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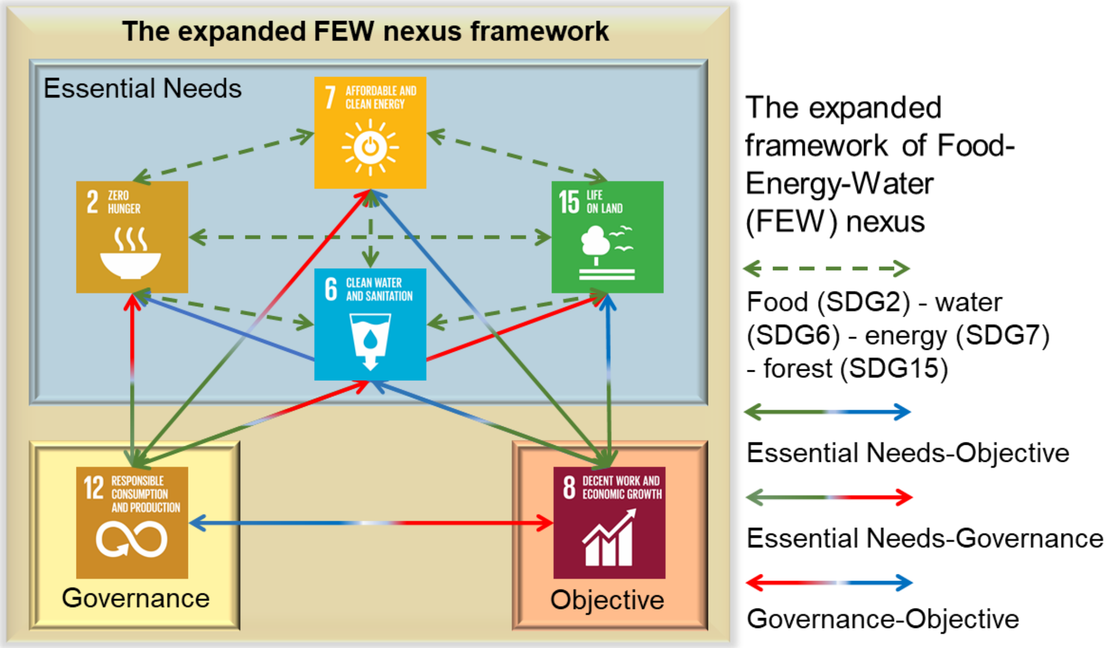
Graphical Abstract

Graphical abstract



Mapping the complexity of the food-energy-water nexus from the lens of Sustainable Development Goals in China

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Highlights

- An expanded food-energy-water (FEW) nexus in China is built from the lens of Sustainable Development Goals (SDGs).
- China has more trade-offs than synergies in the framework of expanded FEW nexus.
- Economic growth has a stronger impact on the FEW nexus than consumption and production patterns.
- Changing the priorities of actions could contribute to transforming trade-offs into synergies.
- Addressing the mutual inhibiting between different sectors is crucial for applying the nexus approach.

Abstract

The nexus approach offers an important heuristic tool for the sustainable management of resources by considering the links among different sectors. The food-energy-water (FEW) nexus corresponds to links among the three of seventeen United Nations Sustainable Development Goals (SDGs), namely SDG2 (No Hungry), SDG6 (Clean Water and Sanitation), and SDG7 (Affordable and Clean Energy), and their interlinkages have a direct or indirect impact on other SDGs. However, there is still a lack of a systematic and quantitative analysis of how the nexus approach could promote achieving SDGs. Here, taking China as a case, we built an expanded FEW nexus framework from the lens of SDGs, which consists of six sectors, including food (SDG2), water (SDG6), energy (SDG7), economic (SDG8), consumption and production (SDG12), and forest (SDG15). We quantified the two-way interactions between the six sectors by the panel vector autoregressive (PVAR) model. Results indicate that sectors exhibit different response characteristics (positive or negative) in their interactions, and these responses could change over time. These results imply that changing the priorities of actions may be an effective measure to transform trade-offs into synergies. Moreover, the contribution of different sectors to each other varies considerably, with economic growth (SDG8) generally having a higher impact on changes in the FEW nexus than consumption and production patterns (SDG12). Our research suggests that strengthening the quantitative assessment of two-way interactions among the FEW nexus has crucial implications for leveraging nexus approaches effectively to achieve sustainable development for all.

Keywords: Sustainable Development Goals, nexus approach, two-way interactions, food-energy-water nexus, PVAR model

1. Introduction

The term food-energy-water (FEW) nexus, which stems from the direct or indirect link among food, energy, and water sectors (Weitz et al., 2017; Huntington et al., 2021), has received widespread attention. It aims to explore integrated solutions to resource shortages and avoid the pitfalls of silo approaches (D'Odorico et al., 2018; Liu et al., 2018). FEW corresponds to the three of seventeen United Nations Sustainable Development Goals (SDGs), namely SDG2 (No Hungry), SDG6 (Clean Water and Sanitation), and SDG7 (Affordable and Clean Energy), all of which desired to be achieved by 2030 to build a better future for humans (Bleischwitz et al., 2018; Putra et al., 2020). Several studies have argued that the nexus approach could promote the achievement of SDGs by enhancing beneficial synergies and resolving harmful trade-offs, also accounting for other cascading processes (Bleischwitz et al., 2018; Liu et al., 2018). However, there is still a lack of quantifying the actual contribution of the nexus approach to the implementation of SDGs (Simpson and Jewitt, 2019; Huntington et al., 2021).

Previous studies have made progress on the FEW nexus mainly from two perspectives. On the one hand, efforts have been devoted to the optimization of resource allocation (Yillia, 2016; Endo et al., 2017). For example, an increase in irrigation efficiency may lead to additional consumption of energy and thus an increase in water costs (Fuso Nerini et al., 2018; Grafton et al., 2018). Thermal electric energy production requires large amounts of water for cooling, putting pressure on water use in other sectors (Yillia, 2016). On the other hand, sustainability among the FEW nexus has been analyzed by assessing the coupling coordination degree (Han et al., 2020; Sun et al., 2021) or other composite indices (El-Gafy, 2017), i.e., the better the indices among the three are, the closer to sustainability. Nonetheless, these results only reflect the strength of interactions among the FEW sectors but do not provide additional guidance for promoting synergies. Additionally, studies using different indicators may even lead to opposite results. For instance, Han et al. (2020) indicated that 63% of provinces in China show a decreasing trend in the coupling coordination degree of FEW nexus from 2005 to 2017. In contrast, Li and Zhang (2020) argued that China's FEW coupling coordination degree has increased between 2003 and 2015, and there was much potential for improvement.

While previous efforts made contributions to unravelling the complexity of FEW nexus, a few of the indicators used in previous studies match those of SDGs (Putra et al., 2020; Malago et al., 2021), especially in different country contexts, which leaving insufficient information on how to advance the implementation of SDGs through the nexus approach (Simpson and Jewitt, 2019). Generally, SDGs consist of a broader set of indicators (UN, 2017). For example, some assessments of nexus between food and water sectors focused only on food production and water use (El Gafy et al., 2017; Saladini et al., 2018); however, the safety of food and drinking water are also included in SDGs (UN, 2015; UN, 2017). Differences in the choice of indicators would considerably impact understandings of contributions of the nexus approach to implement SDGs (Warchold et al., 2022). Thus, assessments based on the SDG indicator framework can further unravel these understandings and identify phenomena that have been overlooked.

Moreover, expanding the FEW nexus is also crucial, i.e., adding other sectors to the FEW nexus (Zhang et al., 2020; El-Gafy and Apul, 2021). It is mainly because the linkages among FEW are embedded in the socio-ecological system, and their interactions can have potential impacts on other sectors (Liu et al., 2018). For example, increasing energy consumption may lead to higher carbon emissions and thus contribute to climate change (Wang et al., 2021); the construction of hydropower facilities can alter aquatic ecosystems and influence biodiversity (Yillia, 2016); and forest vegetation also has a direct or indirect impact on water, food, and energy systems ((Landholm et al., 2019; Melo et al., 2021). Additionally, population growth, economic development, and consumption and production patterns are considered to be important drivers affecting water, food, and energy systems (Sušnik, 2018; Huang et al., 2020). Nevertheless, few studies have simultaneously considered the two-way interactions among the multiple sectors (Chai et al., 2020; El-Gafy and Apul, 2021), including the change in their linkages over time. Filling these knowledge gaps could provide crucial information on enhancing the policy coherence among different sectors.

