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Original Research

Regional Pattern and Coupling Analysis of Water-Energy Natural Capital Utilization in Urban Agglomerations

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Abstract

In this study, two revised indicators, the size and depth of ecological footprint, as the basis for accounting for flow capital occupation and stock capital depletion of water-energy resources, respectively, were selected to evaluate water resource capital utilization (WRCU) and energy capital utilization (ECU) in the Four-City Area in Central China (FcACC) from 2010 to 2020. The coupling coordinated relationship between WRCU and ECU in the FcACC was discussed by using the coupling coordination degree (CCD) model. The results showed that WRCU and ECU of 37 regions were divided into four types, and the intercity pattern had obvious regional agglomeration. The utilization level of stock capital and flow capital generally presented a complementary situation in the FcACC. Slight depletion types of stock capital were the main type of regional WRCU and ECU in the FcACC. The *D* value of the WRCU and ECU in the FcACC overall showed a downward trend, and the basic coordination (BC) between water resource flow capital occupation (WFCO) and EFCO was the main coordination status. Furthermore, the coordination status and capital utilization level of each region changed over time.

Keywords: natural capital flow vs. stock, ecological footprint size vs. depth, coupling coordination degree model, Four-City Area in Central China

Introduction

Water resources and energy resources are two important natural resources necessary for human activities and socio-economic development, which are crucial to the sustainability of China's economic growth. China is now the world's largest energy consumer [1] and the world's second largest water intake country [2]. As a result, China's water and energy use has had a significant impact on the sustainable development related to the global environment. Therefore, China urgently needs to formulate differentiated policies to properly manage the relationship between energy and water resources according to production activities and consumption patterns.

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The term "natural capital" refers to natural resources and the environment surrounding and supporting human life [3]. It is defined as the natural benefits and storage of natural resources that provide a range of products or services, including flow capital and stock capital [4]. Flow capital refers to the interannual supply of renewable resource flows and their ecological services, while stock capital refers to the accumulated reserve of nonrenewable resource flows, which can only be depleted when flow capital is insufficient [4]. Since Georgescu-Roegen introduced the stock-flow model into the bioeconomic paradigm [5], the concept of natural capital has become increasingly important in the field of human centered ecological economy and sustainability [3, 6-7]. Natural capital utilization is an important topic for ecologically sustainable quantification, while research on the flow and stock of natural capital is helpful to analyze the use of natural capital and promote its sustainable development. The ecological footprint (EF) method provides a feasible way to measure the human occupation of natural capital and is regarded as the most important progress in the quantitative field of sustainable development in recent decades. In particular, Niccolucci et al. introduced the perspective of "stock and flow" into the EF and proposed a three-dimensional ecological footprint (3DEF) model, which can identify the importance of natural capital stock and flow [8-9]. However, ecological capital flow cannot be calculated clearly in the 3DEF model, and the offset of ecological deficit and surplus of different land types affects the accuracy of the results. Subsequently, Fang [10-12], Fang and Reinout [13] and Fang et al. [14] optimized and improved the 3DEF model, and conducted a large number of empirical studies, which later confirmed the improved 3DEF model can more accurately reflect the utilization of natural capital in the region.

In recent years, the improved 3DEF (i3DEF) models has been highly recognized and widely used in natural capital utilization accounting and ecological sustainability assessment [15-21]. Coupling is the principle that describes the mutual motion mechanism between two or more systems, while coordination refers to the relationship between subsystems in coordinated operation. Coupling coordination degree (CCD) model depicts the degree of interaction, coordination and mutual promotion among subsystems and reflects the dynamic correlation trend of each subsystem from disorder to order, which has been widely applied in interrelationship assessments, for example, urbanization and ecological environment [22-23], urbanization and green development [24], economy–society–environment [25], urbanization and habitat quality [26], urbanization and ecosystem service value [27-28], ecosystem services and urban development [29], and new urbanization and carbon emissions [30]. Coupling theory is a proven effective approach for exploring the relationship between two or more systems that interact with each other.

Four-City Area in Central China (FcACC) (Fig. 1), also known as the urban agglomerations of the midstream Yangtze River, are not only the key strategic area in the central region, but also play an important role in China's regional development pattern. However, under the influence of the rapid development of urbanization and industrialization, FcACC faces many problems, including excessive resource consumption [31], CO_2 emissions [32-33], and ecosystem health [34], while maintaining stable economic growth and prioritizing ecological protection. Whereas, water resources and energy are fundamental components of our lives in the 21st century, almost inseparable. Recently, the water energy relationship [35-38] and its conceptual expansion [39-40] have attracted the attention of policymakers and researchers, because water and energy are two primary sources of life, the environment and the economy. However, a new perspective based on the EF model to integrate the stock and flow dimensions of natural capital remains to be explored. Ulucak and Lin [41] pointed out that the EF is an important consideration in the implementation of global and local policies, and analyzing the composition and variation of the EF in different subitems will help to explore reasonable natural resource consumption patterns and natural ecosystem protection methods [42]. In view of the above considerations and our previous works [43], the study applied i3DEF model to explain the natural capital utilization of the FcACC in relation to water resources and energy. By measuring the footprint size and footprint depth by each component from 2010 to 2020, the spatiotemporal patterns of flow capital occupation and stock capital depletion in the FcACC were delineated at intercity levels. In addition, this research explored coupling interactions between water resources and energy capital utilization in the FcACC using the CCD model. The highlights of this study are mainly: (1) the i3DEF model based on *NPP* is used for energy natural capital. (2) the use of water and energy as FcACC's main natural capital was investigated. (3) the regional pattern of water-energy resources capital utilization was analyzed. (4) the coupling coordination relation between *WRCU* and *ECU* in FcACC was explored. The results can provide a decision-making reference for the efficient allocation and rational utilization of intercity natural resources, industrial structure adjustment and sustainable development of urban agglomerations in China, and for governments and private sectors who will play an important role in mitigating and adapting to the future challenges of water and energy supply.

