} \tag{9}$$

where, C is the coupling degree value, which is an important indicator to measure the discrete degree of each subsystem, and its distribution interval is [0,1]. The larger the C value is, the smaller the discrete degree of each subsystem is, and the higher the coupling degree is. On the contrary, the smaller the C value is, the larger the discrete degree of each subsystem is, the lower the coupling degree is. U_i is the comprehensive evaluation function of each subsystem, and its value distribution interval is [0,1]. n is the number of subsystems. When n=4,

$$C = \left[\frac{\prod_{i=1}^4 U_i}{\left(\frac{1}{4} \sum_{i=1}^4 U_i \right)^4} \right]^{\frac{1}{4}} = \sqrt[4]{\frac{U_1 U_2 U_3 U_4}{\left(\frac{U_1+U_2+U_3+U_4}{4} \right)^4}} = \frac{4\sqrt[4]{U_1 U_2 U_3 U_4}}{U_1 + U_2 + U_3 + U_4} \tag{10}$$

Substitute the index $F(f)$, $W(w)$, $E(e)$ and $C(c)$ (mentioned in Formula (1) into the Formula (10), and then this study obtains a coupling degree model which is used to evaluate the F-W-E-C nexus.

$$C = \frac{4\sqrt[4]{F(f) \times W(w) \times E(e) \times C(c)}}{F(f) + W(w) + E(e) + C(c)} \tag{11}$$

3.5.2 Coupling coordination degree model

The coupling coordination degree in this article means the harmonious extent and level between four subsystems, namely, the food system, water system, energy system, and carbon system. Although the coupling degree model could reflect the strength of the coupling among the four subsystems, it fails to claim whether the coordination is good or bad. Therefore, based on the coupling degree model, this study further constructs the coupling coordination degree model which not only considers the interaction degree among the four subsystems, but also focuses on the development level of each subsystem. In general, it is a valuable method to evaluate the overall effectiveness and coordination effect of the four subsystems (Shi et al., 2020; Tomal, 2021). The coupling coordination degree model is presented below:

$$D = \sqrt{C \times T} \tag{12}$$

where, C is the coupling index. T T is a comprehensive coordination index among the four subsystems, reflecting the overall synergy effect of food system, water system, energy system, and carbon syetem in urban areas (Zhao et al., 2017; Xu et al., 2020a, 2020b). A higher T value indicates a higher growth of the four subsystems. T value is obtained from the following formula:

$$T = \alpha F(f) + gW(w) + hE(e) + iC(c); \ \alpha + g + h + i = 1 \tag{13}$$

Table 2 Synergy and trade-off relationship of F-W-E-C system

Coupling coordination degree (*D*)	Interval division	Coupling coordination type	Nexus
Maladjustment recession Sect. $0 \leq D < 0.4$	[0.00,0.10)	Extreme maladjustment recession	Strong trade off
	[0.10,0.20)	Severe maladjustment recession	
	[0.20,0.30)	Moderate maladjustment recession	Weak trade off
	[0.30,0.40)	Mild maladjustment recession	
Transition harmonious Sect. $0.4 \leq D < 0.6$	[0.40,0.50)	Near maladjustment recession	Interaction
	[0.50,0.60)	Grudging coordinated development	
Coordinated development section $0.6 \leq D \leq 1$	[0.60,0.70)	Primary coordinated development	Weak synergy
	[0.70,0.80)	Intermediate coordinated development	
	[0.80,0.90)	Fine coordinated development	Strong synergy
	[0.90,1.00]	High-quality coordinated development	

Smaller values of coupling coordination degree indicate stronger trade-off effects (weaker synergies), and larger values of coupling coordination degree indicate stronger synergies (weaker trade-off effects)

where, α, g, h and i are the undetermined weights of the subsystems respectively. Since the four subsystems share the same features, that is, interrelated, interacted and restricted to each other, they play an equally important role in urban sustainable development. Consequently, α, g, h and i are set as equal weight, that is, $\alpha = g = h = i = 1/4$.

First, according to the distribution interval of the *D* value, the coupling coordination degree is divided into three types, that is, the maladjustment recession area, the transition harmonious area, and the coordinated development area. Then, the three types are further subdivided into ten types (Zhang et al., 2018). Finally, the F-W-E-C nexus is divided as shown in Table 2.

3.6 Model of urbanization influence on the F-W-E-C *nexus*

3.6.1 Panel data model

Urbanization is an important driving force to promote regional economic and social development. Because the process is accompanied by economic growth, population concentration, construction land expansion, and energy consumption increasing, which inevitably impact the F-W-E-C nexus. For exploring the urbanization influence on the F-W-E-C nexus, this study constructs the following panel data model:

$$\ln d_{it} = \alpha_0 + \alpha_1 \ln \mathit{buarea}_{it} + \beta \vec{X}_{it} + \mu_i + \pi_t + \varepsilon_{it} \tag{14}$$

where, $\ln d_{it}$ is the natural logarithm of the coupling coordination degree of F-W-E-C system of city i in year t, representing the F-W-E-C nexus in urban. $\ln \mathit{buarea}_{it}$ is the natural logarithm of the urban area of city i in year t t, representing the urbanization level. Besides, its coefficient α_1, which is the core parameter to be concerned in this article, describes the influence of urbanization on the F-W-E-C nexus. Specifically, a positive α_1 indicates that urbanization could promote the coordination level and vice versa. $\vec{X}_{it}$ represents control variables for the city and the environment, which might affect the F-W-E-C nexus. For instance, the control variables for the city include economic development level