To fill these gaps, we assessed China's FEW nexus from the lens of SDGs. We chose China for our study because China is a notable case for implementing the SDGs, with several initiatives already underway and receiving widespread attention (Wang et al., 2020; Xu et al., 2020a). Furthermore, we are familiar with the regional context and have good data availability at a sub-national level (e.g., see Zhang et al., 2022a). Previous studies on the FEW nexus in China mainly focused on the coupling efficiency of different sectors, but they have ignored the two-way interactions between multiple sectors (Chai et al., 2020; Sun et al., 2021). Our study not only has the potential to reveal some unnoticed links among the FEW in China but also can provide implications for research in other countries around the world.

Our study regarded the FEW nexus as the dynamic links among SDG2, SDG6, and SDG7 because of the possibility of using the standard SDG indicator framework to avoid variations in results from using different indicators. We expanded the FEW nexus by adding SDG8 (Decent Work and Economic Growth), SDG12 (Responsible Production and Consumption), and SDG15 (Life on Land) to the analysis framework to understand the FEW interactions with other sectors. These six SDGs are also closely related to the FEW nexus and have been widely discussed in past studies but lack specific quantitative assessment (see Section 2.1 for details). We aim to address the following questions: (1) What are the Spatio-temporal dynamics of the expanded FEW nexus at the national and sub-national levels in China? (2) What are the two-way interactions of the expanded FEW nexus in China from the lens of SDGs? (3) What are the differences in the contribution of each sector to changes in other sectors in the expanded FEW nexus of China? Answering these questions will be of great significance for informing how to advance the SDGs through the nexus approach.

2. Methods

2.1. Expanded framework of food-energy-water nexus

Here, we built the expanded FEW nexus by simultaneously analyzing the interlinkages among the food (SDG2), water (SDG6), energy (SDG7), economic (SDG8), consumption and production (SDG12), and forest (SDG15) sectors (Fig. 1). According to the systematic classification framework of SDGs, which divided the 17 SDGs into three categories, namely “Essential Needs,” “Governance,” and “Objectives” (Fu et al., 2019), SDG2, SDG6, SDG7, and SDG15 are regarded as the “Essential Needs” that humans obtain from ecosystems to sustain themselves. Due to resource scarcity, there may be competing relationships among different needs. Managing the trade-offs among these SDGs effectively and reducing resource waste is necessary for sustainable development. Several studies have called forests the fourth dimension of the FEW nexus (Tidwell, 2016; Melo et al., 2021). It is because forests can be directly linked to water, food, and energy through various processes such as regulating runoff, preventing wind and dust, and growing timber (Melo et al., 2021). Nevertheless, there is a lack of quantitative studies on the interlinkages among different resources. Given that forest is an important element covered by SDG15, the above gap can be filled by analyzing the two-way interactions among SDG2, SDG6, SDG7, and SDG15.

Additionally, given that socio-economic activity is an important driver affecting the FEW nexus (Sušnik, 2018; El-Gafy and Apul, 2021), we incorporated SDG8 and SDG12 into our analytical framework as well (Fig. 1). Based on the systematic classification framework of SDGs (Fu et al., 2019), SDG8 is classified as a “Objectives” category, which represents a human pursuit for wealth and well-being after “Essential Needs” are met, while SDG12 represents a measure of “Governance”, which aims to improve human behaviour to ensure that people are less wasteful of resources while seeking economic benefits. Zhang et al. (2022a) assessed the synergies and trade-offs between the “Essential Needs,” “Governance,” and

"Objectives" in China. They found that SDG8 and SDG12 play a significant role in "Essential Needs" and "Governance," respectively. Therefore, we decided to analyze the impact and response of SDG8 and SDG12 on the FEW nexus. In doing so, we intended to distinguish ourselves from studies that judge synergies and trade-offs among SDGs by assessing the correlation coefficients and focusing our study on the expanded FEW nexus. Although correlation analysis can identify synergies and trade-offs among all SDGs, it does not reflect causality (Warchold et al., 2020; Anderson et al., 2021). By analyzing the two-way interactions, we could find whether the two sectors behave consistently in their mutual influence, allowing us to reveal causal links between different sectors. Although such an analysis may only be in a statistical sense, it helps to explore how trade-offs can be transformed into synergies through the nexus approach.

It should be acknowledged that other SDGs are also related to the FEW nexus to varying degrees, for example, SDG14 (Life below Water) is concerned with the conservation and restoration of marine ecosystems, and it has potential links to water, food, and energy (D'Odorico et al., 2018). However, SDG14 was not considered in this assessment because only 11 provinces in China could obtain data related to SDG14, resulting in changes in SDG14 not being comparable across other provinces. It would be necessary to consider the interactions among SDG14 and FEW if relevant studies were conducted in coastal regions or small island states. Overall, while our analytical framework does not encompass all 17 SDGs, how the FEW nexus is expanded should be influenced by a combination of management systems, geographical location, and spatio-temporal scales of analysis. Nevertheless, our research proposes a framework for integrating social and economic activities into the FEW nexus from the lens of SDGs, which should be flexible and inspiring. This framework will provide novel insights to explore how the implementation of SDGs can be advanced through the nexus approach.

2.2. Data sources and processing

To quantify the two-way interactions between the six sectors in our expanded FEW nexus (Fig. 1), we used the SDG indicator framework applicable to China at the provincial scale, which has been introduced by Zhang et al. (2022a). Generally, this study contains 32 indicators corresponding to 27 targets of the six goals (Table A1 and A2), and we collected indicator data for 31 provinces in China (excluding Hong Kong, Macau, and Taiwan). We assessed changes in performance across sectors by calculating the normalized scores for each SDG. For making the changes comparable across sectors, the original values of each indicator were normalized to a range of 0-100 scores by referring to the methodology in the report of SDG Index and Dashboards (Lafortune et al., 2018). To do so, we first set the corresponding target and baseline values for each indicator (Zhang et al., 2022a). Here, the target value is the value of an indicator at which the target is considered to be achieved, and the baseline value is a reasonable initial value for assessment. After normalization, 0 represents the baseline value, and 100 represents the target value of each indicator. The indicator scores were then aggregated into the scores of SDG targets by arithmetic averaging, and subsequently, SDG target scores were aggregated into SDG scores by following the same method (Lafortune et al., 2018). Applying arithmetic averages for aggregation is a way to consider that each indicator has the same weight and will not cause additional uncertainty in the results due to subjective factors. Zhang et al. (2022a) described the normalization process for each indicator in detail. The time range of the performance for each sector we analyzed is from 2004 to 2018.

2.3. PVAR model

Based on the panel data, which consists of the performance of food (SDG2), water (SDG6), energy (SDG7), economic (SDG8), consumption and production (SDG12), and forest (SDG15) sectors for 31 provinces in China from 2004 to 2018, we assessed the two-way interactions among these sectors using the Panel Vector Autoregressive (PVAR) model. The PVAR model is an extension of the vector autoregressive model based on the inherent advantages of the latter (Holtz-Eakin et al., 1988). PVAR model reduces the requirement for the length of time series and extends the pure time-series data to the spatial dimension. In the PVAR model, when T is the length of time series and m is the lag order, parameter estimation is possible when $T \geq m + 3$ is satisfied, and when $T \geq 2m + 2$, parameter estimation of each lagged variable is possible at the steady-state level (Holtz-Eakin et al., 1988). PVAR model treats all variables as endogenous by default (Swain and Karimu, 2020; Qureshi et al., 2021). By sequentially treating each variable in the model as the dependent variable and the others as independent variables, a concise equation set can be formed (Sigmund and Ferstl, 2021). After estimating the equation set jointly, the feedback of each variable on another variable can be tracked, and this can be interpreted as causal relation (Qureshi et al., 2021). The equation for the PVAR model in this study is as follows.

$$y_{it} = \sum_{j=1}^{p} \beta_j y_{it-j} + v_t + \gamma_i + \varepsilon_{it} \tag{1}$$

where y_{it} is the matrix of endogenous variables, y in this study includes the performance of food (SDG2), water (SDG6), energy (SDG7), economic (SDG8), consumption and production (SDG12), and forest (SDG15) sectors; i is an individual unit, which in this study represents the 31 mainland provinces of China; t is the period, from 2004 to 2018; y_{it-j} is the j order lag term of y_{it}; p is the lag order; β_j is the parameter estimation matrix; v_t is the time fixed effects. γ_i is the individual effect of inter-provincial differences; ε_{it} is the random error term.