Material and Methods

A schematic diagram of *i3DEF* model is shown in Fig. 2. The combination of water ecological footprint (*WEF*) and energy ecological footprint (*EEF*) aims

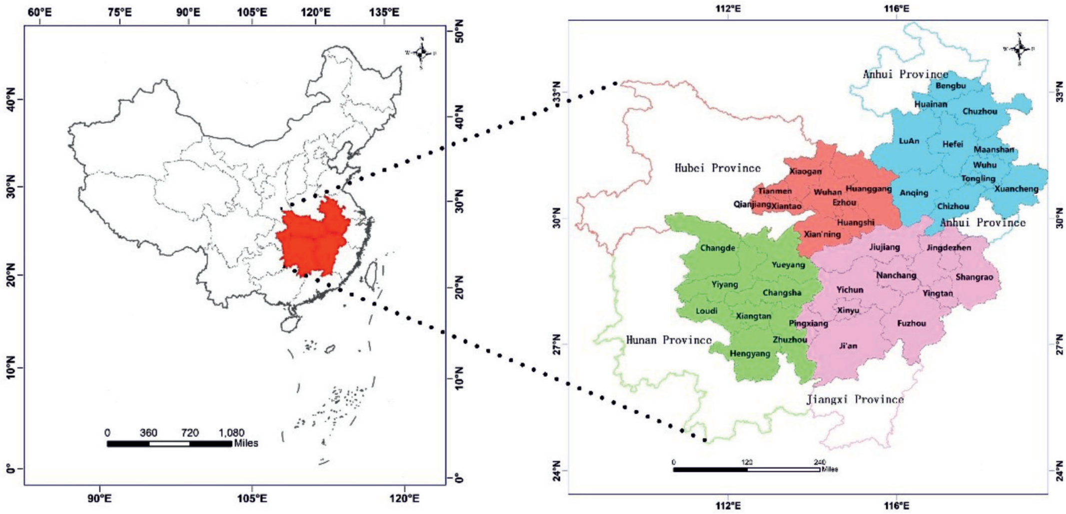

Fig. 1. Location of the Four-City Area in Central China and their contained regions.

to capture the structural and characteristic dynamics of natural capital flows and stocks. This is achieved by providing a two-dimensional footprint account with the third dimension (footprint depth), which conveyed the intensity of inventory depletion and footprint size, which means that humans occupy the annual flow on the x-y plane. In particular, the calculation of the footprint depth differed from the method previously developed by Niccolucci et al. [8-9], as explained below.

WEF model

The *WEF* model and its ecological footprint size/depth analysis was performed as our previously described [43].

EEF and EECC Model Based on Global NPP

EEF Based on Global NPP

EEF based on global net primary production (*NPP*) is defined as the area of various land and water bodies

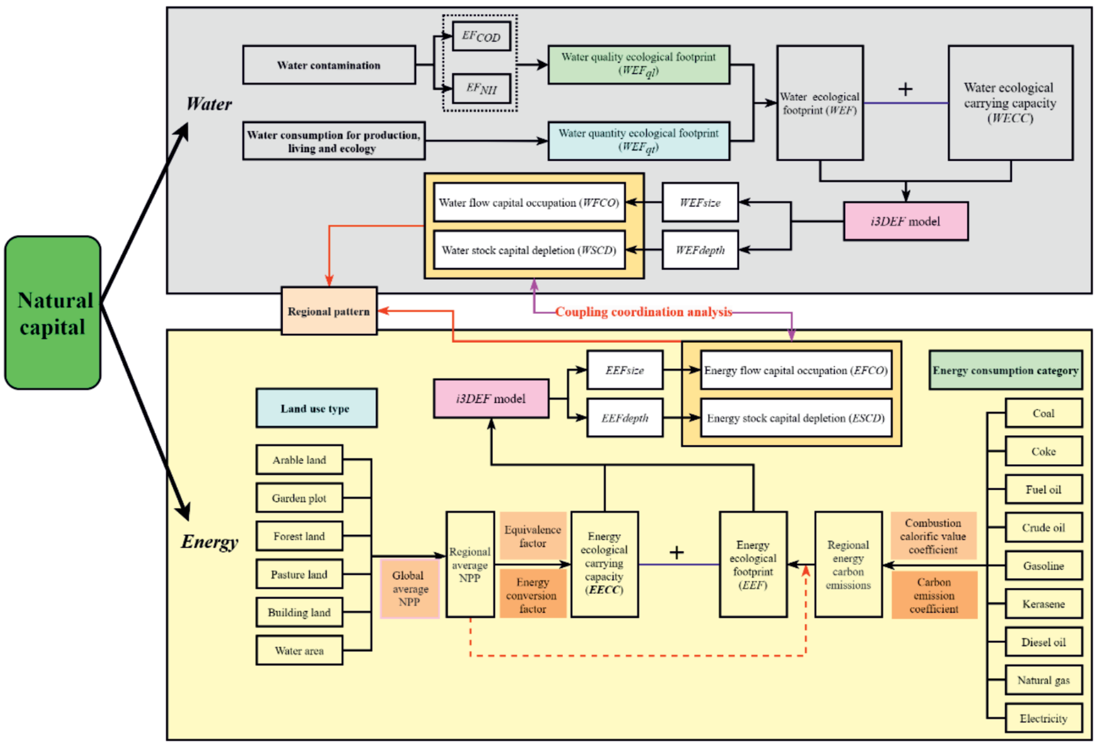

Fig. 2. Schematic of the improved 3DEF model integrating the EEF and the WEF.

required to absorb the amount of carbon emitted in the process of energy consumption under the condition of global surface average net primary production [44]. In this study, according to various bioproductive land areas and the *NPP* of corresponding land ecosystems in the region, the carbon absorption weights of different land ecosystems are calculated, and the regional *NPP* is obtained. The specific method is as follows: the *NPP* of a certain region is the ratio of regional total *NPP* to total land area of the region, and the ratio of the *NPP* of each land ecosystem in a certain period is equal to the ratio of the product of respective *NPP* and the corresponding land area. According to this relation, the calculation formula of regional *NPP* can be expressed as [44-45]:

$$\overline{NPP} = \frac{\sum_{j=1}^{m} A_j \times NPP_j}{\sum_{j=1}^{m} A_j} \tag{5}$$

where represents the regional average *NPP* (t C/hm²·a); NPP_j is the *NPP* of the *j* class bioproductive land ecosystem (t C/hm²·a), A_j is the *j* class bioproductive land area (hm²); and *m* is the number of bioproductive land types. To facilitate international comparison, the global average value of *NPP* [46] for various bioproductive land ecosystems was used for calculation in this study (Table 1). Since land use change always exists, regional *NPP* is a dynamic variable.

Energy consumption is converted into calorific values through the combustion calorific value coefficient, and then CO_2 emissions are calculated according to the corresponding carbon emission coefficients. The land area required to absorb this CO_2 is calculated according to regional NPP, that is, the regional energy ecological footprint is obtained. The improved energy ecological footprint calculation model [47] is as follows:

$$EEF = \frac{\sum_{i=1}^{n} Q_i \times cv_i \times ce_i}{\overline{NPP}} \tag{6}$$

where *EEF* represents the regional energy ecological footprint (hm²); Q_i is the total energy consumption of category *I* (t), and *i* is the energy category; n is the number of energy categories; cv_i is the combustion calorific value coefficient for category *i* (GJ/t); and ce_i is the carbon emission coefficient for category *i* (t C/GJ). Therefore, cv_i and ce_i are taken from IPCC reports [48] (Table 2).

