Environmental Science and Policy 127 (2022) 66–76

Contents lists available at ScienceDirect

Environmental Science and Policy

journal homepage: www.elsevier.com/locate/envsci

Opening the black box of water-energy-food nexus system in China: Prospects for sustainable consumption and security

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ARTICLE INFO

Keywords:
Water-energy-food nexus
Logarithmic mean Divisia index
Spatial and temporal changes
Socioeconomic shocks

ABSTRACT

Water-energy-food (WEF) nexus system enables to examine the implications for sustainability. Inevitably, shocks from socioeconomic subsystems would impact the stability and reliability of the WEF nexus system. This paper aims to identify the reasons for changes in water withdrawal, energy consumption, and crop consumption, and uncover differentiated effects from both the national and provincial perspectives, and finally offer the main strategies in China that balance socioeconomic development and resource-saving from the consumption perspective. Empirical results in China from 2011 to 2017 show that (1) the reduction of per capita energy consumption leads to a decrease in water withdrawal, while increased population and water withdrawal intensity in energy sectors have adverse effects on diminishing water withdrawal. (2) The decrease in energy consumption mainly results from improved energy use efficiency for the whole period. (3) Reduction in national crop consumption is mainly caused by the decline in energy consumption per person over the years, which implies a positive effect of food-energy nexus effect on the decrease in crop consumption. (4) Spatially-temporarily contribution rates of drivers offer implications to the implementation of resource-saving and sustainability in the future. Directions and magnitudes of driving forces are different from the sub-nation perspective, hence, finally takes Beijing-Tianjin-Hebei (BTH) region as an example, we analyze clearly the relative planning and reports and propose several pathways to accelerate the sustainable development in the BTH region.

1. Introduction

Water, energy, and food are essential components of sustainability, which are the main objects of the 17 Sustainable Development Goals of the United Nations (Huntington et al., 2021). Currently, the potential risks of ignoring trade-offs among water-energy-food (WEF) nexus systems have attracted more attention. (Wada et al., 2019) pointed out the necessity of the connection across the water, energy, and food. (Deng et al., 2020) proved that demand for energy and food would increase demand for water by more than 50%, especially in developing countries. In recent years, the conception of the WEF nexus, being first proposed at the Bonn 2011 nexus conference (Hoff, 2011), has gained increasing attention across academic and business attention.

Meanwhile, the WEF nexus components vary by region and time. Although China is known for posseting vast land and various resources, unsustainable demands on clean water, food and energy exist. Fig. 1 draws the resources production ratios across China in 2017, which recovers the uneven distribution of these resources across 31 Chinese provinces. Human beings are disproportionately exposed to natural resources; for example, water is sufficient in south China (such as Sichuan, Yunan, Guangxi, Guangdong, and Hunan, etc.), while water-intensive crops are largely planted and yielded in north China. Additionally, a higher energy production ratio is found in southeast China (such as Sichuan, Shandong, Hebei, and Henan). Besides, China's energy consumption increased by 44% from 2007 to 2017, and these increasing trends have continued (Fan et al., 2020); water withdrawal in South China has increased in the recent 20 years, while water withdrawal in North China has no obvious increasing trend. In general, conflicts about resources supply and demand are overwhelming contemporarily. Arguably, demand control is one of the strategies for balancing resources supply and demand and avoid socioeconomic-related challenges (such as population growth and economic development). Hence, the first motivation is to build an environment for the sustainable management of water, energy, and crops.

Through the lens of the WEF nexus, demand for water, energy and food could be analyzed multilaterally (Howells et al., 2013; Van Vuuren

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https://doi.org/10.1016/j.envsci.2021.10.017
Received 16 October 2020; Received in revised form 6 September 2021; Accepted 18 October 2021
Available online 26 October 2021

et al., 2019). Knowledge of the nexus between WEF dynamically is beneficial to improve resources security from an integrated framework (Bleischwitz et al., 2018; Dalla Fontana et al., 2020). These previous articles used analytical and descriptive tools, whereas less attention is given to quantified approaches and to find potentials for future sustainability. In other words, the existing articles about the WEF nexus in China ignored to provide a blueprint for a sustainable transition in regions. *Hence, the second motivation in this paper is to uncover the internal interaction within a WEF nexus system as well as external socioeconomic effects (population and economic effects are focused in this paper), and then offer managerial insights to sustainable transition for policy-makers from the consumption perspective.*

Previously, synergies have been considered bilaterally, for example, water is irrigated for crops sowing and growth. Meanwhile, water is used for energy (such as crude oil, coal, natural gas) extraction, and electricity generation. In addition, energy consumption consists of pumping water for crop irrigation, water distribution and wastewater treatment (Mahlknecht et al., 2020). What's more, biomass-induced energy has taken part in a large amount in the whole energy production structure. In general, energy production needs hydraulic engineering and biomass combustion; while water pumping, purifying and treatment need energy; in the meantime, crops cannot grow without water and energy consumption. Hence, opening the traditional black box by considering WEF simultaneously is vital for further implementing customized strategies for resources conservation and sustainable development.

Meanwhile, changes across the global population and economic development pose an enormous challenge for water, energy, and food security (Zhang et al., 2019; Shi et al., 2020). Hence, socioeconomic conditions should be considered as a kind of driver when analyzing changing trends in resource demand in this paper. To the best knowledge of the authors, a macroeconomic perspective is more pressing for provincial multiple resources management, especially in China due to its uneven resources supply and demand. Hence, *the third motivation of this paper is to uncover the distinguishing changes in each province across China and find out the driving forces to resources consumption, based on which, customized resources management and sectoral improvement strategies can be offered.*

Some papers are studying the resources nexus at the plant level (Wang et al., 2020), at sector level (Yu et al., 2020; Nawab et al., 2019a, b; Fan et al., 2019; Fabiani et al., 2020), at region level (Nawab et al., 2019a,b; Li et al., 2019; Li et al., 2021) and at country level (White et al., 2018). The studied theme for analyzing nexus includes performance assessment (Mahlknecht et al., 2020; Nhamo et al., 2020) and multi-sector planning (Jin et al., 2020). Previously, methods that were widely used to study nexus included the Environmental Extended Input-Output (EEIO) table (Chen et al., 2018), Life Cycle Assessment (LCA) (Al-Ansari et al., 2015), Ecological Network Analysis (ENA) (Wang et al., 2018), Data Envelopment Analysis (DEA) (Mousavi-Avval et al., 2011), and Multi-scale integrated analysis of societal and ecosystem metabolism (MuSIASEM) (Giampietro et al., 2009). Resources linkages were built based on the EEIO table, based on which, (Feng et al., 2019a) identified critical paths of promoting WEF synergies and reducing tradeoff; however, it is difficult to prepare annual WEF nexus input-output tables. LCA is mainly a quantified approach for evaluating the environmental impacts of a product or system, while it is not suitable to study the internal correlation within a system clearly. ENA is known for its unique strength in examining the structure and function of systems from a system perspective, and it has the function that, for example, discovering the dominant role in urban energy consumption and water use (Fath, 2004; Chen and Chen, 2012). However, it is more suitable to simulate the human activities' impact on the studied system and find out the resiliency and vulnerability of the WEF nexus system coping with socioeconomic shocks. And MuSIASEM characterizes the processes of energy, materials and human labor transformation in a society under human control. It breaks the traditional black-box and explores the interaction between economic sectors and the external environment. However, MuSIASEM just studies two factors (aggregate and structure) when conducting a decomposition analysis (Wang et al., 2017). In all, the above articles reviewed methods applied to nexus, besides, the advantages and disadvantages of these methods are analyzed.