(expressed in per capita GDP, 10,000 yuan/person), industrial structure (expressed by the proportion of the secondary industry and the tertiary industry in GDP respectively, %), opening level (expressed by the actually utilized foreign capital, $10,000), urban greening degree (expressed by the urban garden green space area, hectare). Regarding to control variables for the environment, this study takes the average relative humidity (%) and annual average temperature (℃) in cities as the primary control factors. Apart from average temperature, other variables are taken as logarithmic and expressed in ln $rjgdp$,ln sec,ln thi ,ln $aufc$1,ln $green$,ln rh,tem respectively. μ_i and π_t represent the city effect and time effect to be controlled respectively.ε_{it} refers to the random error terms.

Different from most studies that applied the urbanization rate, that is, the proportion of the urban population in the total population (Ahmed et al., 2019; Yang et al., 2019a, 2019b), this study uses the built areas in municipal districts to represent the urbanization level. The urbanization rate was a reasonable choice for quantifying the urbanization level, but it is not a perfect option nowadays because there is a declining tendency for population growth rate in rural and urban China. However, spatial urbanization, which is a result of the construction and transformation of urban regional carriers, might cause the four sub systems to become more sensitive. Therefore, the urban built areas in municipal districts provide a more reliable data basis for accurately identifying the urbanization influence on the F-W-E-C nexus.

3.6.2 The non-linear impact of urbanization on the F-W-E-C *nexus*

Since Chinese urbanization is a long-term and complicated process, this article attempts to further propose two assumptions. The first one is "Does the urbanization positively or negatively impact the F-W-E-C nexus all the time?". The other is "Does the one-way impact gradually emerge when urbanization level reaches a specific value?". For figuring out the answers, this study decides to control the urban effect and time effect based on Model (14), and then add the quadratic term of ln $buarea_{it}$ for the regression test. Meanwhile, scatter charts of the nonlinear relationship between the urbanization level and the coordinated development degree of the four subsystems are made to analyze the nonlinear influence of urbanization on the F-W-E-C nexus.

3.7 Heterogeneity analysis of different regions, urban scales and periods

Due to the differences in industrial structure, factor endowment, and policy strength, the regional carrier construction and economic development in different cities are imbalanced and inharmonious. In addition, the non-agricultural population proportion, spatial agglomeration degree, infrastructure improvement degree, and economic development degree vary in different regions. Therefore, the sensitivity of urban carrier construction and economic production activities in regions to the urbanization level is also different. In order to further investigate the differential impact of urbanization on the F-W-E-C nexus, this study divides the sample cities into three sub-samples, namely, east, middle, and west, based on the economic development degree. And then, this study regresses the Model (14) with the three sub-samples respectively.

The city scale also is regarded as a perspective to identify the impact of urbanization on the F-W-E-C nexus. According to the *Notice on Adjusting the Standards for City Size Division* issued by the *State Council of China*, the scale of cities is determined by the number of permanent residents. Cities with permanent residents below 500,000 are defined as small cities, with more than 500,000 but less than 1 million are medium-sized, with beyond 1 million are large and above. In order to explore the impact of different city scale, this study divides the samples into various sub-samples based on the city scale, and then regress the Model (14) with the three sub-samples.

In different periods, the urbanization presents different stage characteristics because of various economic development levels, national policies, and urban construction degrees. The samples, according to the time, are classified into two sub-samples, 2003–2006 and 2007–2017, for exploring the urbanization impact on the F-W-E-C nexus in different periods. This study also regresses the with the two sub-samples.

3.8 Mediation effect model for impact pathways analysis

The improvement of urbanization has an impact on the F-W-E-C nexus. Then, what are the internal causes of this phenomenon? this study verifies the pathways of urbanization affecting the coordinated development of the four subsystems. This study uses the intermediary effect model to analyze the pathways from the perspective of technological progress.

Urbanization not only could bring capital inflow and increase the labor population for cities, but also develop technology (Sun & Huang, 2020; Cumming et al., 2014). It is true because cities could attract a large number of professional talents, which is conducive to local technology progress. The fluctuation of technological level impacts the F-W-E-C nexus in urban areas. Therefore, for this reason, this article further decomposes technological progress into two types, that is, input-oriented and output-oriented technological progress, which are represented by the R&D investment (*tech*) and the amount of patent authorization (*totinvent*). The R&D investment is expressed by the proportion of scientific expenditure in financial expenditure. The amount of patent authorization is the sum of the invention patent, utility model patent, and design patent. This study takes input-oriented technological progress and output-oriented technological progress as intermediary variables, and construct the intermediary effect model as follows:

$$\ln d_{it} = \alpha_0 + \alpha_1 \ln buarea_{it} + \alpha_2 \vec{X}_{it} + \mu_i + \pi_t + \gamma_{it} \tag{15}$$

$$\ln tech_{it}(\ln totinvent_{it}) = b_0 + b_1 \ln buarea_{it} + b_2 \vec{X}_{it} + \mu_i + \pi_t + \delta_{it} \tag{16}$$