To avoid the phenomenon of "pseudo-regression" caused by unsteady data, the Levin-Lin-Chu and Im-Pesaran-Shin tests were chosen to test the stability of the data in this study (Levin et al., 2002; Im et al., 2003). The test results were presented in Table A3, from which we can see that all the variables are smooth after one difference. Thus, we can use the data after one difference to construct the PVAR model (see Supplementary Information). We used the generalized method of moments (GMM) for parameter estimation to eliminate the individual and time fixed effects of the variables (Arellano and Bover, 1995). The results of the parameter estimation are given in Table A4. These results demonstrate the direction and strength of the effect of the independent variable on the dependent variable (see Supplementary Information).

It is noteworthy that, despite the insignificance of some of the parameters (Table A4), it cannot be concluded that there is no potential association between the two sectors. We used the impulse response function (IRF) in the PVAR model to assess the two-way interactions between the sectors in our expanded FEW nexus. These results can be used to track the causality between the sectors because the IRF calculates how one sector responds to a shock of one standard deviation to another sector (Swain and Karimu, 2020). Before the assessments through IRF, we tested the stability of our PVAR model by analyzing whether the roots of the companion matrix were less than 1 (Sigmund and Ferstl, 2021). The values of the roots of all the companion matrixes of the model are within the unit circle (Fig. A1), demonstrating the model's stability and allowing for simulation analysis. We assessed the response characteristics of the dependent variable in the following ten periods after a change in the independent variable. This assessment enables us to observe the changing characteristics of the dependent variable's response over time. Furthermore, we used the variance decomposition to quantify the contribution of shocks from one sector to changes in other sectors, thus revealing the key sector that influences each other in the expanded FEW nexus. We applied STATA 16 software for PVAR model construction and statistical analysis. Please see the supplementary information for these testing and assessment processes.

3. Results

3.1. Spatio-temporal dynamics of the expanded FEW nexus

Our findings show that at the national level, the performance of food (SDG2), consumption and production (SDG12), and forest (SDG15) sectors in China has decreased from 2004 to 2018, with SDG2 scores decreasing the most at 16.9 points (Fig. 2a). Meanwhile, we found that the increase in performance was mainly seen in the water (SDG6) and economic (SDG8) sectors, which increased by 24.9 and 22.9 points respectively, while the performance of the energy sector (SDG7) increased by only 4.6 points (Fig. 2a). At the provincial level, the performance of the water (SDG6) and economic (SDG8) sectors show an upward trend in all provinces, but the food sector (SDG2) has decreased in all provinces (Fig. 2b). However, it is not arbitrary to state there is a deterioration in China's food security, which encompasses multiple aspects such as food availability and food safety. For example, although China's grain production has increased over the past decade, food safety issues are coming to the fore (Lam et al., 2013). The decline in the performance of China's food sector is mainly due to improvements in some indicators being offset by deterioration in others (Zhang et al., 2022b). We give a more detailed explanation in the discussion. In addition, the performance for the energy sector (SDG7) increased in 19 provinces, but a decrease in 12 provinces. While the performance for the consumption and production sector (SDG12) increased in 18 provinces, other provinces showed a greater degree of decline, thus making them a downward trend at the national level. Furthermore, for the forest sector (SDG15), only seven provinces showed an increase in their scores, and most did not score above 50 in 2018.

3.2. Two-way interactions in food-water-energy-forest nexus

Fig. 3 shows the two-way interactions among the food (SDG2), water (SDG6), energy (SDG7), and forest (SDG15) sectors in China. The results indicate that some sectors in the expanded FEW nexus are mutually causal, some sectors respond differently, and their responses change over time. For example, SDG2 can respond positively to a shock (an unexpected increase) on SDG6, but SDG6 shows a negative response to a shock on SDG2 (Fig. 3a). This result implies that improving water security (SDG6) is beneficial to enhancing food security (SDG2), but if food security is advanced first, it may inhibit water availability in households. In practice, the construction of water projects (such as the South-North Water Transfer Scheme) greatly contributes to agricultural production and domestic water demand in northern China (Liu and Yang, 2012). However, competition for water in agriculture and domestic use is probably the main reason for the improvement in the SDG2 suppressing the SDG6, especially in arid and semi-arid regions (Song et al., 2020).

Meanwhile, we found that SDG2 responded negatively to the shock on SDG7 in the first period but started to turn positive in the second period (Fig. 3b). This result represents that the development of clean energy (SDG7) may threaten food security in the short term but has long-term benefits. However, SDG7 consistently shows a negative response to the shock on SDG2, i.e., it may indicate that prioritizing food security constrains the development of clean energy in China. Several studies point out that the competition for water and land resources between grain and biofuel production is the main reason for the trade-off between food and energy (Murphy et al., 2011; Herrmann et al., 2018). It could explain why prioritizing SDG2 in China may inhibit the improvement of SDG7. Nonetheless, the development of clean energy contains a variety of avenues, such as hydropower, wind power, and solar energy, and the construction of these facilities does not normally cause extensive damage to farmland (D'Odorico et al., 2018). Therefore, we argue that promoting clean energy could be achieved together with food security by properly selecting clean energy technologies.

For the nexus between food (SDG2) and forest (SDG15) in China, our results showed that SDG2 responded negatively to an unexpected increase in SDG15 over a relatively long period, but SDG15 consistently showed a positive response to shocks on SDG2 (Fig. 3c). This finding means that while forest conservation and restoration projects (SDG15) may inhibit food production (SDG2), prioritizing food security would facilitate forest conservation. Indeed, various forest protection and restoration projects in China compensate residents financially. However, the residents argued that some projects, such as the Grain for Green Project and the Natural Forest Conservation Program, still hurt their livelihoods because these compensations do not cover the loss of abandoning their agricultural production and grazing activities (Cao, 2011). However, practice in some areas has also shown that prioritizing the improvement of livelihoods through different incentives, such as subsidizing clean energy to mitigate deforestation by farmers, can effectively increase the willingness of local people to conserve and thus accelerate forest restoration (Cao et al., 2017). Accordingly, our results demonstrate the possibility that trade-offs between SDG2 and SDG15 can be transformed into synergies. Similarly, we found that SDG15 responded positively to the shock on SDG7, highlighting that clean energy could reduce people's demand for fuelwood and thus strengthen forest restoration (ICSU-ISSC, 2015). Nonetheless, the impact of SDG15 on SDG7 exhibited a fluctuating response process (Fig. 3f), i.e., SDG7 responded positively to a shock on SDG15 in the first two periods, but a negative response from the third period onwards. This fluctuation may be attributed to the conflict between the photovoltaic site or the cultivation of non-native biofuel species for energy production and woodland restoration (WWF, 2018).

Furthermore, our results also reveal that some sectors can exhibit the same response under mutual causality but may manifest themselves in two different ways. Firstly, both SDG6 and SDG7 respond negatively to the unexpected increase in each other (Fig. 3d), implying a severe trade-off between water security (SDG6) and clean energy (SDG7) in China. This trade-off could mainly be because of increased clean energy generation in China (Hepburn et al., 2021) based on water-intensive renewables, e.g., hydropower, bioenergy, and concentrated solar power (Yillia, 2016). Especially, concentrated solar powers are generally located in arid regions and have exacerbated the competition for water resources among different sectors (Yillia, 2016). Hence, resolving the trade-offs between water and energy remains a huge challenge for China. However, secondly, we found that both SDG6 and SDG15 responded positively to each other (Fig. 3e), which indicates a synergistic relationship between water security (SDG6) and forest restoration and protection (SDG15). Although the increase in forest cover may reduce water yields owing to the interception, it also has the function of purifying water (WWF, 2018; Melo et al., 2021). Early forest restoration projects in China have been criticized for neglecting issues such as water carrying capacity and species suitability, but improving forest structure based on ecological thresholds is effective in facilitating the fit among forest and both water and soil nutrients (Zhang et al., 2018; Zhang et al., 2021). Overall, our results prove the potential for achieving a win-win outcome for water conservation and forest restoration.