In general, this paper aims to answer three real-world questions: (1) which factor induces the changes in resources' demands; (2) what are the key strategies that balance a trade-off between socioeconomic development and resources saving. (3) what are the trends in national and provincial resources demand and the differences in driving forces and contribution rates, based on which customized strategies can be offered for policy-makers. For these purposes, the Logarithmic mean Divisia index (LMDI) seems to be a great tool. Derived from (Chai et al., 2020), we find out there is a connection and bilateral influence between the WEF nexus system. To be specific, (Chai et al., 2020) proved the casual relationships among them by using the Bayesian Network (BN). However, the method cannot say explicitly what's the contribution rate of the drivers. Hence, in this paper, we plan to use the LMDI method to calculate these driving forces. At first, there is one preparatory work to be done is designing indexes to represent the studies aspects discussed above. Following this, spatial and dynamic LMDI methods are applied to analyze different decomposition results, which vary by region and time. Hence the contributions of this paper are summarized as follows:

(1) internal and socioeconomic indexes that affect the WEF nexus system are build;

(2) effects on water withdrawal, energy consumption, and crop consumption are identified by province and time, based on which common and differentiated contribution rates of each driving factor are uncovered;

(3) pathways to be sustainable consumption are proposed based on a real-world empirical study in the BTH region.

The remainder of this paper is organized as follows: Section 2 illustrates the methodology used in data analysis, and section 3 conducts an

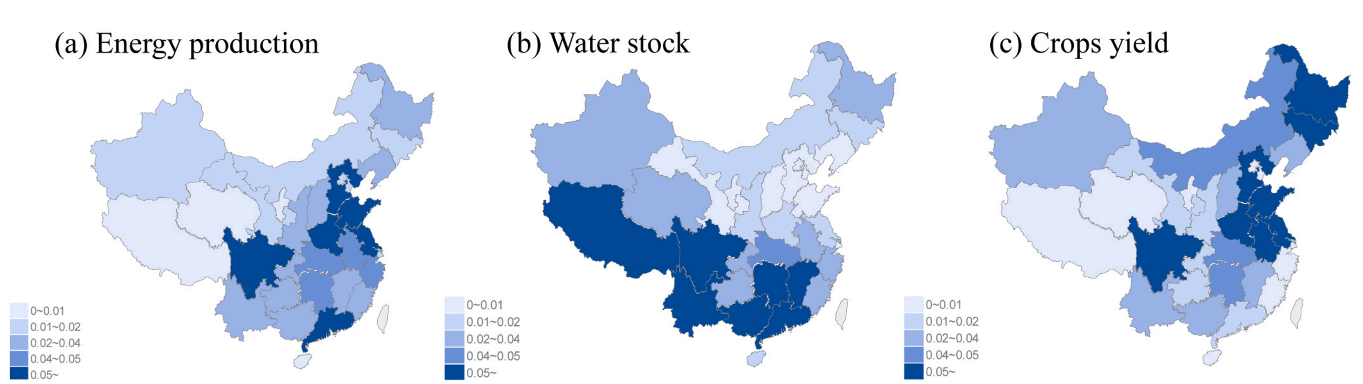

Fig. 1. Distribution ratios of resources supply across China.
Source: National Bureau of Statistics, https://data.stats.gov.cn/staticreq.htm).

empirical study in China, and more discussion is given to offer managerial insights. And section 4 concludes the whole paper.

2. Methodology and data

2.1 Hurst exponent based trend analysis

The Hurst exponent was established in hydrology by (Hurst, 1951) and was generally recognized as a tool to measure persistence in the data (Ivanov et al., 1999). If the time series data conforms to Gaussian, it is easy for human beings to find out the distribution and changing patterns; however, when it contains dependence, long-term memory, and persistence, the traditional model is out of action. On the contrary, the time-dependent Hurst exponent is now widely used to reflect the characteristics of trends, with a distinguishing advantage of removing the effect of time series' distribution (Carbone et al., 2004). In this work, we carry out rescaled range-based Hurst exponent analysis method (code refers to Blok, 2000) to analyze the national resources consumption in China based on the sample period 2011–2017, to determine whether persistence exists in the data and to propose managerial insights on resources management in the future.

Definition 1. (Blok, 2000): Hurst exponent is the slope of the linear fit of log-log plot. Correlations are positive for Hurst exponent $>1/2$ (persistence), besides the stronger the persistence is, the larger the Hurst exponent is when it is larger than 1/2; and negative for Hurst exponent $<1/2$ (anti-persistence). In addition, no correlation is found when Hurst exponent $= 1/2$.

In all, the above autoregressive analysis explains the changes in trend from the time-varying perspective. Later, a decomposition method is applied to find out the drivers for the changes by region and time.

2.2. Logarithmic mean Divisia index

Water, energy, and food security have become a global problem recently. It is known that many governments around the world have carried out policies to sustainably develop. Before that, well knowledge of at which degree these driving factors affect WEF nexus is the first step.

LMDI, first developed in 1998, has been widely used to investigate the driving forces to energy consumption and emissions. By using LMDI, it is accessible to decompose the changes into the sum of changes in drivers. Besides, one of the advantages of LMDI is that it can work without an input-output table (Su and Ang, 2012; Ang, 2015).

There are many ways to decompose water (food, energy) demand for multiple purposes. To uncover the interrelation of the WEF nexus system and discover the socioeconomic factors' effect, we decompose water (food, energy) demand at the provincial scale as follows. Table 1 gives a general decomposition paradigm for it.

2.2.1. Decomposition of water withdrawal

Based on Kaya equation, the LMDI method decompose water withdrawal as follows (Kaya; Ang et al., 1998):

$$WW = P\cdot\frac{EC}{P}\frac{WW}{EC} = P\cdot ECP\cdot WWEC \tag{1}$$

Where *WW* presents the water withdrawal; *P* represents the population; *EC* is the energy consumption, *ECP* represents the per person energy consumption, and *WWEC* represents water withdrawal intensity in energy sectors.

The total change of water withdrawal can be expressed as follows:

$$\begin{aligned}\Delta WW &= WW^{t1} - WW^{t0} = \Delta WW_P + \Delta WW_{ECP} + \Delta WW_{WWEC} \\ &= \omega_W \ln\left(\frac{WW_P^{t1}}{WW_P^{t0}}\right) + \omega_W \ln\left(\frac{WW_{ECP}^{t1}}{WW_{ECP}^{t0}}\right) + \omega_W \ln\left(\frac{WW_{WWEC}^{t1}}{WW_{WWEC}^{t0}}\right)\end{aligned} \tag{2}$$

It's noted that subscript *t0* and *t1* present the base period and the calculation period respectively. $\Delta WW_P, \Delta WW_{ECP}, \Delta WW_{WWEC}$ are population effect, water-energy nexus effect and water withdrawal intensity effect, respectively. And the ratio of each driver' effect among the sum effect of drivers represents the driving force. And $\omega_W, \omega_W = \frac{WW^{t1} - WW^{t0}}{\ln(WW^{t1}/WW^{t0})}$ is called Logarithmic mean weight (Ang, 2015).

2.2.2. Decomposition of energy consumption

Based on Kaya equation, the LMDI method decompose energy consumption as follows (Kaya; Ang et al., 1998):

$$EC = P\cdot\frac{GDP}{P}\cdot\frac{EC}{GDP} = P\cdot GDPP.ECP \tag{3}$$

Where *EC* represents energy consumption; *P* represents the population; *GDP* is the gross domestic product, *GDPP* represents per person GDP, and *ECP* represents energy consumption per person.