$$\ln d_{it} = c_0 + c_1 \ln buarea_{it} + c_2 \ln tech_{it}(\ln totinvent_{it}) + c_3 \vec{X}_{it} + \mu_i + \pi_t + v_{it} \tag{17}$$

where, $\gamma_{it}, \delta_{it}, v_{it}$ are the random error terms of the model. The definitions of the other variables are consistent with those in the preceding paragraph.
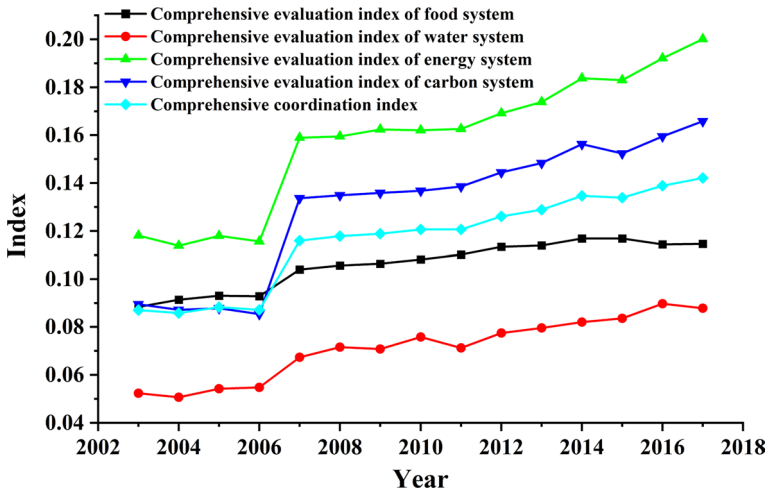
Fig. 3 The comprehensive coordination level of F-W-E-C system. *Note*: The smaller the index, the lower the level of integration of the system, and the larger the index, the higher the level of integration of the system

4 Results

4.1 Temporal evolution of F-W-E-C *nexus*

4.1.1 Comprehensive coordination level of F-W-E-C system

The average value of the comprehensive coordination level of the four subsystems in the sample cities shows an overall upward trend, rising from 0.087 in 2003 to 0.142 in 2017 (Fig. 3). Before 2007, the comprehensive growth rate of the F-W-E-C system is slow. After 2007, due to the rapid growth of the economic development and urbanization, the comprehensive growth rate of the F-W-E-C system increase rapidly, and the growth trend is consistent with the four subsystems. Among them, the rising trend of energy consumption and carbon emissions is relatively fast. The comprehensive evaluation index of energy consumption increased from 0.118 in 2003 to 0.200 in 2017, an increase of nearly 69.49% compared with 2003. Carbon emission level increased from 0.090 in 2003 to 0.166 in 2017, an increase of nearly 84.44%. The rising trend of food system and water system is stable. The comprehensive evaluation index of food system always between 0.088 and 0.115, while water consumption has always been between 0.052 and 0.088. The comprehensive evaluation index of carbon emissions has exceeded the comprehensive evaluation index of food system since 2007.

4.1.2 Coupling coordination degree of F-W-E-C system

The coupling coordination degree of F-W-E-C system in 252 cities is between [0.2, 0.4), indicating that the F-W-E-C nexus is weak trade-off relationship (Fig. 4). After 2007, the type of coupling coordination changed from the moderate maladjustment recession type to the mild maladjustment recession type. With the time passed, the differences between
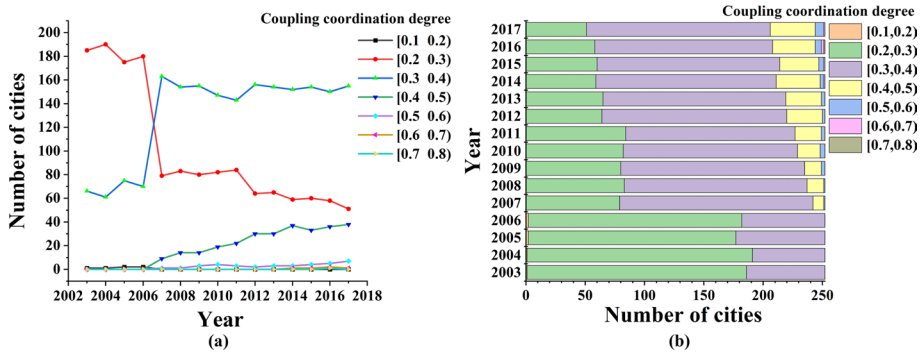
Fig. 4 Number of cities in different intervals of coupling coordination degree. *Note*: The different colors represent the number of cities in each coupling coordination degree interval

the industrial structure and technical level of cities have gradually emerged. The coupling coordination type of some cities has reached the primary coordinated development, and some cities have even reached the intermediate coordinated development. Among them, the number of cities with moderate maladjustment recession declined from 185 in 2003 to 51 in 2017, with mild maladjustment recession increased from 66 in 2003 to 155 in 2017, an increase of 135%, and the number of cities near maladjustment recession raised from 9 in 2007 to 38 in 2017.