3.3. Interactions among food-water-energy-forest nexus and socio-economic factors

We can see the interlinkages among the food-water-energy-forest nexus and socio-economic factors from Fig. 4 and 5. For a unit of structural shock on the SDG8, both SDG2 and SDG15 responded negatively (Fig. 4a). Similarly, the shocks on SDG2 and SDG15 also induced negative responses for SDG8 (Fig. 4b). These results reveal that China's economic growth (SDG8) has trade-offs with food production (SDG2) and forest conservation (SDG15). Several studies have pointed out that China's past economic growth has been overly dependent on resource consumption, including deforestation (Li et al., 2021) and the conversion of agricultural land into land for construction (Zheng et al., 2014). Our findings, therefore, re-emphasize that decoupling economic growth from resource consumption will be key to securing sustainable development in China (Cao et al., 2015).

Additionally, Fig. 4 shows that economic growth (SDG8) and water security (SDG6) can be mutually reinforcing, as SDG6 could respond positively to shock on SDG8, and SDG8 could also show a positive response to shock on SDG6. SDG7 has a positive response to shock on SDG8 (Fig. 4a), but SDG8 responds negatively to shock on SDG7 (Fig. 4b). This result highlights that China's economic growth (SDG8) has contributed to the development of clean energy (SDG7), but clean energy has not yet been able to drive economic growth. In China, clean energies (e.g., wind and solar) are not yet a sufficient substitute for traditional energies (e.g., coal and oil) in maintaining energy supply capacity for socio-economic development due to the lack of sound storage technologies and the high storage costs (Feldman et al., 2020). Nonetheless, given the challenges of environmental pollution associated with the consumption of fossil fuels, promoting clean energy is a major trend for China and the rest of the world (Marinaș et al., 2018; O'Meara, 2020).

For the consumption and production sector (SDG12), we found that an unexpected increase of SDG12 leads SDG6 to respond positively but SDG15 responding negatively (Fig. 5a), implying that transformation of consumption and production patterns (SDG12) in China contributes to water security (SDG6) but may hinder forest restoration (SDG15). Meanwhile, we found that SDG2 and SDG7 showed opposite responses to shocks in SDG12, i.e., SDG2 responded negatively in the first four periods. It then turned positive, but SDG7 responded positively in the first three periods and then negative (Fig. 5a). These results suggest that improvements in consumption and production patterns can have long-term benefits for food security but only short-term benefits for clean energy development. However, when SDG12 is treated as the dependent variable, our results indicated that shocks on SDG2 and SDG15 could make SDG12 respond positively, but SDG6 and SDG7 would have almost no effect on SDG12 (Fig. 5b). This result reflects that prioritizing food security (SDG2) and forest restoration (SDG15) is more beneficial for improving consumption and production patterns (SDG12).

What should be emphasized is that there are direct links between economic growth (SDG8) and consumption and production patterns (SDG12) and that our results reveal a mutual inhibition between SDG8 and SDG12 for China (Fig. A2). This result also reveals that China’s high pollution and emission production patterns have been an important driver of economic growth in the past (Cao et al., 2015). Nonetheless, we acknowledge that few plausible explanations are available for why the interactions between SDG12 and food-energy-water-forest nexus exhibit the above characteristics, as targeted research in this area is lacking (Scoones et al., 2020). Generally, theoretical analysis argued that progress in SDG12 could contribute to other SDGs since it aims to reduce material footprints and waste and increase resource use efficiency (ICSU-ISSC, 2015), but quantitative assessments always found irreconcilable trade-offs (Pradhan et al., 2017; Zhang et al., 2022a). Our results indicate that improvements in SDG12 would primarily enhance water security (SDG6), but we also found that promoting food security and forest restoration would benefit the progress of SDG12._This finding may imply a reverse management paradigm, whereby strict restrictions on the consumption of natural resources could force innovations in sustainable production and consumption patterns (Scoones et al., 2020).

3.4. Contribution of mutual influences across sectors

Compared to impulse response analysis, variance decomposition can further quantify the contribution of a variable to changes in other variables, thus revealing the key impact factors (Swain and Karimu, 2020). As we can see in Fig. 6, besides the highest impact of each sector on itself, there is an upward trend in the impact of the other sectors. Our results show that economic growth (SDG8) in China has a more important impact on food (SDG2), water (SDG6), and energy (SDG7) sectors. In contrast, consumption and production patterns (SDG12) have a more important impact on forest restoration and conservation (SDG15) (Fig. 6). Additionally, the impact of the energy sector (SDG7) on economic growth (SDG8) stays above 8% from the first period. Meanwhile, the impact of the water sector (SDG6) on economic growth (SDG8) gradually increases from the third period. It means that clean energy always has a certain impact on economic growth, while water conservation has a delayed effect.

Another remarkable result is that the forest sector (SDG15) contributes only marginally to changes in other sectors. This finding contradicts the consensus that forests can always have a significant impact on food, water, energy, and economic development (Tidwell, 2016; Melo et al., 2021). However, our findings could be interpreted through potential interlinkages among the specific indicators. Previous studies pointed out that forest landscape restoration can contribute to agricultural production by promoting pollination and resisting erosion (Melo et al., 2021). However, food security (SDG2) is not only concerned with food production and supply but also with food safety, such as malnutrition or related diseases (Lam et al., 2013). Food safety is rarely directly related to forests but is more influenced by human behaviours, such as the use of harmful food additives. Similarly, universal access to sanitation and urban wastewater treatment are included in SDG6. However, improvements in these indicators rely heavily on financial support and engineering measures and generally do not have direct links to forests. These absences in connections might be the major reason for the low contribution of SDG15 to the change in other SDGs. Nonetheless, these results do not arbitrarily conclude that forests are unimportant for other sectors but rather underscore the limitations of forests in the context of the FEW nexus.

4. Discussion

Our study provides several novel insights for analyzing the FEW nexus and transforming the trade-offs between different sectors into synergies through the nexus approach while addressing the research questions. First, we need to stress that using different indicators may make the results different, as presented in other studies (Putra et al., 2020). For example, our results show that the performance of the food sector (SDG2) in China's provinces shows varying degrees of deterioration, but some previous assessments suggest a gradual improvement (Xu et al., 2020a; Sachs et al., 2021). This difference is mainly because previous studies used indicators more related to food production, including cereal production and growth rates, and crop irrigation and crop water use efficiency to assess SDG2. However, they do not elaborate on the correspondence between these indicators and SDG targets, which may cause redundancy, i.e., reflect more indicators with better performance.

To avoid the redundancy of the selected indicators, the indicators used in this study are numbered to correspond to the serial number of SDG targets and SDG indicators (Table A1).

Accordingly, the deterioration in the performance of China's food sector (SDG2) was due to the decline in the score of the food safety-related indicator (indicator 2.1.1), offsetting the improvement in food production (indicator 2.1.2) (Zhang et al., 2022b). Meanwhile, we considered the Agriculture Oriented Index (AOI, indicator 2.a.1) for provinces in China, which is defined as the Agriculture Share of Central Government Expenditure, divided by the Agriculture Share of Gross Domestic Product (UN, 2017). The decline in AOI scores is also a key contributor to the deterioration of performance in the food sector across China's provinces (Zhang et al., 2022b). Since the AOI has not been assessed in previous studies, it may cause some uncertainty to our results.

Additionally, the two-way interaction characteristics between some sectors in our study are also inconsistent with other studies due to differences in the choice of indicators. For example, we found that progress in the performance of the food sector (SDG2) in China inhibits the progress in water sectors (SDG6), but that improving the performance of the water sectors (SDG6) as a priority can have a positive effect on food sector (SDG2). Nonetheless, Yan et al. (2020) showed that the shock on food production in China could positively affect the water supply. However, changes in the water supply can cause a negative response to food production. Despite some discrepancies between our results and other assessments, they do not indicate which assessment is more accurate but rather reveal issues that have been overlooked in past studies, thus generating a wider discussion.

Second, our research highlights that in the expanded FEW nexus, the mutual influence between different sectors might vary. By recognizing such variations, we could explore ways to use synergies between different sectors and avoid trade-offs, providing critical information for translating nexus thinking into nexus action (Liu et al., 2017; Simpson and Jewitt, 2019). Generally, our results suggest that changing the prioritization of management actions may transform trade-offs into synergies for the overall implementation of the SDGs and highlight the need for more attention to addressing mutual inhibitions between some sectors in future sustainability policy. For example, we found that although forest restoration may be detrimental to food security for some time, prioritizing food security facilitate synergistic development in both sectors. Similarly, the mutual inhibition between water security and clean energy development is the critical impediment for China to achieve the SDGs. While our research is an exploratory analysis of two-way interactions between the expanded FEW nexus from the SDG lens, these results reflect that China’s past management measures and actions have led to the current state of interlinkages between different sectors. Hence, these implications would make sense for the security of the FEW nexus and advancing SDGs through the nexus approach.