The total change of water withdrawal can be expressed as follows:

$$\begin{aligned}\Delta EC &= \Delta EC^{t1} - \Delta EC^{t0} = \Delta EC_P + \Delta EC_{GDPP} + \Delta EC_{ECP} \\ &= \omega_E \ln\left(\frac{EC_P^{t1}}{EC_P^{t0}}\right) + \omega_E \ln\left(\frac{EC_{GDPP}^{t1}}{EC_{GDPP}^{t0}}\right) + \omega_E \ln\left(\frac{EC_{ECP}^{t1}}{EC_{ECP}^{t0}}\right)\end{aligned} \tag{4}$$

$\Delta EC_P, \Delta EC_{GDPP}, \Delta EC_{ECP}$ are population effect, economic development effect and energy consumption intensity effect, respectively. And ω_E, $\omega_E = \frac{EC^{t1} - EC^{t0}}{\ln(EC^{t1}/EC^{t0})}$ is called Logarithmic mean weight (Ang, 2015).

2.2.3. Decomposition of crop consumption

Based on Kaya equation, the LMDI method decompose crop consumption as follows (Kaya; Ang et al., 1998):

$$CC = P\cdot\frac{EC}{P}\cdot\frac{CC}{EC} = P\cdot ECP\cdot CCEC \tag{5}$$

Where *WW* presents the water withdrawal; *P* represents the population; *EC* is the energy consumption, *ECP* represents the per person energy consumption, and *WWEC* represents water withdrawal intensity in energy sectors.

The total change of water withdrawal can be expressed as follows:

Table 1
Representative indicators and their driving factors.

	Representative indicators	Driving factors*	Notes
Water subsystem	Water withdrawal	Population	–
		Water withdrawal per unit of energy consumption	Water withdrawal intensity in energy sectors
		Energy consumption per person	–
Energy subsystem	Energy consumption	Population	–
		GDP per person	–
		Energy consumption per GDP	Energy use efficiency
Food subsystem	Crop consumption	Population	–
		Energy consumption per person	–
		Crop consumption per unit of energy consumption	Biomass energy production ratio

*Referring to (Chai et al., 2020; Sušnik, 2018; Yamauchi et al., 2014; Li et al., 2019; Taniguchi et al., 2017; Lissner et al., 2014).

$$\Delta CC = \Delta CC^{t1} - \Delta CC^{t0} = \Delta CC_P + \Delta CC_{ECP} + \Delta CC_{CCEC}$$
$$= \omega_C \ln\left(\frac{CC_P^{t1}}{CC_P^{t0}}\right) + \omega_C \ln\left(\frac{CC_{ECP}^{t1}}{CC_{ECP}^{t0}}\right) + \omega_C \ln\left(\frac{CC_{CCEC}^{t1}}{CC_{CCEC}^{t0}}\right) \tag{6}$$

$\Delta CC_P, \Delta CC_{ECP}, \Delta CC_{CCEC}$ are population effect, food-energy nexus effect and biomass energy intensity effect, respectively. And $\omega_C, \omega_C = \frac{CC^{t1} - CC^{t0}}{\ln(CC^{t1}/CC^{t0})}$ is called Logarithmic mean weight (Ang, 2015).

2.3. Studied area and data description

It's reported that demands for water, energy, and food resources are forecasted to rise by 40%, 50% and 35% in 2030 (Deng et al., 2020). China, known as the second-largest economic community, has the responsibility to pursue water, energy and food securities. In the empirical study based on data from China, we compare their driving forces to WEF-Nexus in 31 provinces across China, from 2011 to 2017, to better understand their changes and trends holistically and fragmentally. Years (2011–2015) belong to the 12th Five-Year Plan, and years (2016–2017) lie in the 13th Five-Year Plan. It is noted that data in 2018, 2019 and 2020 is scarce, so two years (2016 and 2017) are considered to present the values in the 13th Five-Year Plan period.

With primary data from the *CHINA STATISTICAL YEARBOOK* (2011–2018), *CHINA ENERGY STATISTICAL YEARBOOK* (2011–2018) and some regional *WATER RESOURCES BULLETINS* (2011–2018), 31 provinces were selected, including four municipalities and four autonomous regions. Energy consumption (kg of standard coal) is calculated by multiplying the annual capita energy consumption of households and the population.

3. Results and discussion

3.1. Trends analysis of resources consumption

At first, based on the autoregressive model, we find that national water withdrawal increases before 2013 and shows a slowly decreasing trend for 2014–2017. This downward parabola ($y = -9,0627x^2 + 36492x - 4e + 07$, where y is the value of water withdrawal, and x presents the year) is fitted by the national water withdrawal data, with a goodness-of-fit of $R^2 = 0.6945$ (Fig. 2 (A)). We find that the increase rate slows down before 2014 and then shows a rising trend after that year (with an opposing slope direction before 2013). The autoregressive model implies that the year 2013 was an inflection point. From Fig. 2(B)-(C), we identify that national energy consumption and crop consumption decrease at a rising rate, while crop consumption decreases with a declining rate. In general, based on the collected data, water withdrawal, energy consumption, and crop consumption show declining trends.

Later, it is vital to discuss the persistence property in these trends. The Hurst exponent method is used to reflect the trend properties on national resources consumption. The results find that national water withdrawal tends to decrease soon with a strong persistence (the value of Hurst exponent is 0.87). While national energy consumption has an opposite trend with that in the near past, with the value of Hurst exponent 0.33, energy consumption would increase or back to a higher level of energy consumption soon; and the same finding goes for crop consumption.

The above trend analysis presents the evolution of water withdrawal, energy consumption, and crop consumption separately. Later, to find out the interrelation within the WEF nexus system and the socioeconomic shocks' effect, we deepen into the decomposition analysis as follows.

3.2. Reasons for national resources consumption's changes over time

3.2.1. Drivers of water withdrawal

We try to identify the effect of drivers on the water withdrawal trend. Over the studied period (2011–2017), the decrease in water withdrawal was largely attributed by water-energy nexus effect (accounting for 1106%,[1] as shown in Table 2 and Fig. 3(A)), which means that the improved energy use efficiency would decrease the amount of water withdrawal if the other factors were not considered; meanwhile, water withdrawal intensity effect (with the contributory of water withdrawal intensity effect being 429×10^9 m^3) plays a negative role in the decline in water withdrawal, which implies that if energy provision sector consumed less water in the past few years, the total water withdrawal would have decreased. Similarly (Spang et al., 2014), proved that China's water withdrawal for energy production was larger than several other developed countries, which reflected that the technological intensity of water withdrawal for energy production in China should be improved in the future. In addition, population expansion in China leads to the possibility of an increasing trend in water withdrawal, which is similar to the results solved by (Li et al., 2018).

Temporal differences in driving forces are analyzed. During the 12th Five-Year Plan, the reduction of energy consumption per person leads to an overwhelming decrease in water withdrawal even though the increase in population-scale and the ratio of water withdrawal and energy consumption would increase water withdrawal potentially. The result implies that energy consumption growth indeed increased water withdrawal during the 12th nation's Five-Year Plan (Liu et al., 2020). Between 2015 and 2016, the driving forces to water withdrawal are the same as those over the studied period (2011–2017). During the 13th Five-Year Plan, the increase in water withdrawal resulted from population expansion and the increasing water withdrawal for energy production. The result implies that renewable energy generation has gradually replaced energy from fossil fuel combustion. It is obvious to find a sharp decrease in water withdrawal between 2015 and 2016, which is a connection period between the 12th and 13th Five-Year Plan. In general, water-energy nexus and water use intensity effects on water withdrawal should be paid more attention to in the future.