EECC Model Based on Global NPP

The calculation of energy ecological carrying capacity (*EECC*) based on global *NPP* is based on the idea of carbon absorption transformation, adding land types for carbon absorption, and calculating the upper limit of land area that can be provided by the region for carbon absorption [46]. In this study, different bioproductive land areas are converted into land areas with global average NPP through the equivalence factor (r_i) and energy conversion factor (*ef*), and the calculation model [46] is as follows:

$$EECC = N \times eecc = ef \times \sum_{i=1}^{m} A_j \times r_j, \quad ef = \frac{\overline{NPP}}{NPP_{Glo}} \tag{7}$$

where *EECC* represents energy ecological carrying capacity (hm²); *N* is the population; *eecc* represents energy ecological carrying capacity per capita (hm²/cap); r_j is the equivalence factor of the *j* class bioproductive land (Table 1); and NPP_{Glo} is global net primary production (Table 1).

Table 1. Global average net primary production (*NPP*) and equivalence factor of different bioproductive.

Land use type	*NPP* (t C/hm²·a)	Equivalence factor
Arable land	4.243	2.121
Garden plot	5.415	2.708
Forestland	6.583	3.292
Pasture land	4.835	2.418
Building land	0.997	0.498
Water area	5.344	2.672
Global	2.000	-

Table 2 Energy ecological footprint calculation parameters.

Category	*cv*(GJ/t)	*ce*(tC/(GJ)
Coal	20.91	0.0272
Coke	28.00	0.0258
Fuel oil	40.19	0.0211
Crude oil	41.82	0.0200
Gasoline	44.80	0.0189
Kerosene	44.75	0.0196
Diesel oil	43.33	0.0202
Natural gas	29.27	0.0161
Electricity*	36.00†	0.2330‡

Note: * There are no power calculation parameters in the IPCC report. † represents data derived from China's electrical energy conversion coefficient, unit: GJ/10^4 kwh [49]. ‡ represents data derived from the China power carbon emission coefficient in the International Energy Agency Database, unit: tC/GJ [50].

EEF Size/Depth

Ecological footprint size refers to the interannual occupied area of bioproductive land within the limits of biocapacity, which is used to represent the occupancy levels of human society development to natural flow capital [10, 12], and its calculation formula is as follows:

$$EEF_{size} = \min\left(EEF, EECC\right) \tag{8}$$

where EEF_{size} are the regional energy ecological footprint size (hm^2).

Ecological footprint depth refers to how many times the existing land area is needed to regenerate the resource amount of regional real consumption, which is used to represent the depletion extent of humans to natural stock capital [10], and its calculation formula is as follows:

$$EEF_{depth} = 1 + \frac{\max\left\{\left(EEF - EECC\right), 0\right\}}{EECC} \tag{9}$$

where EEF_{depth} are the regional regional energy ecological footprint depth (dimensionless), and its physical meaning is as follows: 1) when $EEF \le EECC$, $EEF_{depth} = 1$, indicating that human beings only need to occupy flow capital to meet the needs of their own development; and 2) when $EEF > EECC$, $EEF_{depth} > 1$, indicating that the capital flows have been unable to meet the needs of human beings, and the stock capital begins to be consumed. The greater the EEF_{depth} values are, the more depletion of stock capital and the more unsustainable development will be.

CCD Model

Due to the large difference in the dimensions of the data obtained, they cannot be directly used as the final values of the model for calculation and comparative analysis. Therefore, the range method is used for the dimensionless processing of normal standardized data. Considering that the data after standardization may be 0, the following translation processing is required [51]:

$$x'_{ij} = \left[\frac{x_{ij} - x_{\min}}{x_{\max} - x_{\min}}\right] \times 0.99 + 0.01 \tag{10}$$

where x'_{iij} represents the value of footprint size (or footprint depth) j in year *i*, and x_{max} and x_{min} indicate the maximum and minimum values of footprint size (or footprint depth) j among all years.

Water resources and energy are central to concerns over the sustainability of China's economic growth. Therefore, the coupling degree model of water resource capital utilization (*WRCU*) and energy capital utilization (*ECU*) is constructed in this study, and the type of coupling coordination development is divided. The coupling coordination degree model (CCDM) is expressed by the following formulas [52]:

$$C = \sqrt{\frac{Uw \times Ue}{\left[\alpha Uw + \beta Ue\right]^2}} \qquad D = \sqrt{C \times \left(\alpha Uw + \beta Ue\right)} \tag{11}$$

where *C* is the coupling degree between *WRCU* and *ECU* and *D* is the coupling coordination degree between *WRCU* and *ECU*. *Uw* and *Ue* represent *WRCU* and *ECU*, respectively, calculated by x'_{ij} described in Formula

Table 3. Coupling coordinated development classification standards of water resource capital utilization and energy resource capital utilization.

D	Coupling stage	Coordination status	Capital utilization level
$0 < D \le 0.3$	Low coupling	Seriously uncoordinated	$Uw - Ue > 0.1$, energy capital utilization lag
			$Ue - Uw > 0.1$, water capital utilization lag
			$-0.1 < Uw - Ue \le 0.1$, coordinated utilization
$0.3 < D \le 0.5$	Antagonistic stage	Basic incoordination	$Uw - Ue > 0.1$, energy capital utilization lag
			$Ue - Uw > 0.1$, water capital utilization lag
			$-0.1 < Uw - Ue \le 0.1$, coordinated utilization
$0.5 < D \le 0.8$	Running-in stage	Basic coordination	$Uw - Ue > 0.1$, energy capital utilization lag
			$Ue - Uw > 0.1$, water capital utilization lag
			$-0.1 < Uw - Ue \le 0.1$, coordinated utilization
$0.8 < D \le 1.0$	High coupling	Good coordination	$Uw - Ue > 0.1$, energy capital utilization lag
			$Ue - Uw > 0.1$, water capital utilization lag
			$-0.1 < Uw - Ue \le 0.1$, coordinated utilization

(10). α and β are the contributions of *WRCU* and *ECU,* respectively, and $\alpha = \beta = 0.5$ [52]. On the basis of the coupling coordination *D* and *WRCU Uw a*nd *ECU Ue,* the classification of the coupling coordination types is used as a reference [52-53]. The coupling types of *WRCU* and *ECU* are divided into ten stages (Table 3).