Thirdly, we stressed that economic growth has a more important impact on the food-energy-water-forest nexus than consumption and production patterns in China. Actually, substantial efforts have been dedicated to expanding the framework of the FEW nexus. Several studies have highlighted that ensuring the FEW security nexus cannot ignore the influence of other socio-economic activities, excluding each sector itself. Our results further reveal that economic growth (SDG8) in China has a higher contribution to changes in food (SDG2), water (SDG6), and energy (SDG7) sectors. In comparison, consumption and production patterns (SDG12) mainly have an even higher contribution to changes in the forest sector. Nevertheless, the trade-offs between economic growth and food production, and forest restoration remain the key challenges that need to be addressed (Zhang et al., 2022a). Additionally, the reasons behind a lower contribution of transformations in consumption and production patterns to changes in other sectors may be because shifts in irrational consumption and production patterns are constrained by financial, technological, and institutional factors, all of which may inhibit the synergies between SDG12 and other SDGs (Scoones et al., 2020). However, achieving sustainable development lies in decoupling economic growth from resource consumption and environmental pollution, which requires advances in production technology and a shift in human behaviour (Fletcher and Rammelt, 2017). Nevertheless, these advances and shifts may not be achievable based on one region's capacity. Promoting collaboration between regions at different development levels and encouraging economic and technical assistance from developed regions to less developed regions will be crucial to leverage the positive impact of the fundamental transformations (Sachs et al. 2019; Fu et al., 2020).

Several deficiencies in our study deserve continuous refinement. First of all, our findings were obtained from panel data analysis, which does not fully represent the actual situation of the multi-sectoral linkages in China. Quantitative studies on the FEW nexus at different spatial scales and specific indicators still need to be strengthened in the future (Liu et al., 2017; Liu et al., 2020). Meanwhile, these results are largely influenced by choice of indicators, including the amount and reliability of indicator data. As data availability improves, it will be necessary to develop a uniform indicator framework at the sub-national level to enhance the relevance of the results for policy formulation. Second, the PVAR model can only analyze direct interactions between two variables. However, indirect effects among multiple variables exist in the real world, which is outside the scope of this study. Methods based on path analysis or system dynamics can effectively detect such indirect effects, but they also require prior knowledge of the causal links among different variables (Anderson et al., 2021). The present results can provide important information for developing complex system dynamics models.

Last but not least, although we expanded the FEW nexus by simultaneously considering food (SDG2), water (SDG6), energy (SDG7), economic (SDG8), consumption and production (SDG12), and forest (SDG15) sectors, other SDGs could also be linked to the FEW nexus to varying degrees. For example, extreme poverty can force people to cut down forests for energy or growing food, so reducing poverty (SDG1) is significant for the security of the regional FEW nexus (Cao et al., 2017). Besides, keeping human well-being and health (SDG3) is closely linked to the FEW nexus (Liu et al., 2018). For example, modern diets rely too much on meat and foods with high sugar or fat levels, and these diets are considered harmful to human health and a major cause of increased carbon emissions (Tilman and Clark, 2014; Pradhan and Kropp, 2020). More importantly, when the security of the FEW nexus is compromised, not everyone faces the same threats, and the poorer population may be affected more in general. Therefore, considering inequalities (SDG10) in ensuring the FEW nexus security draws attention (Romero-Lankao and Gnatz, 2019). Overall, how the analytical framework of the FEW nexus is expanded should be flexible and context-specific since the differences faced by different regions are variable. However, the key is to reflect the actual issues in the region and to help find solutions.

5. Conclusion

By expanding the framework of the FEW nexus from the lens of SDGs and quantifying the two-way interactions between different sectors in China, our results suggest that although there are more trade-offs than synergies between sectors in the expanded FEW nexus, changing the prioritization of management actions can effectively reduce the negative impact of changes in one sector on others. However, exploring ways to address the mutual inhibition among some sectors still needs to be given adequate attention. While the findings presented here describe the situation in China, they raise several thought-provoking issues. More quantitative assessments on the FEW nexus and its expanded framework should be encouraged, including assessments in different countries, regions, and scales. Differences in results may exist due to disparities in data, but this allows for the timely identification of inconsistencies between qualitative and quantitative, thus guiding the policy-making. Meanwhile, only considering the indicators within the SDGs may not adequately capture the actual linkages and issues among food, energy, water, and other sectors. It is mainly because the SDGs are the major concern from 2016 to 2030 and do not fully reflect all the challenges regarding long-term sustainable development. Finally, discovering the trade-offs is often an important step toward sustainable development. However, it is incumbent upon scientists to further explore effective measures to address trade-offs, something that has been rarely reported in existing studies.

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Figure captions

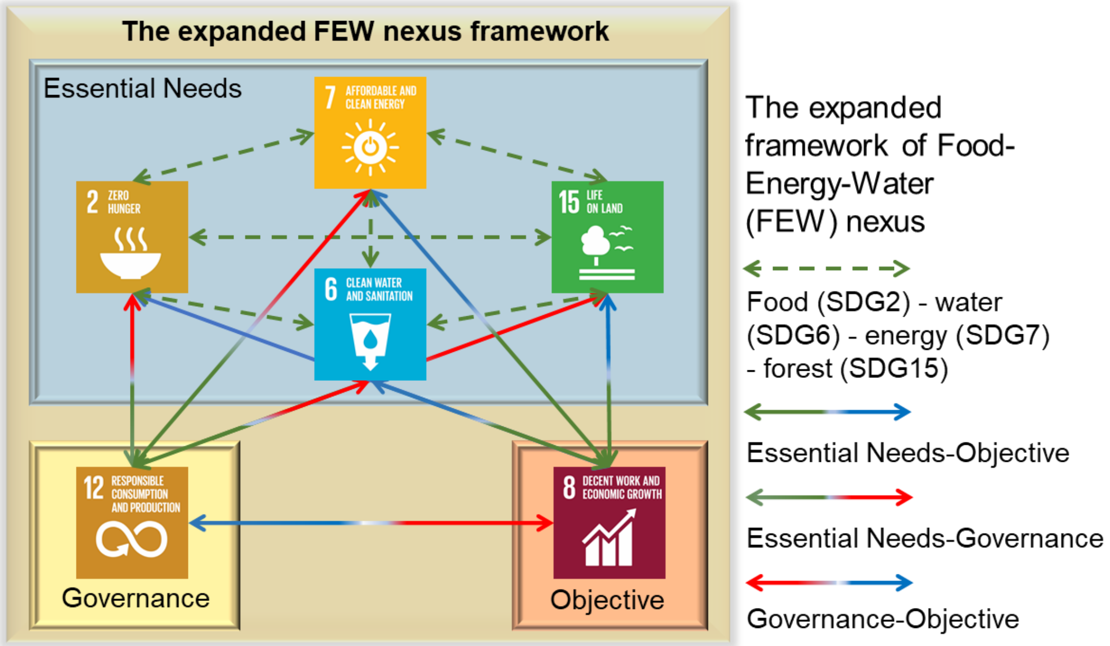

Fig. 1. The expanded framework of the food-energy-water (FEW) nexus from the lens of SDGs in this study. Here, food, water, and energy sectors correspond to SDG2 (No Hungry), SDG6 (Clean Water and Sanitation), and SDG7 (Clean Energy). Considering forests as an important natural resource closely linked to water, food, and energy, SDG15 (Life on Land) is used as the fourth dimension of the FEW nexus. Besides, we considered the potential linkages of the FEW nexus with socio-economic activities, including economic growth (SDG8) and consumption and production patterns (SDG12). According to the systematic classification framework of SDGs proposed by Fu et al. (2019), SDG2, SDG6, SDG7, and SDG15 is "Essential Needs" for human survival. The green dashed line with double arrows indicated their linkages. The SDG8 belongs to the "Objectives", representing the human quest for wealth, which can come at the cost of resource depletion, and therefore has different links to the SDGs in the "Essential Needs". These links are connected by two-way arrows made up of blue and green. Meanwhile, SDG12 is a "Governance" approach to improve human behaviour and reduce resource waste. The links between SDG12 and the SDGs in "Essential Needs" are shown by the solid line in green and red. Additionally, there is a direct link between SDG12 and SDG8, indicated by the solid line in blue and red.