3.2.2. Drivers of energy consumption

Over the studied period (2011–2017), a monotone decreasing trend was found in Table 2. The decrease in energy consumption resulted from the improved energy consumption intensity. In contrast, the joint function of increased population and GDP per person negatively impacts the decrease in energy consumption. Fortunately, the change in energy consumption per GDP dominated the decreased energy consumption in China. Besiede, (Rahman et al., 2020) also proved the strong relationship between GDP growth and energy (coal, oil, or gas) consumption, which also proved the necessity of integrating economic growth with energy consumption. Hence, combined with the results, we suggest that decision-makers should monitor the performance of energy use and the demands for energy under the changing environment.

3.2.3. Drivers of crop consumption

It was found that the food-energy nexus effect (a decrease in energy consumption per person over the years) leads to a reduction in national crop consumption. On the contrary, increased crop consumption is caused by population expansion and inefficient biomass energy intensity, which implies the potential for the improvement of biomass energy intensity in China in the future. Moreover, the driving force of energy consumption per person is the largest, accounting for 149% of the total change, which causes an unsustainable environment for energy

[1] 1106 = −706.2/−63.8, the value presents the contributing rate of water-energy nexus effect; and −706.2 presents water-energy nexus effect based on (Kaya) equation; and −63.8 presents the changes in water withdrawal

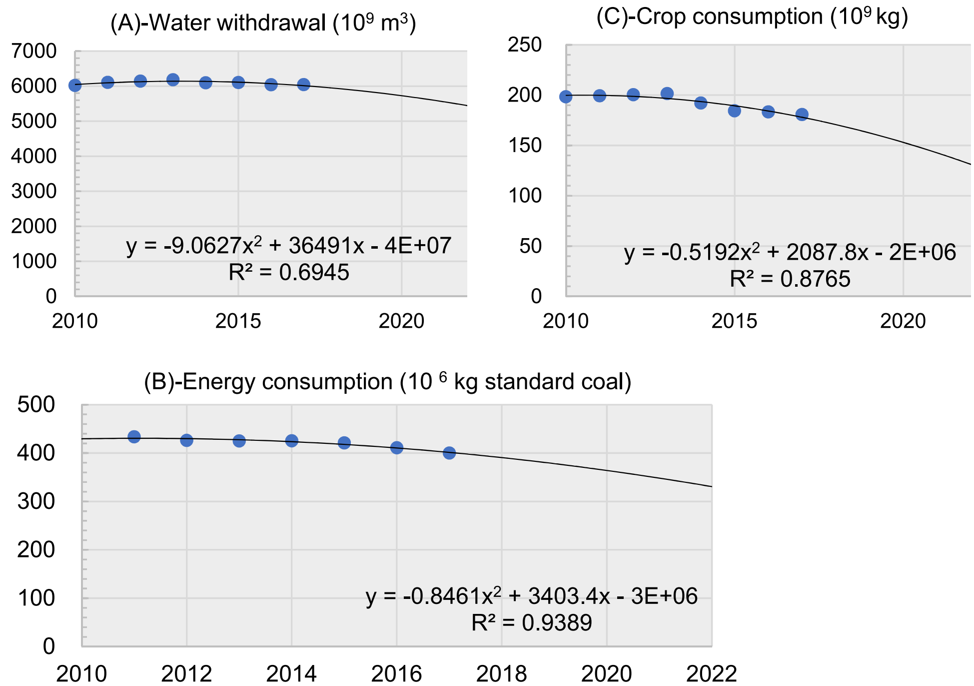

Fig. 2. Changes in China resources consumption.

Table 2
Results of changes and their driving forces in China over time.

Years		Driving factors' effects		
Water subsystem	Water withdrawal (10^9 m^3)	Population effect	Water-energy nexus effect	Water withdrawal intensity effect
2011–2015	-3.6	137.2	-317.6	176.9
2015–2016	-64.3	39.6	-188.8	84.9
2016–2017	1.1	37.1	-200.2	164.2
2011–2017 (Total)	-63.8	213.4	-706.2	429.0
Energy subsystem	Energy consumption (10^6 kg standard coal)	Population effect	Economic development effect	Energy consumption intensity effect
2011–2015	-12.6	9.6	129.4	-151.7
2015–2016	-10.2	2.7	29.0	-41.9
2016–2017	-10.9	2.5	30.9	-44.4
2011–2017 (Total)	-33.8	14.6	185.9	-234.3
Food subsystem	Crop consumption (10^9 kg)	Population effect	Food-energy nexus effect	Biomass energy intensity effect
2011–2015	-14.9	4.3	-10.0	-9.3
2015–2016	-1.1	1.2	-5.7	3.4
2016–2017	0.2	0.0	-0.2	0.3
2011–2017 (Total)	-14.9	6.7	-22.3	0.6

and crop demands. Antar et al. (2021) supported the result that enhancing biomass production efficiency was helpful to sustainable energy supply in the face of climate change. Besides, based on the above analysis, we find that to reduce the dependence on fossil energy sources, biofuel production can be an alternative. Additionally, it is suggested for decision-makers to increase the awareness of energy-saving and crop saving in the future.

Stage differences of driving forces were found in both magnitude and direction from the 12th Five-Year Plan to the 13th Five-Year Plan. The Biomass energy intensity effect shows a jumbled variation during the studied periods, while population and food-energy nexus play positive and negative impacts on the change of crop consumption. Specifically, during the 12th Five-Year Plan, the food-energy nexus is the crucial factor that leads to the increment of crop consumption, followed by biomass energy intensity effect (explaining 62% of the decrement of total crop consumption). By comparison, population-scale and biomass energy intensity effect positively affect crop consumption growth since 2016, while the food-energy nexus effect is the reason for the potential decrease in crop consumption.

3.3. Temporal reasons for resources consumption's changes

The quantified interrelations among the WEF nexus system from 2016 to 2017 are summarized in Table 3, to illustrate the temporal effects on changes in resources consumption. Based on the results, several insights are given, which enable policy-makers to make holistic decisions to eventually lead nations toward sustainability (Ravar et al., 2020). To be specific:

(1) **Improving resource use efficiency is an essential factor helping to achieve the sustainability of the WEF nexus system**. Derived from the above results, we find that less energy tends to be consumed with the gross industrial production increases, because the improved energy use efficiency has a positive impact on energy consumption. Meanwhile, results- "The change of *Δ* ECP pushes water withdrawal downward" and "The change of *Δ* ECP pushes crop consumption downward" imply that the performance of energy use is vital for reducing water withdrawal and crop consumption.

(2) **Integrated WEF strategies are of significant requirement.** Based on the above results, we find the connections among food, energy and crops from the consumption perspective. For example, the reduction of energy consumption would decrease water withdrawal and crop consumption in recent years. Hence, combining the energy production strategies with water management strategies and crop irrigation strategies, the systematic benefit can be found in one nation's sustainable development.