Data Sources

Based on data availability and authority, water resource use data were derived from the Water Resources Bulletin (2011-2021) of each province and the Statistical Yearbook, Statistical Bulletin on National Economic and Social Development and Statistical Bulletin of the Environmental Situation of 37 cities in the Four-City Area in Central China (2011-2021). Data on land use types (including arable land, garden plots, forestland, pasture land, building land, and water areas) and energy consumption data (including nine categories: coal, coke, fuel oil, crude oil, gasoline, kerosene, diesel oil, natural gas, and electricity) comes from the China City Statistical Yearbook, China Energy Statistical Yearbook and the Statistical Yearbooks (2011-2021) of Hubei Province, Hunan Province, Jiangxi Province and Anhui Province. The missing data were supplemented according to the environmental protection planning of provinces and prefecture-level cities.

Results and Discussion

Regional Pattern of WRCU and ECU

In this study, footprint size and footprint depth were standardized to explore the relationship between footprint size and footprint depth by the quadrant method [54], then according to the quadrant map and its division method, the WRCU and ECU of 37 cities in the FcACC are divided into four types from 2010 to 2020, and the spatial pattern of flow capital occupation and stock capital depletion is obtained (Fig. 3). The details are as follows:

I: Types of severe depletion of stock capital*,* which are characterized by a high footprint depth and a small footprint size, low occupancy of local flow capital and high level of stock capital depletion; for WRCU, Hefei, Huainan, Bengbu, Ma'anshan, and Chuzhou in 2010 and 2015 and Bengbu in 2020 are included. For ECU, Wuhan and Qianjiang in 2010, Wuhan, Hefei and Wuhu in 2015, and Wuhan, Hefei, Wuhu and Huainan in 2020 are included. Such regions have high population density, low flow capital makes it difficult to maintain sustainable development, and local capital stock depletion is serious. During the study period, the average WEF_{size} of this type was only 0.42-1.06 hm^2/cap and 2.91-7.33 for WEF_{depth} and only 0.39-0.66 hm^2/cap for EEF_{size} and 1.86-4.19 for EEF_{depth}.

II: Types of moderate depletion of stock capital*,* which are characterized by a higher footprint depth and a larger footprint size, higher local flow capital occupancy and slightly higher stock capital depletion. These types included Ezhou and Tongling in 2015 for the WRCU. For ECU, these types included Huangshi, Ezhou, Wuhu, Huainan, Ma'anshan, and Tongling in 2010; Huangshi, Ezhou, Qianjiang, Huainan, Ma'anshan, and Tongling in 2015; and Huangshi, Ezhou, Qianjiang, Ma'anshan, and Tongling in 2020. These regions have limited available resources, relatively high flows of capital per capita and serious local capital stock depletion. During the study period, the average WEF_{size} of this type was only 1.55-1.80 hm^2/cap and 1.74-1.88 for WEF_{depth} and only 0.52-0.87 hm^2/cap for EEF_{size} and 1.58-4.23 for EEF_{depth}.

III: Types of slight depletion of stock capital*,* which are characterized by a small footprint depth and footprint size and relatively low stock capital depletion. For WRCU, there were 11 regions, including Wuhan, Huangshi, Xiaogan, etc., in 2010; 14 regions, including Wuhan, Xiaogan, Huanggang, etc., in 2015; and 21 regions, including Wuhan, Huangshi, Xiaogan, etc., in 2020. For ECU, there were 23 regions, including Xiaogan, Huanggang, Xianning, etc., in 2010; 18 regions, including Huanggang, Xianning, Xiantao, etc., in 2015; and 15 regions, including Huanggang, Xianning, Xiantao, etc., in 2020.

IV: Relative lag type of stock capital, which is characterized by more flow capital occupancy and relatively less stock capital depletion, and the level of stock capital depletion lags behind flow capital occupation. For WRCU, there were 21 regions, including Ezhou, Xianning, Xiantao, etc., in 2010; 16 regions, including Huangshi, Xiantao, Qianjiang, etc., in 2015; and 15 regions, including Ezhou, Xiantao, Qianjiang, etc., in 2020. For ECU, there were 6 regions, including Xiangtan, Yueyang, Pingxiang, Xinyu, Yingtan, and Hefei in 2010; 10 regions, including Xiaogan, Xiangtan, Yueyang, etc., in 2015; and 13 regions, including Xiaogan, Xiangtan, Yueyang, etc., in 2020. However, the lag of stock capital depletion in this type is relative to its high level of flow capital occupation. In fact, once the stock capital declines, the sustainability of regional natural capital utilization is weakened.

As shown in Fig. 3, (1) during the study period, natural capital utilization in some regions changed. For example, for WRCU, Ezhou and Tongling were converted from type II in 2015 to type IV in 2020; for ECU, Wuhu was converted from type II to type I in 2010, which continued to 2020; Tongling changed from type II in 2010 and 2015 to type I in 2020. (2) The spatial pattern of the natural capital utilization type had obvious regional agglomeration. For example, type I was mainly concentrated in the regions with high socioeconomic development levels and high local production footprint pressure. Type II and III were mainly concentrated in the regions with relatively underdeveloped technological development and low per capita resource ownership due to the dense population. Type IV was mainly concentrated in regions with low population density, low levels of economic development