Before 2007, the F-W-E-C nexus show a stable fluctuation trend around 0.280, belonging to the moderate maladjustment recession, and the coordination level between the four subsystems was not high. However, after 2007, the coupling coordination level of the four subsystems rise rapidly, and the four subsystems are in a stage of mild maladjustment recession (Fig. 5). Before 2007, the economic aggregate level entered a rapid growth period, but the quality of economic development is still at a low level. The increase in urban energy consumption and water use caused by low-quality economic growth has exacerbated the shortage of water resources, further restricted the development of food system, and led to the unbalanced development of the four subsystems. After 2007, with the upgrading of industrial structure, the transition of economic growth mode from extensive to intensive, and the improvement of water consumption and energy utilization efficiency, the water conflict with the agricultural sector has been alleviated, which is conducive to the development of food system. At the same time, the intensity of carbon emissions has decreased, and the coordination of F-W-E-C system have been enhanced, but the bottleneck of urban economic development has not been broken. It increases the difficulty of achieving sustainable urban development based on a low-carbon economy.

From 2003 to 2017, the overall coupling degree was between 0.911 and 0.929. It was at a high level, but showed a slightly oscillatory downward trend. It indicated that the interaction between the four subsystems was very strong. However, the interaction degree was weakened.

4.2 Spatial evolution of F-W-E-C *nexus*

The coupling coordination degree of the sample cities shows an upward trend, and the coupling coordination level of cities in the south is higher than that in the north (Fig. 6). Only Wuhu has reached the primary coordinated development. A few cities that have reached the
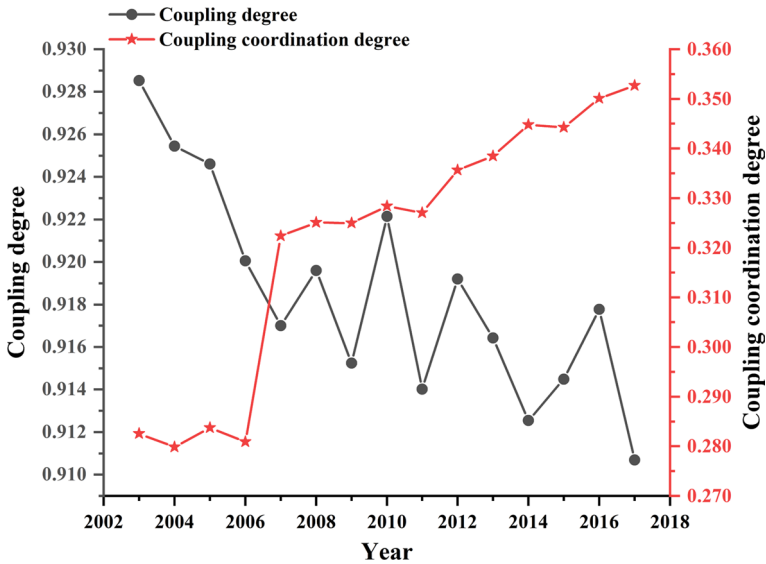
Fig. 5 Temporal evolution of mean coupling degree and coupling coordination degree. *Note*: The coupling degree is the degree of interaction between food, water, energy and carbon, regardless of whether it is good or bad. The coupling coordination degree indicates the synergies and trade-offs between food, water, energy and carbon
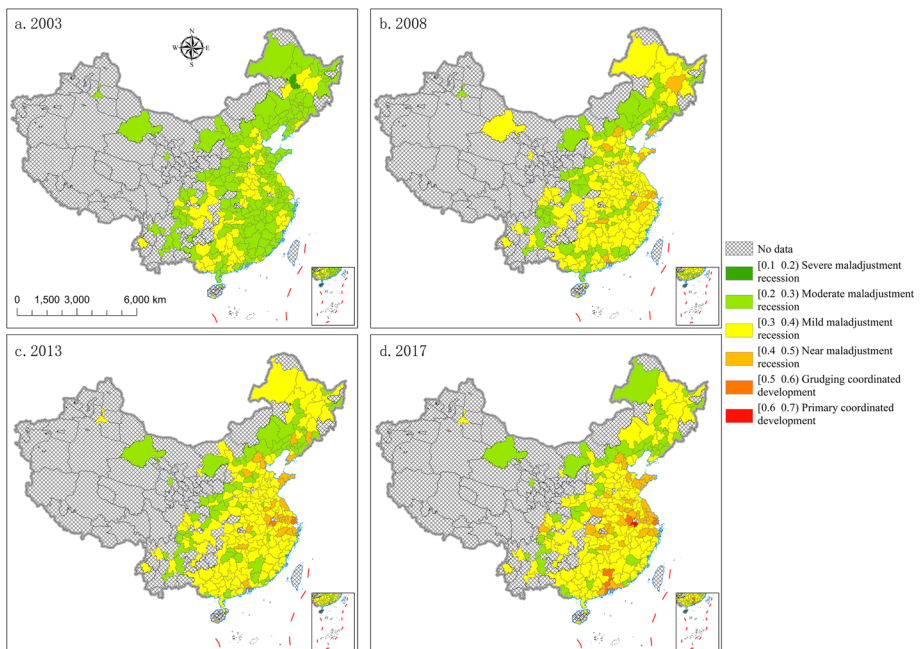

Fig. 6 Spatial evolution of the coupling coordination of F-W-E-C system. *Note*: Different colors represent different types of coupling coordination