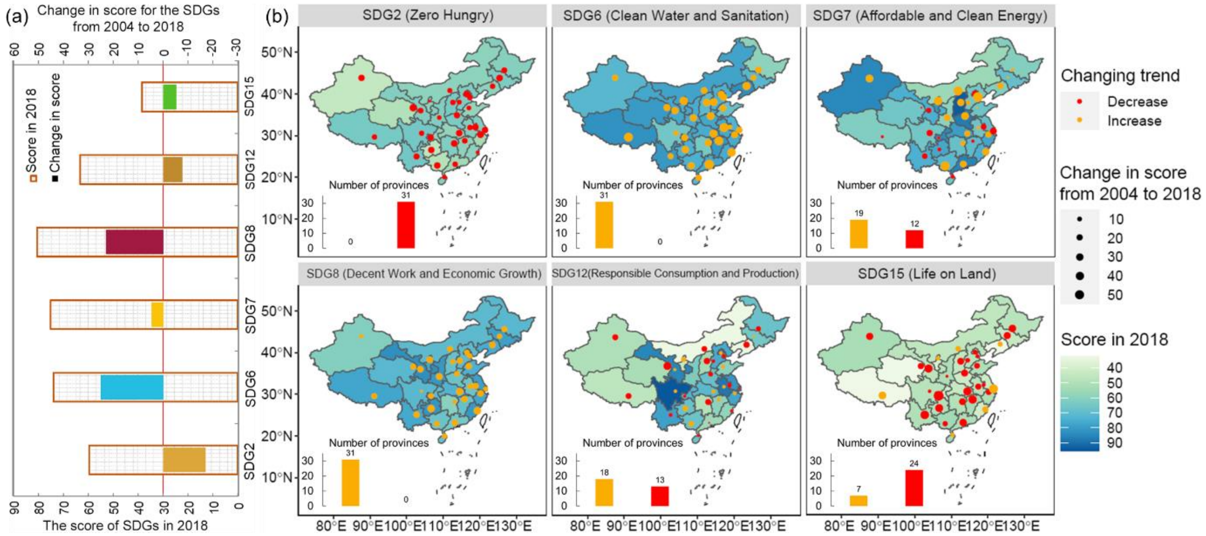

Fig. 2. Spatial and temporal dynamics of the expanded FEW nexus in China from 2004 to 2018, which consists of food (SDG2), water (SDG6), energy (SDG7), economic (SDG8), consumption and production (SDG12), and forest (SDG15) sectors. (a) The progress of each sector at the national in 2018 and the changing characteristics from 2004 to 2018. (b) The progress of each sector in 31 provinces in 2018 and the changing characteristics from 2004 to 2018.

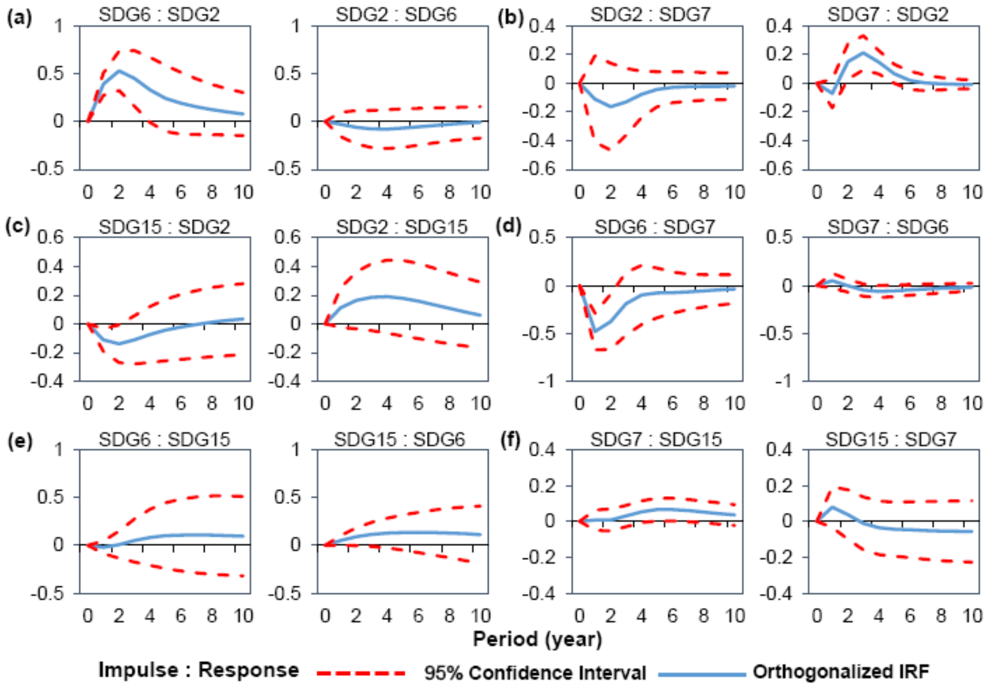

Fig. 3. The two-way interactions of food-water-energy-forest nexus from the lens of SDGs, which correspond to SDG2 (No Hungry), SDG6 (Clean Water and Sanitation), SDG7 (Clean Energy), and SDG15 (Life on Land), respectively. The SDG on the left represents the impulse variable, and the right one is the response variable. The solid blue line in the middle represents the orthogonalized impulse response function (IRF). The vertical axis is the response value, and the horizontal axis is the lag period before the response. The red dashed line is the 95 percent confidence band constructed based on 500 replications.

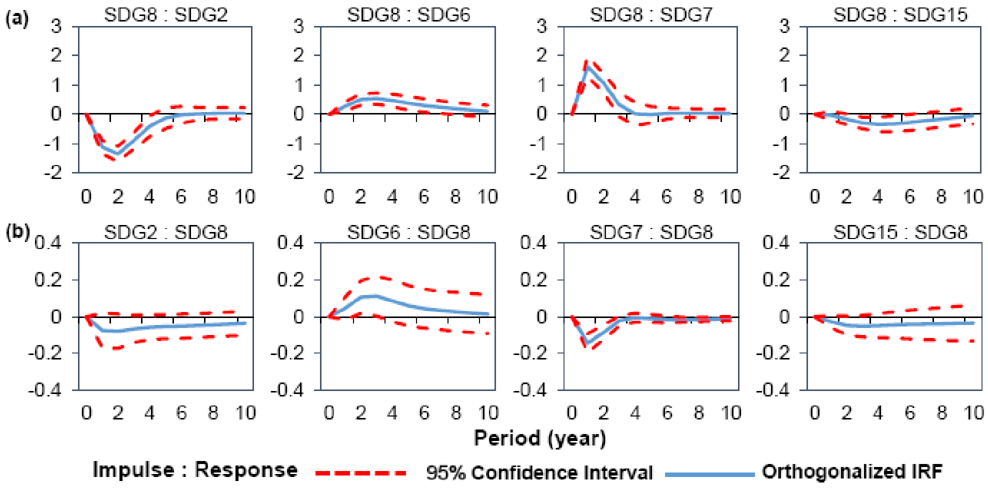

Fig. 4. The impact and response of economic growth on food, water, energy, and forest. Economic growth is represented by SDG8 (Decent Work and Economic Growth), and food, water, energy, and forest sectors correspond to SDG2 (No Hungry), SDG6 (Clean Water and Sanitation), SDG7 (Clean Energy), and SDG15 (Life on Land). The solid blue line in the middle represents the orthogonalized impulse response function (IRF). The vertical axis is the response value, and the horizontal axis is the lag period before the response. The red dashed line is the 95 percent confidence band constructed based on 500 replications.