(3) **Resources saving strategies are different and should be assessed in an integrated framework, such as the WEF nexus system.** Water, energy, and food demand are reported to increase by 40%, 50% and 35% in 2030. Hence, faced with the increase in predicted resource demand, intervention strategies can be proposed from a multi-

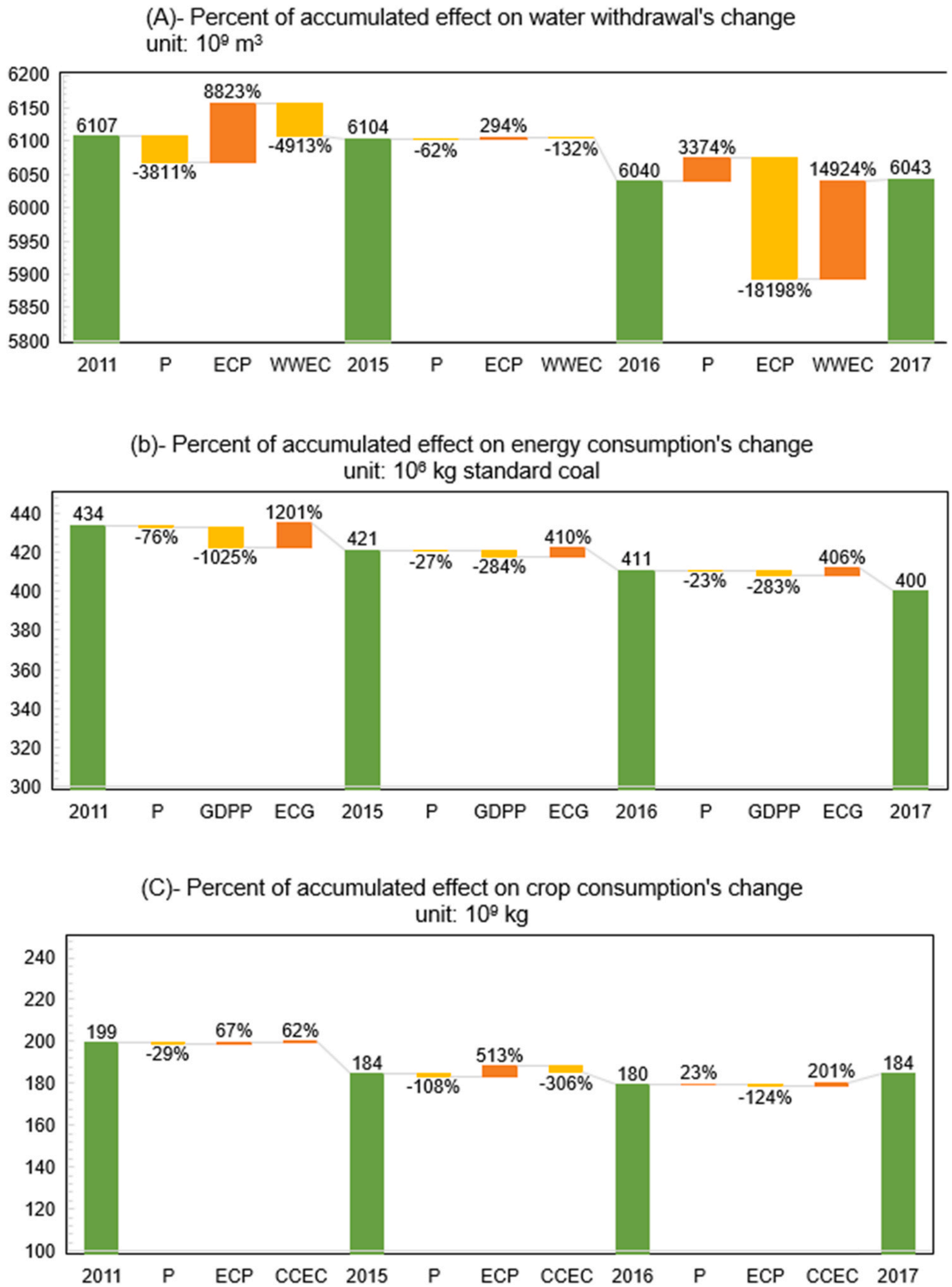

Fig. 3. Contributions of socioeconomic drivers to the change in national resources consumption., (A) changes in water withdrawal; (B) changes in energy consumption; and (C) changes in crop consumption.

dimensional perspective, such as improving resource use efficiency, enhancing the water-energy nexus effect, etc.

3.4. Regional differences of the interrelations

At the province level, the changes in driving forces are calculated. In this way, the answer to what factor should be regulated and how is revealed. As shown in Figs. 4–7, the color blue presents the negative impact while the color red reflects the positive influence. As the color deepens, the driving force adds.

In general, there is no noticeable difference in the effects on crop consumption's change. On the contrary, a much more apparent difference can be found when identifying drivers' contributions to water withdrawal and energy consumption.

Over a long period (2011–2017), taking Hunan province as an example, we find that the decreasing amount of water withdrawal resulted from jointly population shrink and improved water withdrawal intensity. It implies that to achieve reducing water withdrawal, promoting the water use efficiency is an accessible tool; however, less investment is put into this part in many provinces, such as Anhui. Hence, energy-related water conservation should be focused on in the near future (Feng et al., 2019b; Jia et al., 2021).

Regarding energy consumption change and its drivers, we would like to take Tibet and Tianjin provinces as examples because the driving forces in the two provinces are relatively larger. For Tibet, a decrease in energy consumption per GDP essentially explained the reduction of energy consumption even though the economic expansion adds energy consumption. The results imply that Tibet has developed rapidly since the implementation of the 12th Five-Year Plan while reducing energy consumption and improving energy use efficiency. It is worth noting

Table 3
Drivers and driving directions (Period from 2016 to 2017).

	Drivers	Driving directions
Water withdrawal	Δ P	The change pushes water withdrawal upward
	Δ ECP	The change pushes water withdrawal downward
	Δ WWEC	The change pushes water withdrawal upward
Energy consumption	Δ P	The change pushes energy consumption upward
	Δ GDPP	The change pushes energy consumption upward
	Δ ECG	The change pushes energy consumption downward
Crop consumption	Δ P	The change pushes crop consumption upward
	Δ ECP	The change pushes crop consumption downward
	Δ CCEC	The change pushes crop consumption upward

Note: Δ*(P, ECP, CCEC, etc.): factor's effect on water, energy and crop consumption' change.

that the directions of drivers in Tianjin are fully different from those in Tibet, that is, the energy consumption per GDP increases while the population shrinks.

Figs. 5–7 reveals the differences of the driving forces over three periods, i.e., 2011–2015, 2015–2016, and 2016–2017. In general, a more negligible difference is found in the driving forces when it comes to crop and energy consumption. Regarding water withdrawal, the differences in drivers by province among 31 provinces are clear.

3.5. Pathways to sustainable management from the consumption perspective: a specific analysis in the BTH region

The coordinated development of the Beijing-Tianjin-Hebei (BTH) region is a major national strategy devised and promoted by President Xi Jinping. It is of great significance to realize the "Two Centenary Goals" and the Chinese dream of national rejuvenation. The past few years have fully proved that national strategy on regional development is an effective measure to build a new engine of innovation-driven development. In addition, based on the appeal for integrated management of natural resources at the National People's Congress and Chinese People's Political Consultative Conference (NPC and CPPCC) in 2019, we believe for a long time, making a good understanding of water, energy, and food consumption and their drivers are imperative to balance a trade-off between resource-saving and socioeconomic development in BTH region. This section elaborates on natural resources' consumption trends in the BTH region, corresponding driving forces.

3.5.1. Enhancing the water-energy nexus is beneficial for water-saving

From the perspective of water withdrawal, we find a rising trend in Beijing and Tianjin regions, while a decreasing trend is in Hebei province. As a whole, potentials for water saving in Beijing and Tianjin are found. Besides, combined with decomposition results, the water-energy nexus effect is found to be the main reason for water withdrawal reduction. However, the population effect and water withdrawal intensity effect over the studied periods (from 2011 to 2017) leads to an increment in water withdrawal. In addition, driving forces to resources consumption's changes vary across the BTH region. Hence, based on the common and differentiated results, we suggest to enhance the water-energy nexus by improving the water withdrawal intensity in the energy sector, especially in Beijing and Tianjin.