Fig. 7 The urbanization impact on the F-W-E-C nexus. *Note*: Group **1** is the estimated result with a series of urban control variables and the urban fixed effect. Group **2** is the estimated result with a series of environmental control variables based on Group (**1**). Group (**3**) is the estimated result with the time fixed effect based on Group (**2**). The greater the coefficient, the greater the urbanization impact on the F-W-E-C nexus. See Supplementary Table 1 for detailed results and data
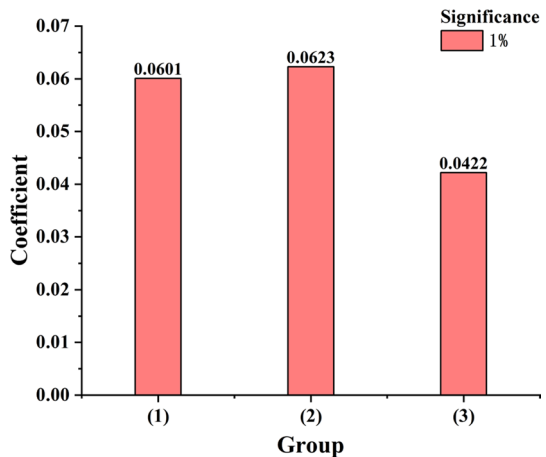
grudging coordinated development are located in Guangdong, such as Dongguan, Shenzhen, etc. Many cities with low levels of maladjustment recession and coordinated development are located in the northeast and northwest China. The coupling coordination level of cities in the Shandong Peninsula, Jiangsu, Zhejiang, and other parts of the eastern China has changed from mild maladjustment to near maladjustment, and the level of coupling coordination is maintained at the near maladjustment recession stage. At the same time, the cities with the coupling coordination level of near maladjustment recession expand from the eastern China to the central China.

4.3 The impact of urbanization on the F-W-E-C *nexus*

The urbanization promotes the synergy relationship of F-W-E-C nexus (Fig. 7, Supplementary Table 1). The urbanization improves the coupling coordination degree of F-W-E-C system, and positively impacts the coupling coordination degree of F-W-E-C system. The impact is positive and significant at the 1% significance level. This indicates the urbanization can improve the coupling coordination degree of F-W-E-C system.

In the meantime, the urbanization has negative effect in the early stage while has positive effect in the late stage on the coupling coordination development of F-W-E-C system (Fig. 8, Supplementary Table 2). According to the nonlinear impact of urbanization on the F-W-E-C nexus, in the early stage of urbanization, the coupling coordination degree of F-W-E-C system decreases. However, in the late stage of urbanization, the coupling coordination degree of F-W-E-C system increases. Therefore, the urbanization has nonlinear influence on coupling coordination degree of F-W-E-C system.

4.4 The heterogeneity of regions, urban scales and periods

The impact of urbanization on the coordination degree of F-W-E-C system varies significantly in different regions, urban scales and periods (Fig. 9, Supplementary Table 3). The urbanization significantly positively impact the coupling coordination degree of F-W-E-C system in central and eastern cities ($\alpha_{1,central} = 0.0793$, $P_{central} < 0.01$; $\alpha_{1,east} = 0.0418$, $P_{east} < 0.1$), and the positive effect of central cities is greater than that of eastern cities.
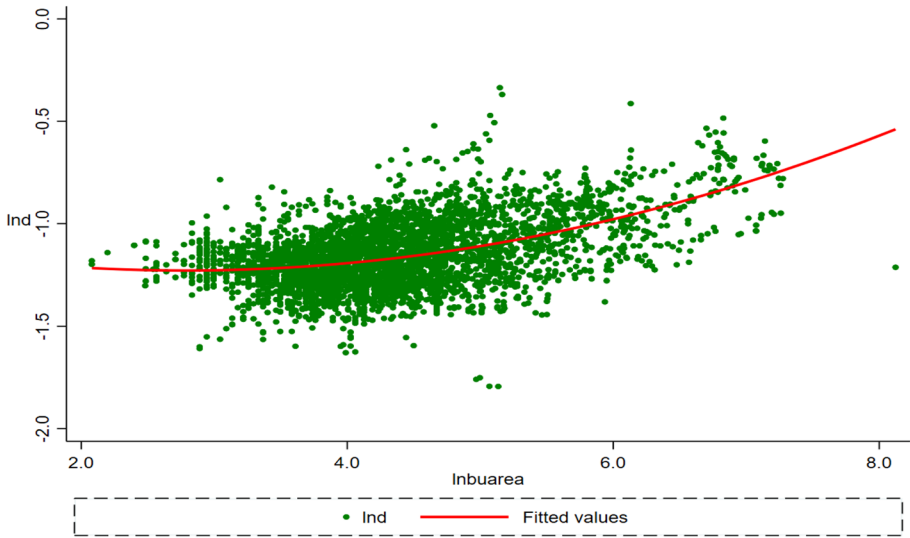
Fig. 8 Nonlinear impact of urbanization on the F-W-E-C nexus. *Notes*: **1**) *lnbuarea* is the natural logarithm of the urban area, representing the level of urbanization. **2** *lnd* is the natural logarithm of the coupling coordination degree, indicating the F-W-E-C nexus. See Supplementary Table 2 for nonlinear regression results and data
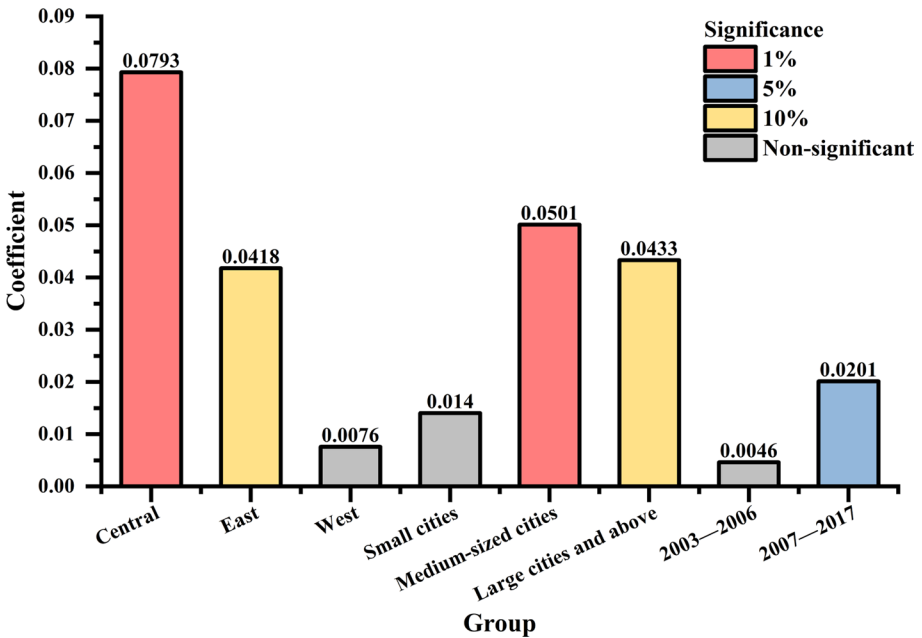