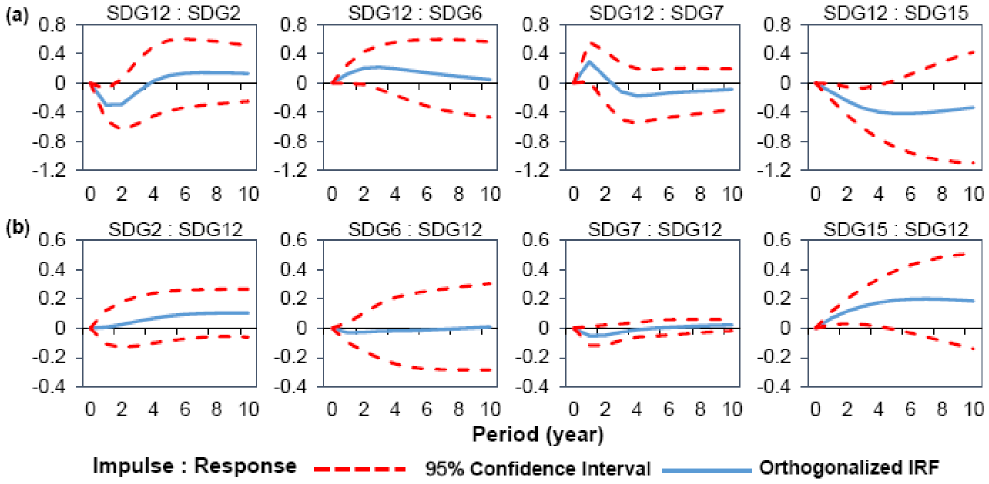

Fig. 5. Impacts and responses of consumption and production patterns on food, water, energy, and forest. Consumption and production patterns are represented by SDG12 (Responsible Production and Consumption), and food, water, energy, and forest sectors correspond to SDG2 (No Hungry), SDG6 (Clean Water and Sanitation), SDG7 (Clean Energy), and SDG15 (Life on Land). The solid blue line in the middle represents the orthogonalized impulse response function (IRF). The vertical axis is the response value and the horizontal axis is the lag period before the response. The red dashed line is the 95 percent confidence band constructed based on 500 replications.

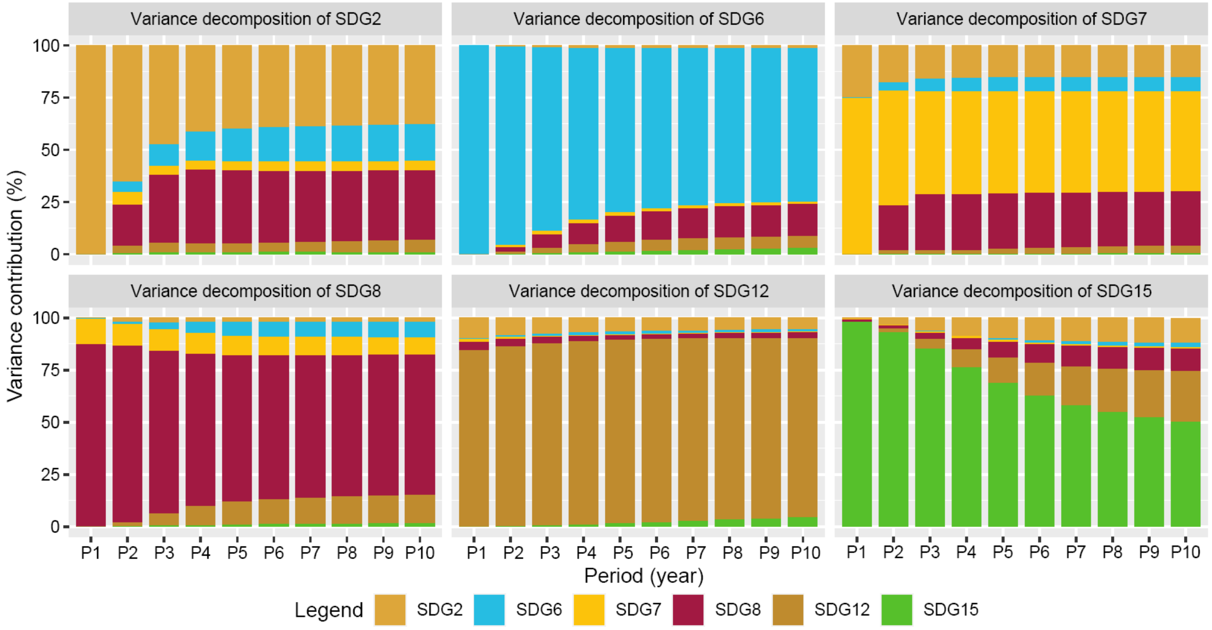

Fig. 6. The variance contribution of mutual influences across sectors in the expanded food-energy-water (FEW) nexus in China at different periods. The expanded FEW nexus consists of food (SDG2), water (SDG6), energy (SDG7), economic (SDG8), consumption and production (SDG12), and forest (SDG15) sectors. The horizontal axis shows the lag periods from first to tenth.

Appendix – Supplementary methods, tables, and figures

Mapping the complexity of the food-energy-water nexus from the lens of SDGs in China

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SUPPLEMENTARY METHODS

Panel vector autoregression model

In this study, based on the normalized score data of different Sustainable Development Goal (SDG) indicators published by Zhang et al. (2022), we used the Panel Vector Autoregressive (PVAR) model to simulate the two-way interactions between the six sectors in the expanded food-energy-water (FEW) nexus in China, including the food (SDG2), water (SDG6), energy (SDG7), economic (SDG8), consumption and production (SDG12), and forest (SDG15) sectors. Specific information about the indicator data was shown in Tables A1 and A2.

To avoid the pseudo-regression caused by unstable data, we checked the stability of the data before the modeling. For panel data, when it is mean and variance do not change over time, if the covariance of the data is equal for any two periods with the same time interval (unrelated to the starting point of time), then the panel data is stable. Considering that the augmented Dickey-Fuller (ADF) test is less effective when applied to the panel data, we chose the Levin-Lin-Chu (LLC) test and Im-Pesaran-Shin (IPS) test to test the stability of the data in this study (Levin et al., 2002; Im et al., 2003). The test results show that the raw score data of SDG6, SDG7, and SDG8 are stable in the LLC test. Although the raw data of SDG2 and SDG12 were not stable, they could be converted into stable data after the first-order difference. In addition, the original data of SDG6 and SDG8 were found to be stable series under the IPS test, and the other data could be transformed into stable series after first-order differencing (Table A3). Overall, it can be seen that all variables belong to the first-order single-integer series, i.e., the cases after first-order differencing are all stable series, so the PVAR model can be constructed using the data after first-order differencing.

Since lagged variables are associated with fixed effects, a system that estimates a fixed-effects model in a small sample is subject to “Nickel bias” (Swain and Karimu, 2020). To address this bias, we use the generalized method of moments (GMM) for parameter estimation

(Arellano and Bover, 1995), which can eliminate individual fixed effects and time effects by forwarding mean difference and cross-sectional mean difference methods, respectively. Since a larger lag order results in a smaller degree of freedom for the sample, we choose the default first-order lag of the STATA16 software for modeling. The parameter estimation results are shown in Table A4. The parameters of each variable can reveal the direction and strength of the independent variables on the dependent variables. For example, when SDG2 is the dependent variable, the coefficients for SDG2 and SDG6 with a one-period lag are 0.577 and 0.391 respectively and are significant at the 1% level, indicating that the above two SDGs have a positive impact on SDG2 and are more influential by itself. In addition, SDG8, SDG12, and SDG15 had a significant negative impact on SDG2, but SDG7 did not have a significant negative impact (Table A4).

While some parameters are not significant, the impulse response function and variance decomposition could be used to provide insight into the potential links between different SDGs (Swain and Karimu, 2020). To ensure the accuracy of the impulse response analysis and variance decomposition results, we performed a stability check on the PVAR model. By comparing the modulus of the accompanying matrix roots with 1, if all of them are less than 1, the model is stable, and vice versa, the model is unstable (Hamilton, 1994; Sigmund and Ferstl, 2021). Our results show the values of all the accompanying matrix roots of the model lie within the unit circle (Fig. A1), which indicates that the PVAR model constructed in this study is stable and can be used for simulation analysis. Fig. A2 illustrates the impulse response function among all SDGs. We applied an orthogonal impulse response function that captures the response of one variable to an orthogonal shock of another variable. Using this method, we can identify the effects of one shock at a time, while keeping the other shocks constant (Swain and Karimu, 2020).

SUPPLEMENTARY TABLES

Table A1. Indicators selected in this study and their data sources (Zhang et al., 2022).