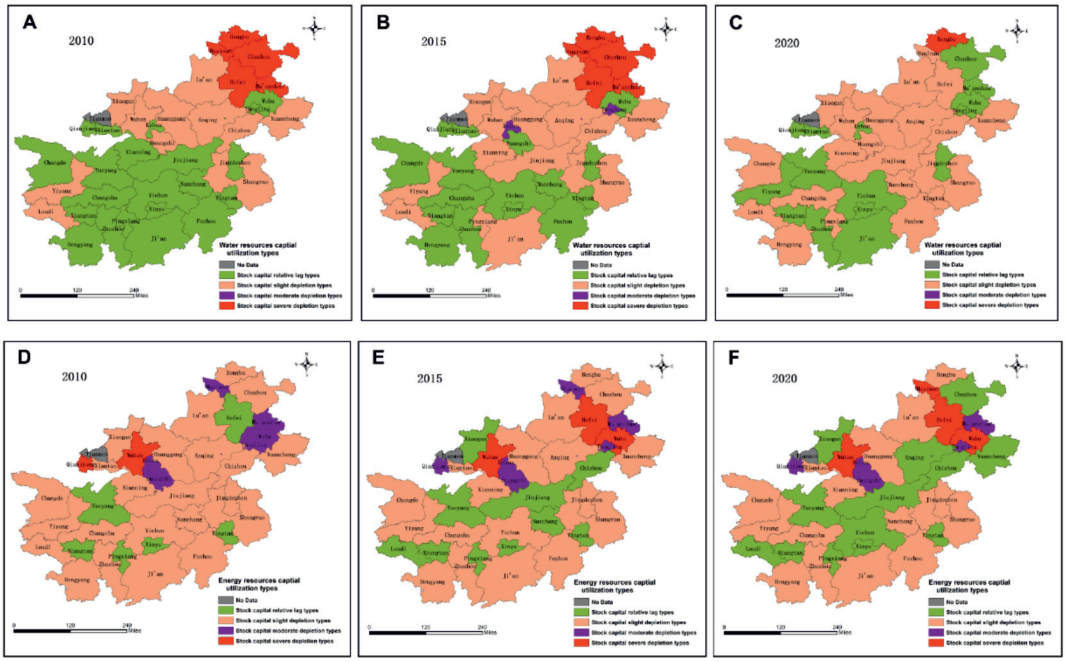

Fig. 3. Spatial pattern of flow capital occupation and stock capital depletion for water resources and energy in the Four-City Area in Central China in 2010, 2015 and 2020.

and rich forest and water resources. (3) The utilization level of stock capital and flow capital generally presented a complementary situation. In general, stock capital depletion is greatly affected by human factors, while flow capital occupation is mainly affected by natural factors. (4) Slight depletion types and stock capital relative lag types were the main types of regional WRCU in the FcACC. For example, in 2010 and 2020, there were 21 regions with stock capital relative lag types and stock capital slight depletion types, accounting for 56.76% of 37 regions in the FcACC. Slight depletion types of stock capital were the main type of regional ECU in the FcACC. For example, there were 23 regions with slight depletion of stock capital, 18 regions in 2015, and 15 regions in 2020, accounting for 62.16%, 48.65%, and 40.54% of 37 regions in the FcACC, respectively.

Coupling Relationship between WRCU and ECU

Coupling and Coordination Relationship of Flow Capital Occupation

The disorder between water resource flow capital occupation (WFCO) and energy flow capital occupation (EFCO) will eventually lead to an imbalance in regional natural capital utilization. Combined with Table 3, Xinyu had the highest *D* value (>0.8), while Huanggang had the lowest (<0.42) in 2020 (Fig. 4). Furthermore, the *D* values of WFCO and EFCO overall showed a slight downward trend from 2010 to 2020 except in Xiaogan, Qianjiang, Yueyang, Yiyang, Yichun, Huainan, Ma'anshan, Anqing, Chuzhou, Chizhou and Xuancheng. However, except for Hunan and Hubei, Huanggang, Shangrao, Hefei, Bengbu and Lu'an, the annual mean *D* values of WFCO and EFCO in the other regions were greater than 0.5, implying that the regional flow capital utilization in most regions of the FcACC was still in the running-in stage. These results reflected that the regional difference and time trend of WFCO and EFCO are highly consistent with the characteristics of the coupling coordination degree. The effective way to improve the level of coupling coordination development of some regions should mainly focus on WFCO and EFCO. This result is consistent with the findings of Luo et al. [25] in the Yangtze River Delta urban agglomeration.

Fig. 5 shows the coupling coordination relationship between WFCO and EFCO for 37 regions of the FcACC in 2010, 2015, and 2020, which clearly reflects the coordination status and capital utilization level of each region. As shown in Fig. 5, during the study period, the number of regions with basic uncoordinated and good coordination status in the FcACC decreased, while the number of regions with basic coordination (BC) status increased, and the BC status was the main coordination status. The BC status chain is mainly shaped by the levels of WfL, EfL and Wf-EfC, accounting for more than 70% of the coordination status. In 2010, there were 27 BC regions, of which EfL contributed 22 regions (81.5%), followed by Wf-EfC at 14.8% and WfL at only 3.7%. In 2015, there were 29 BC regions, of which EfL contributed 23 regions (79.3%), followed by Wf-EfC at 20.7%. In 2020, there were 30 BC regions, of which EfL contributed 20 regions (66.7%), followed by Wf-EfC at 30% and WfL at only 3.3%. This underscored

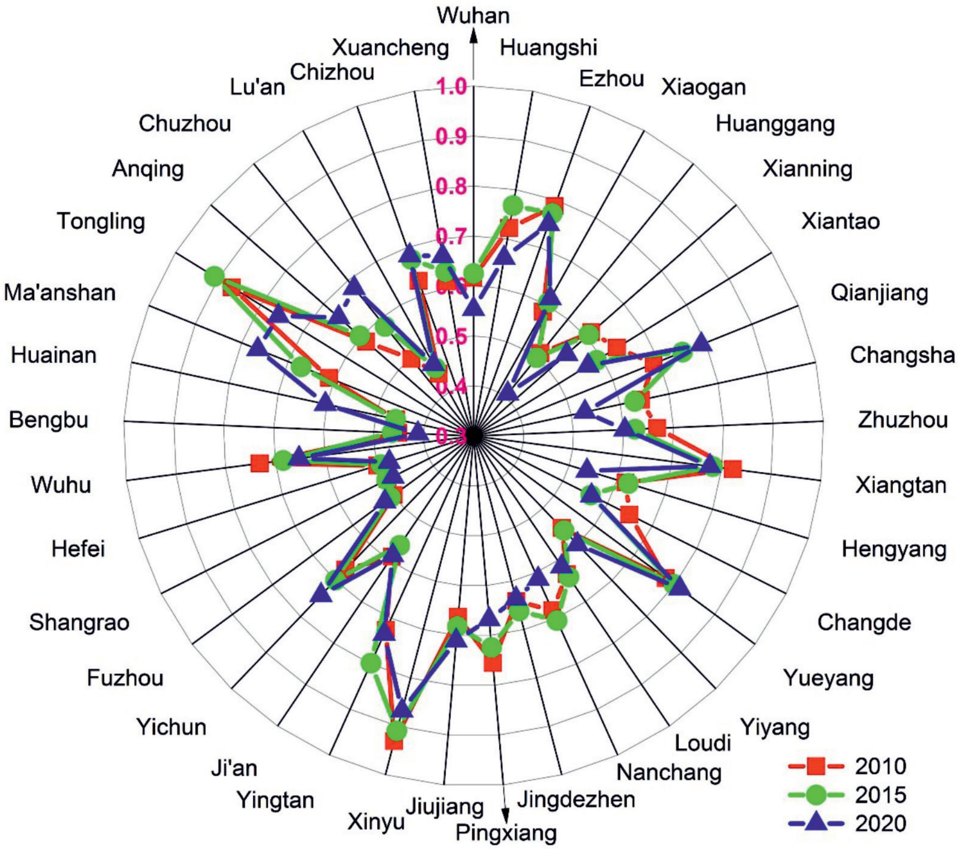

Fig. 4. Coupling coordination degree (*D*) of water resource flow capital occupation and energy flow capital occupation for each region in 2010, 2015 and 2020.

the large impacts of EfL among the basic coordination regions; although the contribution of Wf-EfC increased, its effect on the basic coordination status chain was still small.