Fig. 9 The heterogeneous urbanization impact on the F-W-E-C nexus in different regions, city scales and periods. *Note*: A positive coefficient indicates enhanced synergies and a negative coefficient indicates enhanced trade-offs. See Supplementary Table 3 for detailed results and data
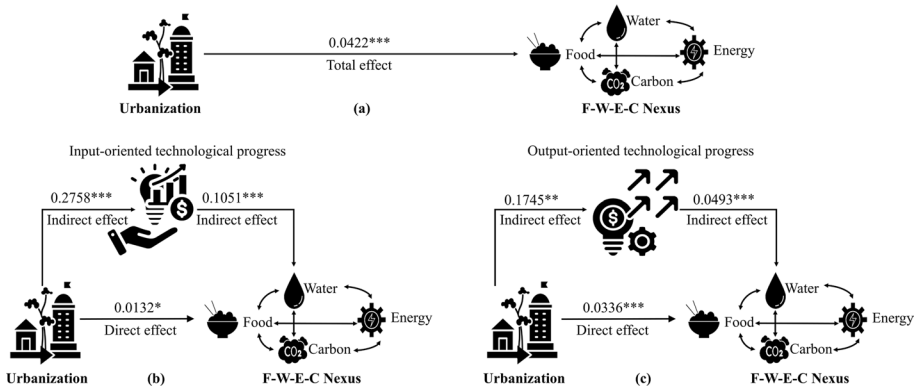
Fig. 10 Impact Pathways: technological progress channel. All icons are from The Noun Project (https://thenounproject.com). *Note*: **1a** is the total effect of the urbanization on the coordinated development of F-W-E-C system. **2a** and **b** are the test results of the path "urbanization—input-oriented technological progress—coordinated development of F-W-E-C system". **3a** and **c** are the test results of the path "urbanization—output-oriented technological progress—coordinated development of the F-W-E-C system". See Supplementary Table 4 for detailed results and data. **4** ***, **, * denote 1%, 5%, and 10% significance levels, respectively

However, the urbanization doesn't significantly impact the coupling coordination degree of F-W-E-C system in western China ($\alpha_{1,west} = 0.0076$, $P_{west} > 0.1$).

The urbanization of small cities has no significant positive impact on the coupling coordination degree of the F-W-E-C system ($\alpha_{1,small} = 0.0140$, $P_{small} > 0.1$). For medium-sized cities, large cities and above, the urbanization has a stronger positive effect on the coupling coordination degree of the F-W-E-C system than that in small cities ($\alpha_{1,medium} = 0.0501$, $P_{medium} < 0.01$; $\alpha_{1,l\arg e,and,above} = 0.0076$, $P_{l\arg e,and,above} > 0.1$).

Before 2007, there was a positive relationship between urbanization and the coupling coordination degree of the F-W-E-C system, but the positive impact of cities was not significance ($\alpha_{1,2003-2006} = 0.0046$, $P_{small} > 0.1$). Since 2007, the urbanization has significantly promoted the coupling coordination degree of the F-W-E-C system ($\alpha_{2007-2017} = 0.0201$, $P_{medium} < 0.05$).

4.5 The impact pathways of urbanization on the F-W-E-C *nexus*

The urbanization has stimulated the input-oriented and output-oriented technological progress, and the input-oriented and output-oriented technological progress have promoted the coordination degree of F-W-E-C system. Therefore, the input-oriented and output-oriented technological progress are important impact pathways for urbanization to affect the coordinated degree of F-W-E-C system (Fig. 10). The coefficient of ln *buarea* is positive in Fig. 10b, c indicating that the continuous progress of urbanization has indeed promoted local technological progress. Furthermore, the positive effect of urbanization on input-oriented technological progress is greater than that on output-oriented technological progress ($b_{1,(b)} > b_{1,(c)}$).