To be specific, common results are found in Beijing and Tianjin, that is, increasing trends of water demand derived from population effect and water withdrawal intensity effect were uncovered. Besides, the water-energy nexus gives the pathway for a decline in water withdrawal. Unfortunately, the driving forces of population effect and water withdrawal intensity effect in Beijing and Tianjin are much larger than the water-energy nexus effect's driving force, which further leads to the growth of water withdrawal. When it comes to Hebei province, a decreasing trend of water withdrawal was found because of the significant impact of the water-energy nexus.

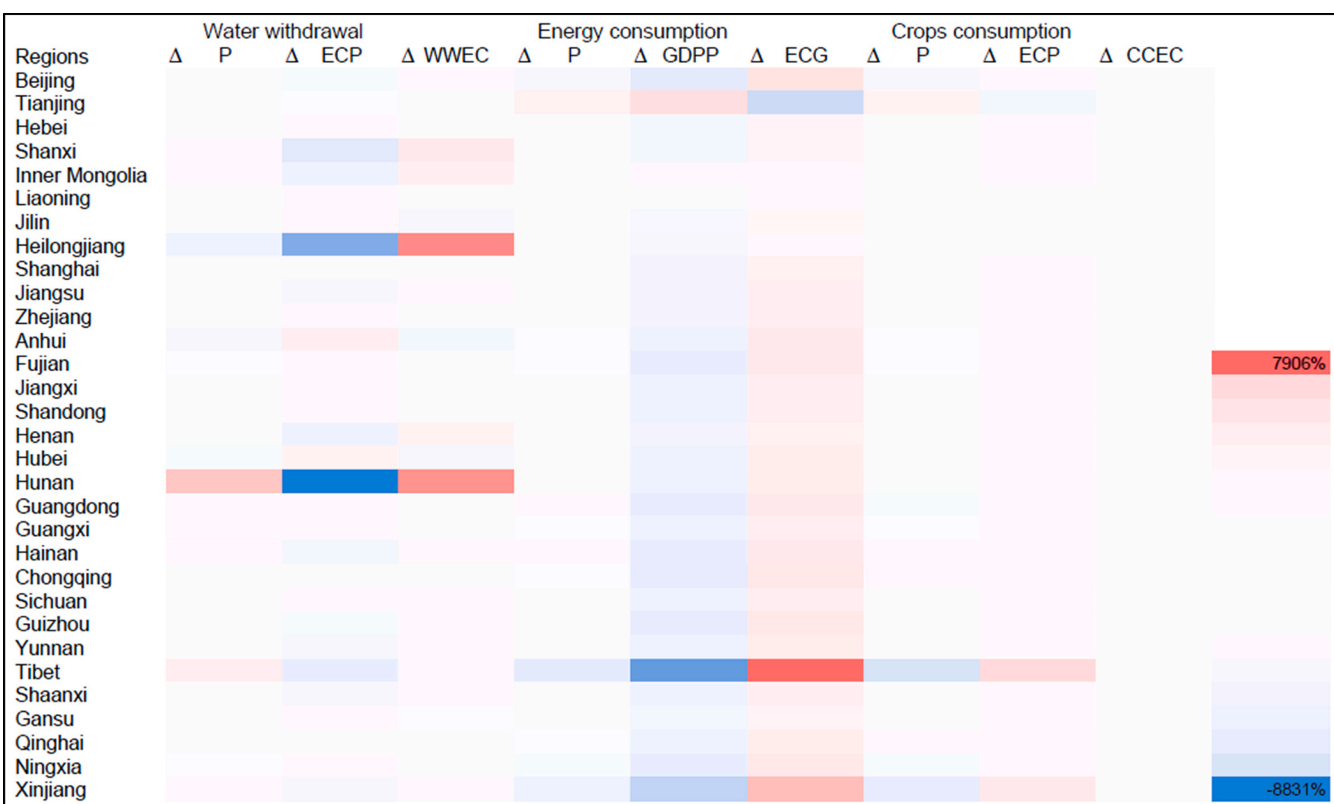

Fig. 4. The driving forces of changes in resource demand in 31 provinces (2011–2017).

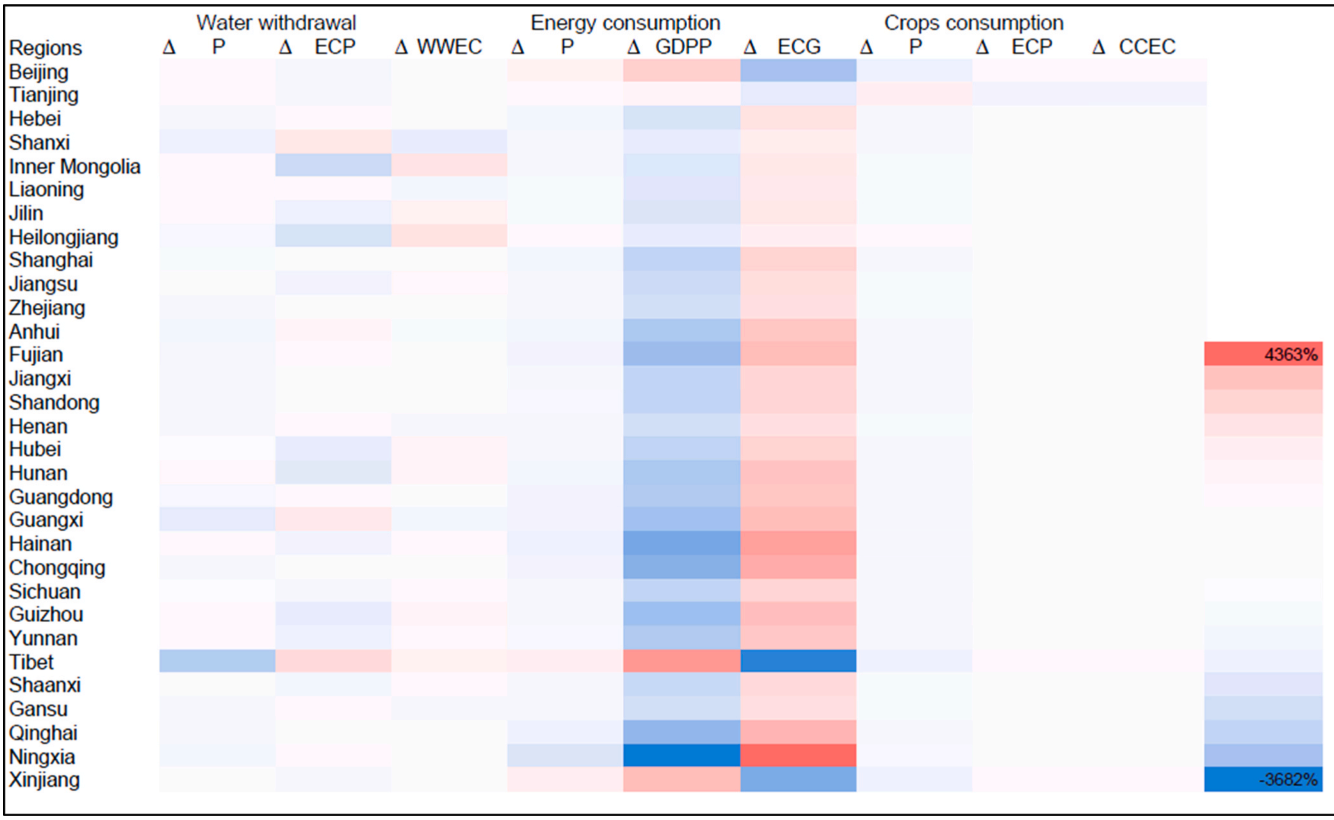

Fig. 5. The driving forces of changes in resource demand in 31 provinces (2011–2015).