Fig. 5 shows that the coupling coordination status in each region changed from 2010 to 2020. For example, Huainan gradually transferred from the stage of "basic uncoordinated and water resource flow capital occupation lag" in 2010 to the stage of "basic coordination and energy resource flow capital occupation lag" in 2020 at the end of the study period. Huanggang gradually transitioned from the stage of "basic coordination and energy resource flow capital occupation lag" in 2010 to the stage of "basic uncoordinated and energy resource flow capital occupation lag" in 2020. This transformation may be caused by multiple geographical environments, historical, resource background and other factors. This finding is similar to those of Fu et al. [52] and Ye et al. [55]. However, from the perspective of the flow capital occupation level, improving the level of EFCO is necessary, despite the presence of a basic coupling coordination relationship between WFCO and EFCO. Chen et al. [56] also pointed out that the high resource–environment pressure in the urban agglomerations of the midstream Yangtze River was mostly from the pressure of carbon emissions, while the massive exploitation and inefficient utilization of energy resources increased the carbon footprint and CO_2 emissions [57].

Coupling and Coordination Relationship of Stock Capital Depletion

As shown in Fig. 6, the *D* value of water resource stock capital depletion (WSCD) and energy stock capital depletion (ESCD) overall showed a downward trend in most regions for the surveyed period. The average *D* value of Huainan was the highest (0.86), the average *D* values of Ma'anshang, Wuhan, Ezhou, Tongling, Heifei and Qianjing were in the range of 0.51 and 0.8, and the average *D* values of the other 30 regions were in the range of 0.32 to 0.5. These results implied that the regional stock capital depletion in most regions of the FcACC was in the antagonistic stage. This is mainly due to the different economic development levels and technology levels in each region. Yang et al. showed the imbalance between economic development and natural capital occupation in the urban agglomerations of the midstream Yangtze River [58].

Fig. 7 shows the coupling coordination relationship between WSCD and ESCD for 37 regions of the FcACC in 2010, 2015, and 2020, which clearly reflects the coordination status and capital utilization level of each region. As shown in Fig. 7, during the study

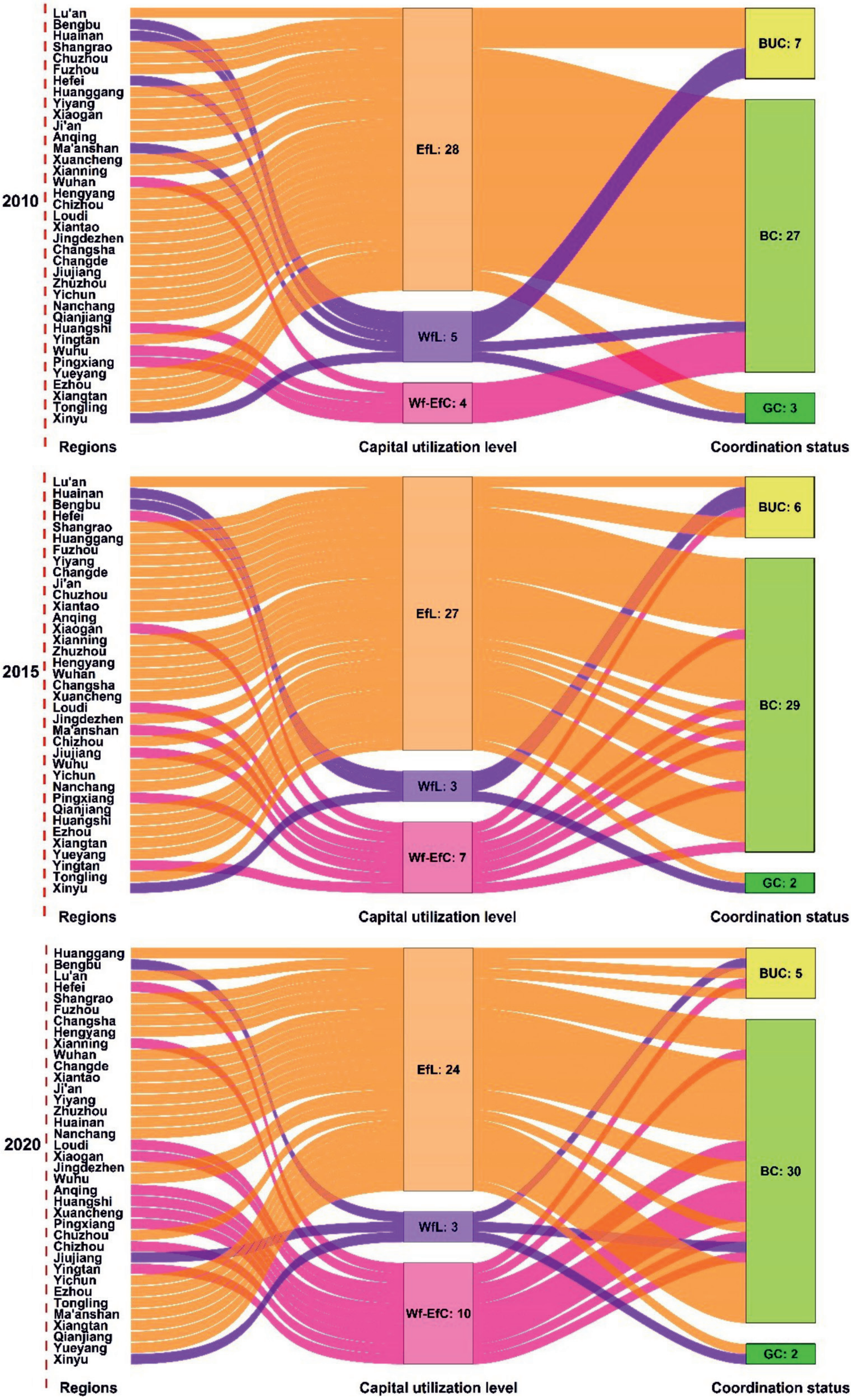

Fig. 5. Coupling coordination relationship between water resource flow capital occupation and energy flow capital occupation in 2010, 2015 and 2020. Note: WfL, EfL, and Wf-EfC represent water resource flow capital occupation lag, energy flow capital occupation lag, and coordinated development of water resources and energy flow capital occupation, respectively. BUC, BC, and GC represent basic incoordination, basic coordination, and good coordination, respectively. The numbers represent the total number of regions.