In Fig. 10b, c, the coefficient of ln *tech* and ln *totinvent* is significantly positive indicating that technological progress, especially the input-oriented technological progress, on the one hand, has driven the development of food production, reduced energy consumption and therefore decreased carbon emission intensity. On the other hand, it indirectly stimulates

the rise of energy consumption demand, leads to the increase in water demand and carbon emissions, and ultimately promotes the coordinated degree of F-W-E-C system. It further verifies that the positive effect of technological progress on the coordinated development of F-W-E-C system is greater than its inhibition effect.

In addition, in Fig. 10b, c, the coefficients of ln *buarea* are smaller than those of ln *buarea* in Fig. 9a (($c_{1,(b)} > a_{1,(a)}$); ($c_{1,(c)} > c_{1,(a)}$)), indicating that technological progress is a part of the intermediary factor of urbanization affecting the coordinated degree of F-W-E-C system. The intermediary effects of the input-oriented and output-oriented technology progress are 68.69% and 20.39%, respectively (($0.2758 \times 0.1051) \div 0.0422 \times 100\% = 68.69$ %; $(0.1745 \times 0.0493) \div 0.0422 \times 100\% = 20.39\%$).

5 Discussion

This study systematically evaluates the impact of urbanization on the F-W-E-C nexus and its pathways, and provides beneficial experiences for other countries around the world to better achieve sustainable urbanization. The results can implement better sustainable management of food production, water consumption, energy consumption and carbon emissions in the process of urbanization in China and the world, and promote the coordinated development of the F-W-E-C system. At the same time, it makes up for the deficiencies of the existing related research, which is lack of systematic analysis and quantitative analysis of the impact of urbanization on the F-W-E-C nexus and its pathways.

The relationship between F-W-E-C system is interacted. There is a steady upward trend in the growth level of the four subsystems. The F-W-E-C nexus is weak trade-off relationship (Figs. 2 and 3). Among them, energy consumption and carbon emissions grew rapidly, but food production and water consumption increased at a relatively moderate speed. Therefore, on the one hand, the energy consumption should be reduced, the industrial structure transformation may be promoted, and the carbon emission intensity needs to be lessened. On the other hand, the government should pay more attention to green food production and strictly stick to the red line of arable land (the amount of arable land shall not be less than 1.8 billion mu) to avoid a food crisis. Furthermore, due to an uneven distribution of water, the urban government needs to improve the water management measures, improve the water supply infrastructure, reduce water waste, and increase the efficiency of water use.

China's urbanization has promoted the synergy and coordinated development of F-W-E-C system. In China's urbanization, regional greenhouse gas emissions and environmental degradation mainly come from energy use in the process of production and consumption. This negative impact of urbanization also appears in Indonesia and some African countries (Prastiyo & Hardyastuti, 2020; Nathaniel & Adeleye, 2021). Globally, urbanization has also been regarded as an important driving factor for the rise in energy consumption and the sharp increase in carbon emissions (Wang et al., 2018). Extensive urbanization will not only affect energy consumption and carbon emissions, but also limit the development of food production and cause a water consumption crisis. These are just microcosms for the global urbanization. Therefore, with the continuous promotion of the global urbanization movement, we should be alert to the increasingly prominent negative accumulation effect and prevent the emergence of "urban diseases" such as high pollution, high energy consumption, and high emissions.

There are obvious regional differences in the impact of urbanization on F-W-E-C system in China. Therefore, it is important for urban governments to make plans, such as the construction of the regional spatial layout based on local situations. More specifically, the government should ensure the relationship between the four subsystems is reasonable as well as orderly, and then formulate relative policies (Zhang et al., 2018). Labor-intensive industries and energy-consuming industries are concentrated in some cities, such as Dong-guan and Shenzhen, which increase carbon emissions. These cities should adjust the economic development mode, reduce the dependence on labor-intensive industries and energy, constantly optimize the industrial structure, and promote the low consumption and low-carbon development. The economic development and urbanization level in northwest and northeast China are backward, the population loss is serious, and the heat in winter is insufficient and vulnerable to cold waves. Given the northwest, northeast, and backward areas of urbanization level, more policy support should be provided in the process of urban construction. Local urban construction need to be rationally planned. Urbanization space construction and population transfer maybe be actively guided. Regional element advantages should be fully utilized to explore the urbanization development path suitable for local characteristics. Some cities in the Shandong Peninsula, Jiangsu, Zhejiang, and other regions in the east China have relatively superior natural climate conditions, which are suitable for the development of food production. The port trade is developed, and the urbanization is in the acceleration stage. Industrialization is gradually changing to the middle and late stages. High-end manufacturing is gradually replacing traditional manufacturing, energy utilization efficiency is improved, and carbon emission intensity is reduced. Therefore, the coupling coordination degree of some cities in the Shandong Peninsula, Jiangsu, Zhejiang is stable in the transition harmonious section. Under the condition of good economic development, the coupling coordination of these cities are in a relatively reasonable range. These cities can take advantage of their geographical location to attract professional talents, make full use of capital and industrial advantages, and break through the bottleneck of economic development. The government should also pay more attention to the sustainable development of these cities and the quality of the ecological environment, to realize the coordinated development of the regional economy and ecological environment.