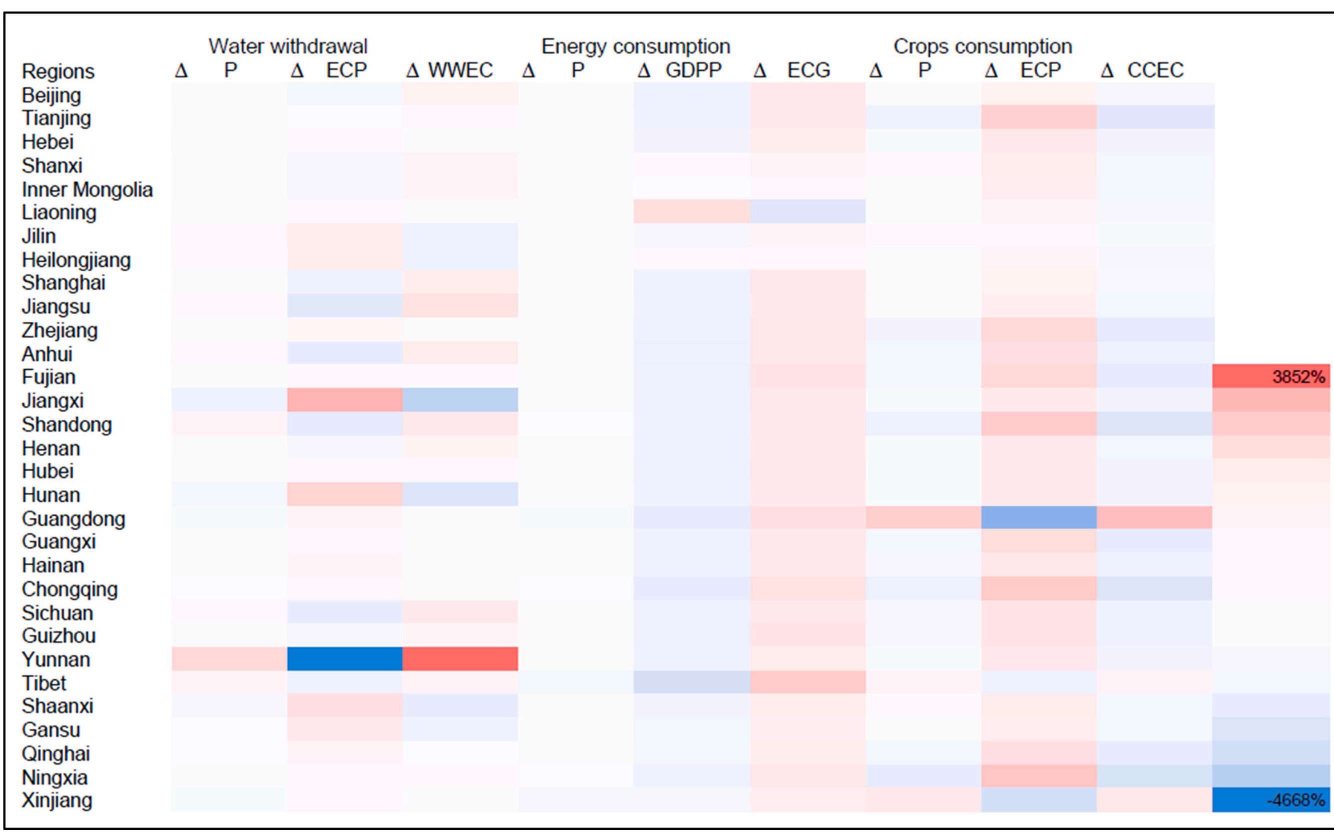

Fig. 6. The driving forces of changes in resource demand in 31 provinces (2015–2016).

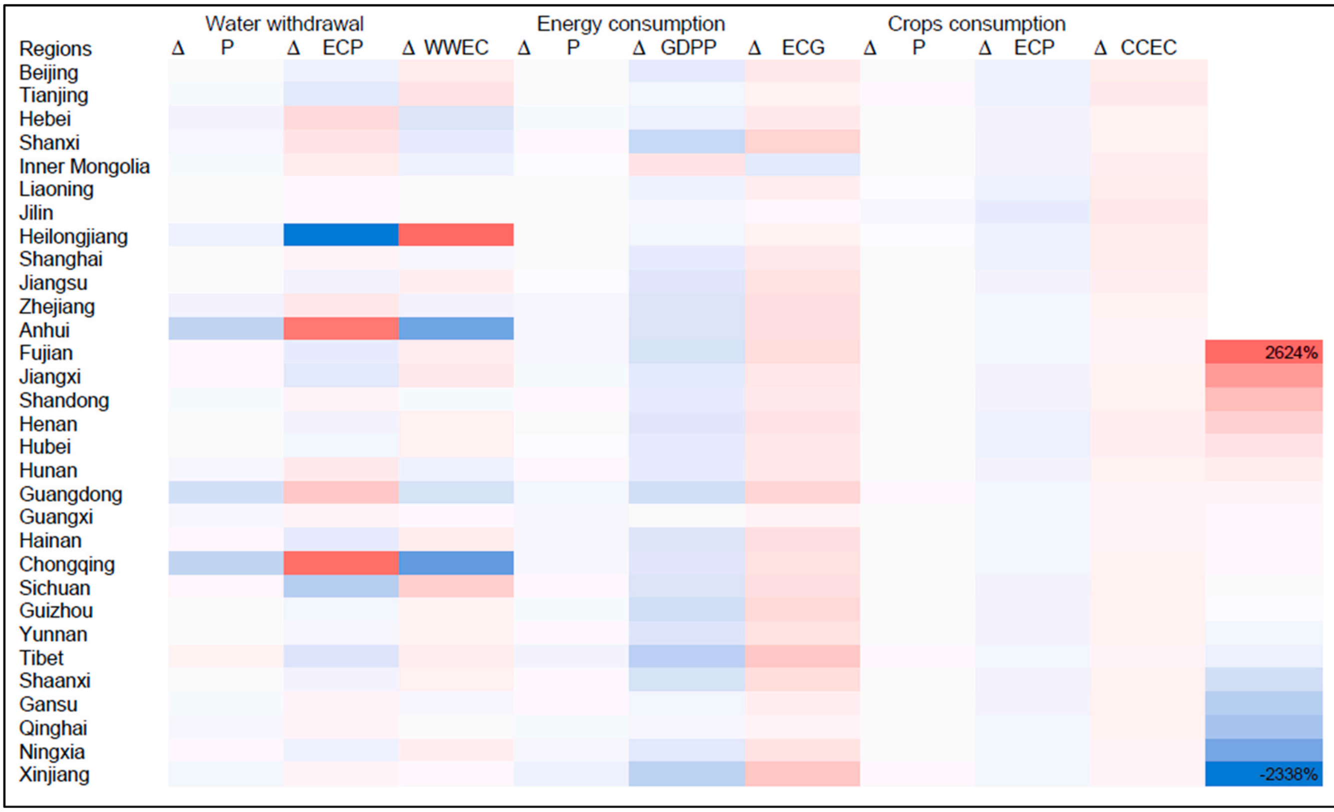

Fig. 7. The driving forces of changes in resource demand in 31 provinces (2016–2017).