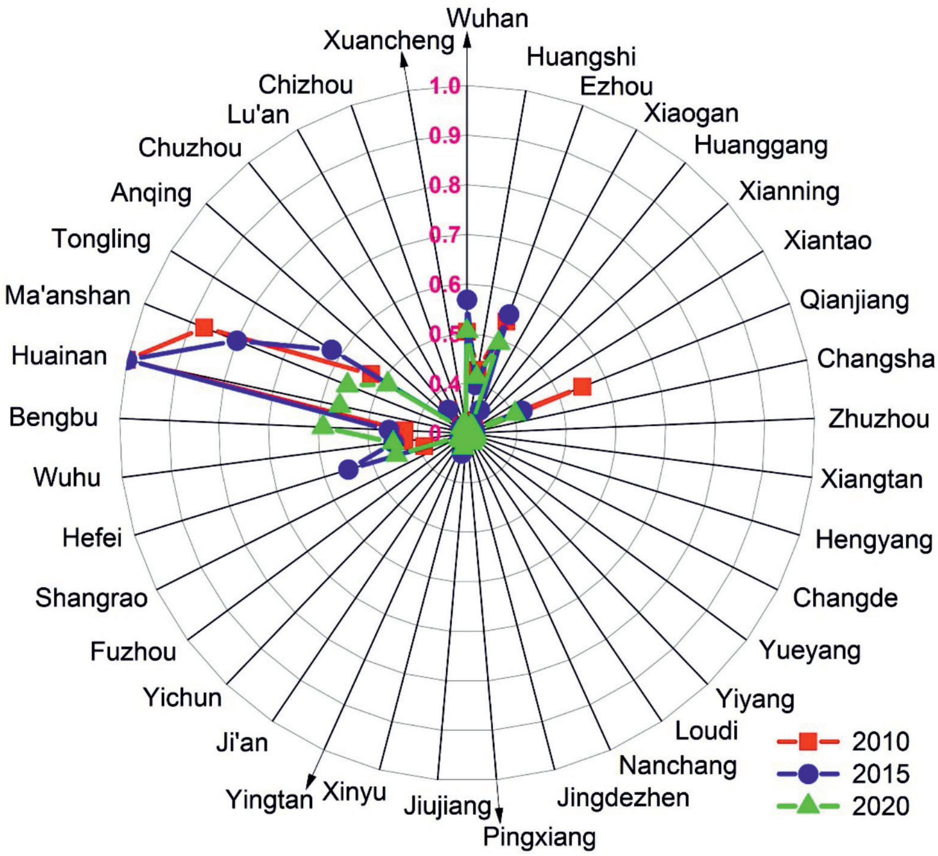

Fig. 6. Coupling coordination degree (D) of water resource stock capital depletion and energy stock capital depletion for each region in 2010, 2015 and 2020.

period, the number of regions with good coordination status in the FcACC decreased, while the number of regions with basic incoordination (BUC) status first decreased and then increased, and the BUC status was the main coordination status. The BUC status chain is mainly shaped by the levels of WsL, EsL, and Ws-EsC, accounting for more than 83% of the coordination status. In 2010, there were 32 BUC regions, of which Ws-EsC contributed 28 regions (87.5%) and WsL and EsL contributed 6.25%. In 2015, there were 31 BUC regions, of which Ws-EsC contributed 27 regions (87.1%), followed by WsL at 9.7% and EsL at only 3.2%. In 2020, there were 33 BUC regions, of which Ws-EsC contributed 23 regions (81.8%), followed by WsL at 18.2%. This also showed that the occupation of natural capital flow alone can no longer meet the demand of human beings for natural resources, and it is necessary to deplete stock capital to maintain ecological demand, resulting in ecological deficits [13]. In this case, even if there is coordinated development of water resources and energy stock capital depletion, the basic coordination status of water resources and energy natural capital utilization can hardly be formed. Therefore, improving water–energy efficiency is critical for the region to curb increasing energy and water use and achieve water–energy flow capital to meet regional needs with rapid economic development [36].

As shown in Fig. 7, the coupling coordination status in each region also changed from 2010 to 2020. For instance, Bengbu gradually transferred from the stage of "basic incoordination and energy stock capital depletion lag" in 2010 to the stage of "basic coordination and energy stock capital depletion lag" in 2020 at the end of the study period. Huainan gradually transitioned from the stage of "good coordination and coordinated development of water-energy stock capital depletion" in 2010 to the stage of "basic coordination and water stock capital depletion lag" in 2020. The changing trend of coupling coordination status in this study from 2010 to 2020 was found to be similar to the research results of Ariken et al. [23].

Uncertainties and Limitations

In terms of future steps, this study undeniably confronted certain limitations, which can be improved upon. First, the quality, availability, and reliability of data may bring certain biases or distortions to conclusions. Second, natural capital includes the common stock of natural resources (water, minerals, land, etc.) and ecosystems. Therefore, when describing the human consumption of natural capital, environmental footprints such as the water footprint, land footprint and material footprint should be comprehensively quantified.