As an intermediate channel for urbanization to affect the coupling coordination of F-W-E-C system, technological progress should be given full attention to its regulatory role. This study only pays attention to the direct impact of urbanization on the coordination degree of F-W-E-C system, but ignore the indirect impact of urbanization on the coupling coordination degree of F-W-E-C system through technological progress channels. However, technological progress do not reduce the coupling coordination of F-W-E-C system as expected, but promoted the synchronous and coordinated development of F-W-E-C system (Fig. 10b, c). This shows that the energy rebound effect caused by technological progress promotes the coordination degree of F-W-E-C system (Liu et al.,). The positive effect of technological progress reflects that China still has the problems of insufficient investment intensity and weak innovation capacity. The local government needs to pay attention to the role of input-oriented technological progress and output-oriented technological progress, and constantly increase the input intensity and output capacity. In the future process of urban continuous development and construction, this study will make full use of technical means to regulate regional food production, water consumption, energy consumption, and carbon emissions, and promote the coordinated development of F-W-E-C system.

There are also two limitations in this study. First, this study take thes urbanization, food production, water consumption, energy consumption, and carbon emissions of China's prefecture-level cities as the research object. Based on the consideration of data

availability, the number of cities involved in the study is only 252, and the research period is 2003–2017. If the data of other prefecture-level and after 2017 can be obtained, a comprehensive study could be carried out on the Spatial–temporal coordination degree of the F-W-E-C system in recent years, as well as the impact of urbanization on the coordination degree of the F-W-E-C system. Secondly, when building the indicator system of food production, water consumption, energy consumption, and carbon emissions, the selected indicators are not comprehensive enough, which may bring some errors to the estimation results of the model.

6 Conclusions

Using the prefecture-level data from 2003 to 2017 of 252 cities in China as research objects, this study constructs a coupling coordination degree model to evaluate the Spatial–temporal coupling characteristics of F-W-E-C nexus. Then this study utilizes the panel data model and intermediary effect model to examine the impact of urbanization on the F-W-E-C nexus and reveal the impact pathways. This study gets the following conclusions.

First, the growth level of F-W-E-C nexus in the sample cities is in a steady upward trend, in which energy consumption and carbon emissions are growing rapidly, while food production and water consumption are growing relatively slowly. Benefiting from the continuous dividend release of the Reform and Opening Up policy, the urban economy and society have entered the stage of sustainable development, and the comprehensive level of the F-W-E-C nexus is in a steady upward trend. The continuous adjustment of industrial structure and rapid industrial development have led to the rapid growth of energy consumption and carbon emissions and relatively slow growth of food production. The effective management of water resources has resulted in a relatively slow increase in water consumption.

Second, the coupling coordination level of F-W-E-C system in China is low, and the F-W-E-C nexus is weak trade-off relationship. From the time dimension, the coupling coordination degree of F-W-E-C system in most cities is on the rise. From the perspective of spatial pattern, the coupling coordination degree of southern cities is higher than that of northern cities. As of 2017, the cities in the coordination stage include Wuhu, Shaoguan, Shenzhen, Zhongshan, Guangzhou, Zhuhai, Hefei, and Shanghai.

Third, the urbanization promotes the synergy relationship of F-W-E-C nexus. Due to different regions, city scales, and periods, urbanization has different impacts on the F-W-E-C nexus. Among them, the positive effect of urbanization on the coordinated development of F-W-E-C system is more obvious in central and eastern cities, and the positive effect of central cities is greater than that of eastern cities. While the positive effect of western cities is not obvious. The positive effect of urbanization on the coordinated development of the medium-sized cities is significantly higher than that of small cities, big cities, and cities above. As time passed, the positive effect of urbanization on the coordinated development of the F-W-E-C system is becoming more and more obvious.

Fourth, technological progress is an important intermediate channel for urbanization to affect the F-W-E-C nexus. Urbanization can significantly promote technological progress, especially input-oriented technological progress. Technological progress has indirectly driven the demand for energy consumption growth, and aggravated the consumption of water resources and carbon emissions. Thanks to technological progress, food production

has developed rapidly, ultimately promoting the coordinated development of F-W-E-C system.

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Authors and Affiliations

Chenggang Li[1,2] · Yong Liu[1] · Zhenci Xu[3,4] · Gang Zhao[1] · Youhui Bao[1] · Chengcheng Cai[5] · Yu Lu[6] · Yufeng Mao[1] · Alexander Boxuan Wang[7] · Liang Wu[8]

✉ Zhenci Xu
  xuzhenci@hku.hk

1   School of Big Data Application and Economics, Guizhou University of Finance and Economics, Guiyang 550025, China

2   Guizhou Key Laboratory of Big Data Statistical Analysis, Guizhou University of Finance and Economics, Guiyang 550025, Guizhou, People's Republic of China

3   Department of Geography, The University of Hong Kong, Hong Kong 999077, People's Republic of China

4   HKU Shenzhen Institute of Research and Innovation, Nanshan District, Shenzhen 518057, People's Republic of China

5   School of Critical Studies, University of Glasgow, Glasgow G12 8QQ, Scotland, UK

6   School of Foreign Languages, Guizhou University of Finance and Economics, Guiyang 550025, China

7   High School, Shanghai American School Pudong Campus, Shanghai 201201, People's Republic of China

8   School of Economics and Management, Guizhou Normal University, Guiyang 550025, People's Republic of China