Other stage decomposition results refer to Figs. 5–7. Based on the results, distinguished driving forces are found in the BTH region. Although efforts of policies and regulations on resources-conservation and resources security implemented by the Beijing and Tianjin governments can be seen (as shown in Table 4), there is a long way to save freshwater. Hence, it is suggested to control the water production efficiency in energy sectors while promising water security.

3.5.2. A multi-pronged approach improves the speed of energy-saving

Based on historical data on energy consumption, Tianjin consumes a higher amount of energy over the years, while Beijing and Hebei provinces consume little energy during the studied period. The decomposition results in Beijing and Hebei province showed that the effects of population and economic development are adverse, while the energy consumption intensity effect is positive. An explanation for the phenomenon is that energy use efficiency is well improved in the past few years. Later, we analyzed driving forces in the BTH region. The improvement of energy use efficiency is found to be the main reason for the decrease in energy consumption, while population expansion and developed economy negatively influence the decline in energy consumption. Spatial differences in driving forces have been found, that is, the improvement of energy use efficiency in Tianjin is not able to relatively reduce the total energy use over the years. In contrast, the progress of energy use efficiency in Beijing and Hebei explicitly leads to decreased energy consumption, accounting for 1347.4% and 517.6%, respectively.

Arguably, accelerating resources transfer and improving resources use efficiencies among provinces are beneficial for energy saving. Besides, to relieve energy provision stress, more advanced technology can be continually imported from developed countries. Also, the appropriate management paradigm is of equal importance, such as intensifying the multi-layer management to twist the unsustainable development problem in the BTH region. Additionally, a combination of macro-control and customized modification in a province is suggested, which resembles the idea of “to seek common ground while reserving differences”. Besides, optimizing the energy production and consumption structure and innovating the talents management policies enables the studied area to balance economic development requirements and energy-saving and environmental control.

Table 4
Policy and regulations.

	Files	Content
China	“Outline of national Land Planning (2016–2030)”	promoting the balance between population, resources and the environment and the unity of economic, social and ecological benefits
BTH region	“the Outline of the Plan for Coordinated Development for the Beijing-Tianjin-Hebei Region”	synergetic development; coordinating production, life and ecology…
Beijing	“Overall Urban Planning of Beijing (2016–2035)”	building a resource-conserving and environment-friendly society
Tianjin	“Opinions of Tianjin Municipal Committee of the CPC and Tianjin Municipal People’s Government on Further Strengthening Planning and Land Management”; “Regulations of Tianjin municipality on The Administration of River Courses” and “Mineral Resources Planning (2021–2025)”	implementing multiple layer management, strengthening the security of resources supply
Hebei	“Digital Economy Development Plan of Hebei Province (2020–2025)”	building a smart city, pursuing technological advance

3.5.3. The food-energy nexus is the mainstay for saving crops, while integrated technological and labor advantages could assist in crop security

It's found that a greater amount of crops is consumed in Tianjin, while fewer crops are consumed in Beijing and Hebei provinces. Based on the decomposition results, we discover that population expansion and increasing ratio of biomass energy production largely increase the amount of crop consumption in Tianjin. Meanwhile, the decrease in energy consumption per person also leads to a decrease in crop consumption. In addition, the decrease in total crop consumption in Beijing and Hebei province mainly resulted from the food-energy nexus effect. On the contrary, population expansion and biomass energy intensity effect cause an increase in crop consumption in Tianjin province, while food-energy nexus had a weak positive effect on the decrease in crop consumption.

In general, the difference in contributing degree of food-energy nexus in the BTH region leads to the different crop consumption's changing direction. Hence, several insights are given to control the amount of crop consumption and further promise food security. For example, (1) obeying the principle of reducing the quantity and improving efficiency and adjusting the energy mix structure based on the annual crop yields. (2) Considering the future uncertainty, such as drought or extreme wet weather, the "white area" should be stored for timing modification for crops growth. What's more, (3) Integrated management of resources is beneficial in the BTH region: for example, increasing the hydro or marine energy consumption in Tianjin and optimize the energy mix structure, which is helpful to save crops while promising energy security. Population control and energy mix structure optimization in Beijing and Hebei provinces are suggested. In conclusion, to encourage whole sustainable development in China, analyzing the regional difference and improvement pathways in resources management has been recognized as the precondition.

4. Conclusions

After the proposal of the WEF nexus, the connection of three resources—water, energy and food—has been studied by scholars and policymakers. In the previous articles, bilateral relationships, such as water-energy, water-food and food-energy on regional, national or global scales are wildly studied. However, fewer articles focus on the WEF nexus and the internal relationship and external relationship within an integrated analytic framework; in addition, most of the existing papers made nexus evaluation at a specific time, which ignores the dynamic change. To narrow the studying gap, this paper develops a WEF nexus conceptual framework. In this way, the internal linkages and external socioeconomic shocks can be analyzed together. Meanwhile, considering the difference in area and time, a spatial and temporal analysis of the contribution rates of each driving force in China are calculated. To be specific, LMDI method is used to decompose changes in water withdrawal.

l into changes in population, per capita energy consumption and water withdrawal per unite of energy consumption; decompose changes in energy consumption into changes in population, GDP per person, and energy consumption per GDP; decompose changes in crop consumption into changes in population, per capita energy consumption and crop consumption per unit of energy consumption. In this way, the drivers and their driving forces can be identified comprehensively. Hence, the main contributions of this paper include:

(1) driving forces' contribution direction and magnitude are uncovered within an integrated analytical framework;

(2) the general and customized strategies are pointed out based on the decomposition results from time and region perspectives.

Furthermore, (3) pathways to be sustainable from the consumption perspective are proposed based on an empirical study in the BTH region.

An empirical study is conducted in China from 2011–2017, containing two periods (12th and 13th Five Plans). The results, in general, are summarized as: (1) water-energy nexus effect leads to the decrease in water withdrawal, while population effect and water withdrawal intensity effect have an opposite impact over the studied period; (2) The decrease in energy consumption results from the improved energy consumption intensity, which implies the importance of energy use efficiency's improvement; (3) Reduction of national crop consumption results from food-energy nexus effect over the years, which implies the imperatively integrated management of energy and crops. (4) Spatially-temporarily distinguishing contribution rates are found, which supports customized implications to resource-saving implementation.

BTH agglomeration is taken as an example to analyze the performance of relative planning and reports and offer several contemporary and differentiated actions to accelerate sustainable and coordinated development in the BTH region. As we knew, sustainable consumption is related to resources utilization and saving contemporarily. Hence, we suggest enhancing the WEF nexus and focusing on integrated technological and labor advantages. Specifically, restructuring energy production, such as increasing the ratio of hydraulic and marine energy in Hebei Province; improving the water withdrawal efficiency in Beijing and Tianjin Province.

CRediT authorship contribution statement

Zhongwen Xu: Methodology, Calculation, and Results analysis; **Liming Yao:** Conceptualization, Funding acquisition.

Declaration of Competing Interest

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

Acknowledgment

The work is supported by the National Natural Science Foundation of China (Grant No. 71771157), the Fundamental Research Funds for the Central Universities, Sichuan University (Grant No. 2019hhs-19), Funding of Sichuan University (Grant No. skqx201726), and Social Science Funding of Sichuan Province (Grant No. SC19TJ005, SC20EZD026), Ministry of Ecology and Environment (Grant No. 2020QT017-K2020A003).

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