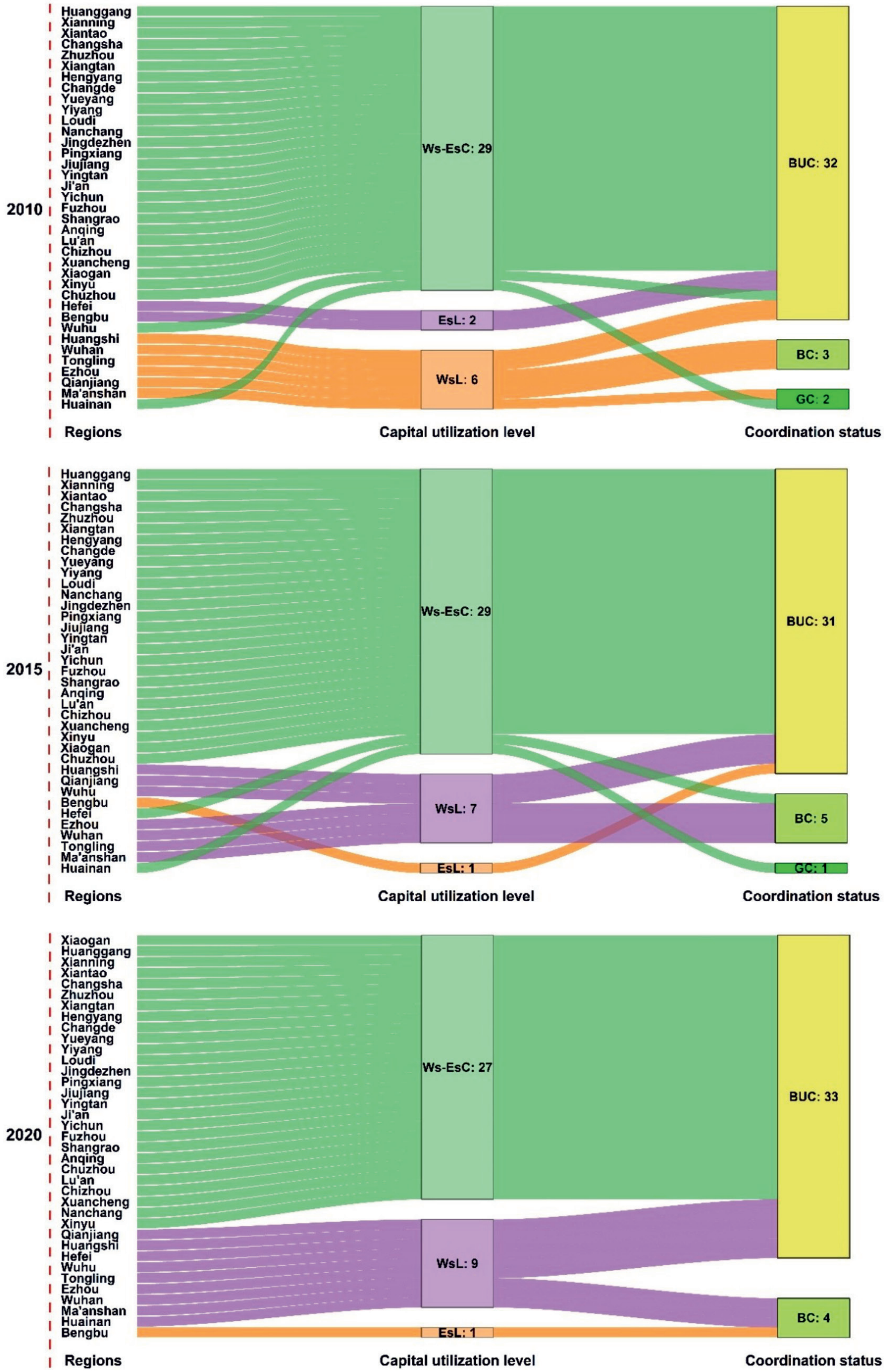

Fig. 7. Coupling coordination relationship between water resource stock capital depletion and energy resource stock capital depletion in 2010, 2015 and 2020. Note: WsL, EsL, and Ws-EsC represent water resource stock capital depletion lag, energy stock capital depletion lag, and coordinated development of water resources and energy stock capital depletion, respectively. The other letters are the same as in Fig. 6.

Last, the CCD model of natural capital utilization of water and energy resources should be improved; more indicators, including economic development, urbanization level, technological innovation, population density, and environmental regulations, should be considered subsystems in the CCD model. These issues will be further explored in our future work.

Conclusions and Suggestions

This paper investigated the use of water and energy as critical natural capital in the FcACC by integrating water ecological footprint assessment (WEFA) and energy ecological footprint assessment (EEFA) into the i3DEF model. A coupling coordination degree model was used to analyze the coupling coordination state of regional water-energy natural capital utilization, as well as the difference in coordination from the two dimensions of time and space. Overarching conclusions were drawn. The WRCU and ECU of 37 regions in the FcACC were divided into four types: types of severe depletion of stock capital, types of moderate depletion of stock capital, types of slight depletion of stock capital, and types of relative lag of stock capital, which are related to the spatial pattern of natural topography, land use and socioeconomic conditions and have obvious regional agglomeration. Types of slight depletion of stock capital and types of relative lag of stock capital were the main types of regional WRCU and ECU in the FcACC. The *D* values of the WRCU and ECU in the FcACC overall showed a downward trend in most regions for the surveyed period. The WFCO and EFCO in most regions were in the running-in stage, while the WSCD and ESCD were in the antagonistic stage. For the coupling coordination relationship between WFCO and EFCO, during the study period, the number of regions with a BUC and GC status decreased, while the number of regions with a BC status increased, and the BC status was the main coordination status. For the coupling coordination relationship between WSCD and ESCD, during the study period, the number of regions with a GC status decreased, while the number of regions with a BUC status first decreased and then increased, and the BUC status was the main coordination status. In addition, the coordination status and capital utilization level of each region changed over time.

Based on the results of this study, the following policy suggestions are proposed to achieve sustainable and healthy development of the FcACC. First, regarding sectors with great betweenness-based and consumption-based WSCD and EFCO pressures, various measures should be adopted (such as water-saving energy generation technologies, popularizing energy-saving and clean energy technologies and implementing incentive policies) to reduce dependency on coal and steer water toward less energy-intensive sectors. Moreover, local government officials should disseminate both energy and water saving information through television programs, newsletters, regional workshops, and symposia. Last, for the relationship of WRCU and ECU, efforts should focus on strengthening synergies and adaptive capacities between regional socioeconomic development and resource and environmental capacities, and single-stage development should be avoided. In addition, the Bureau of Energy Resources and Ministry of Water Resources should strengthen communication and cooperation in all aspects to coordinate the conflicts between energy and water resources from an overall perspective. When formulating an energy-water policy, the government should flexibly use various policy measures from a synergistic perspective to achieve the best energy-saving and water-saving effects.

Abbreviations

EF Ecological footprint;
3DEF Three-dimensional ecological footprint;
CCD Coupling coordination degree;
FcACC Four-City Area in Central China;
WEF Water ecological footprint;
WEF_{size} Water ecological footprint size;
WEF_{depth} Water ecological footprint depth;
$WECC$ Water ecological carrying capacity;
EEF Energy ecological footprint;
EEF_{size} Energy ecological footprint size;
EEF_{depth} Energy ecological footprint depth;
$EECC$ Energy ecological carrying capacity;
NPP Net Primary Production;
WRCU Water resources capital utilization;
ECU Energy capital utilization;
WSCD Water resources stock capital depletion;
ESCD Energy stock capital depletion;
WFCO Water flow capital occupation;
EFCO Energy flow capital occupation;
WfL Water flow capital occupation lag;
EfL Energy flow capital occupation lag;
Wf-EfC Coordinated development of water-energy flow capital occupation;
WsL Water stock capital depletion lag;
EsL Energy stock capital depletion lag;
Ws-EsC Coordinated development of water-energy stock capital depletion;
BUC Basic uncoordinated;
BC Basic coordination;
GC Good coordination.

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Conflict of Interest

The authors declare no conflict of interest.

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