Goals	Targets	Indicators		Time range
2	2.1 By 2030, end hunger and ensure access by all people, in particular the poor and people in vulnerable situations, including infants, to safe, nutritious and sufficient food all year round	2.1.1	Number of patients with foodborne diseases (per million population)	2012-2018
2	2.1	2.1.2	Cereal yield per unit area (tons/ha)	1991-2018
2	2.2 By 2030, end all forms of malnutrition, including achieving, by 2025, the internationally agreed targets on stunting and wasting in children under 5 years of age, and address the nutritional needs of adolescent girls, …	2.2.2	Proportion of moderate to severe malnutrition in children under 5 years old (%)	2002-2018
2	2.a Increase investment, including through enhanced international cooperation, in rural infrastructure, agricultural research and extension services, technology development and …	2.a.1	Agriculture orientation index for government expenditures	2007-2018
6	6.1 By 2030, achieve universal and equitable access to safe and affordable drinking water for all	6.1.1	The proportion of the population benefiting from the treated water in the total population of the sick area — Endemic fluorosis (water type) (%)	2002-2018
6	6.2 By 2030, achieve access to adequate and equitable sanitation and hygiene for all and end open defecation, paying special attention to the needs of women and girls and those in vulnerable situations	6.2.1	The penetration rate of sanitary toilet in rural area (%)	2008-2018
6	6.3 By 2030, improve water quality by reducing pollution, eliminating dumping and minimizing release of hazardous chemicals and materials, halving the proportion of untreated wastewater…	6.3.1	Sewage treatment rate in cities (%)	2002-2018
6	6.4 By 2030, substantially increase water-use efficiency across all sectors and ensure sustainable withdrawals and supply of freshwater to address water scarcity…	6.4.1	Water-use efficiency (m^3/RMB)	2003-2018
6	6.4	6.4.2	Ratio of total water consumption to total water resources (%)	2003-2018
6	6.a By 2030, expand international cooperation and capacity-building support to developing countries in water- and sanitation-related activities and programmes, …	6.a.1	Investment in environmental pollution control as a percentage of GDP (%)	2003-2018
7	7.1 By 2030, ensure universal access to affordable, reliable and modern energy services	7.1.2	Gas penetration rate in cities (%)	1999-2018

7	7.2 By 2030, increase substantially the share of renewable energy in the global energy mix	7.2.1	Proportion of clean energy power generation to total power generation (%)	1995-2018
7	7.3 By 2030, double the global rate of improvement in energy efficiency	7.3.1	Energy intensity (ton standard coal per 10,000 RMB)	2000-2018
8	8.1 Sustain per capita economic growth in accordance with national circumstances and, in particular, at least 7 per cent gross domestic product growth per annum in the least developed countries	8.1.1	Annual growth rate of real GDP per capita (%)	1994-2018
8	8.4 Improve progressively, through 2030, global resource efficiency in consumption and production and endeavour to decouple economic growth from environmental degradation, …	8.4.2	Wood consumption per unit of added value of construction industry (m^3/10,000 yuan)	2004-2018
8	8.5 By 2030, achieve full and productive employment and decent work for all women and men, including for young people and persons with disabilities, and equal pay for work of equal value	8.5.2	The urban registered unemployment rate (%)	1999-2018
8	8.6 By 2020, substantially reduce the proportion of youth not in employment, education or training	8.6.1	Proportion of employed persons who have never attended school (%)	1996-2018
8	8.8 Protect labour rights and promote safe and secure working environments for all workers, including migrant workers, in particular women migrants, and those in precarious employment	8.8.1	The determination of work-related injuries per 10,000 employed persons	2006-2018
8	8.8	8.8.2	Work-related injury insurance coverage rate (%)	2003-2018
8	8.9 By 2030, devise and implement policies to promote sustainable tourism that creates jobs and promotes local culture and products	8.9.1	The added value of the tertiary industry as a proportion of GDP (%)	1996-2018
12	12.2 By 2030, achieve the sustainable management and efficient use of natural resources	12.2.1	SO_2 emissions per capita (kg/person)	2002-2018
12	12.2	12.2.2	Wood consumption per unit of added value of construction industry (m^3/10,000 yuan)	2004-2018
12	12.4 By 2020, achieve the environmentally sound management of chemicals and all wastes throughout their life cycle, in accordance with agreed international frameworks, and …	12.4.2	Amount of hazardous waste generated per capita (kg/person)	1999-2018
12	12.5 By 2030, substantially reduce waste generation through prevention, reduction, recycling and reuse	12.5.1	Comprehensive utilization rate of industrial solid waste (%)	2000-2018
15	15.1 By 2020, ensure the conservation, restoration and sustainable use of terrestrial and inland freshwater ecosystems and their services, in	15.1.1	Forest cover rate	2004-2018

	particular forests, wetlands, mountains and drylands, …			
15	15.1	15.1.2	The area of wetland ecological nature reserve accounts for the proportion of forestry system nature reserve area	2009-2018
15	15.2 By 2020, promote the implementation of sustainable management of all types of forests, halt deforestation, restore degraded forests and substantially increase afforestation and reforestation globally	15.2.1	The area of forest ecological nature reserves accounts for the proportion of forestry system nature reserves	2009-2018
15	15.3 By 2030, combat desertification, restore degraded land and soil, including land affected by desertification, drought and floods, and strive to achieve a land degradation-neutral world	15.3.1	The proportion of desertified land in total land area (%)	2004-2018
15	15.4 By 2030, ensure the conservation of mountain ecosystems, including their biodiversity, in order to enhance their capacity to provide benefits that are essential for sustainable development	15.4.1	The proportion of the area of wild animal and plant nature reserves in the area of nature reserves in the forestry system	2009-2018
15	15.5 Take urgent and significant action to reduce the degradation of natural habitats, halt the loss of biodiversity and, by 2020, protect and prevent the extinction of threatened species	15.5.1	Ecological protection and construction investment as a percentage of forestry investment	2011-2018
15	15.a Mobilize and significantly increase financial resources from all sources to conserve and sustainably use biodiversity and ecosystems	15.a.1	Forestry investment as a percentage of GDP	2011-2018
15	15.b Mobilize significant resources from all sources and at all levels to finance sustainable forest management and provide adequate incentives to developing countries to advance such management, …	15.b.1	State investment as a percentage of forestry investment	2011-2018

Table A2. Descriptive statistics of SDG indicators and their attribute characteristics (Zhang et al., 2022).

Goals	Targets	Indicators	Target value	Baseline value	Attributes	Sample size	Minimum	Maximum	Average	Standard Deviation	Percentile: 2.5%	Percentile: 97.5%
2	2.1	2.1.1	0	77.4162	Negative	217	0.13	108.38	20.45	19.24	1.75	80.03
		2.1.2	8.6	0.2	Positive	890	2.42	8.02	5.12	1.06	3.02	6.89
	2.2	2.2.2	0	42.3	Negative	544	0.06	9.59	1.84	1.46	0.13	5.43
	2.a	2.a.1	9.79	—	Moderate	384	0.32	19.7	1.73	2.39	0.53	9.08
6	6.1	6.1.1	100	14	Positive	486	1.92	148.57	68.98	24.34	13.59	103.01
	6.2	6.2.1	100	9.7	Positive	344	32.6	99.8	71.95	16.46	38.39	98.48
	6.3	6.3.1	100	19	Positive	534	0.06	98.6	71.21	23.31	18.94	96.86
	6.4	6.4.1	0.0024	0.125	Negative	512	0	0.27	0.02	0.03	0.00	0.12
		6.4.2	12.5	647	Negative	512	0.53	915.47	76.51	139.31	0.80	647.57
	6.a	6.a.1	3.1	0.45	Positive	512	0.05	4.66	1.33	0.69	0.44	3.20
7	7.1	7.1.2	100	35	Positive	639	23.5	113.84	83.91	15.74	46.60	100.00
	7.2	7.2.1	84	0.05	Positive	377	0	95.67	25.70	25.70	0.05	89.05
	7.3	7.3.1	0.31	4	Negative	590	0.25	23	1.31	1.48	0.40	4.00
8	8.1	8.1.1	7	—	Moderate	800	-27.9	46.03	13.28	7.85	0.68	31.40
	8.4	8.4.2	0.29	3.45	Negative	480	0.14	27.15	1.18	1.42	0.29	3.34
	8.5	8.5.2	0.5	25.9	Negative	629	0.62	6.5	3.52	0.72	1.43	4.50
	8.6	8.6.1	0	32	Negative	703	0.14	67.5	7.02	8.62	0.44	32.17
	8.8	8.8.1	2	54	Negative	415	0.9	66.66	13.79	12.54	2.15	54.12
		8.8.2	100	3	Positive	507	0.06	106.07	23.98	19.23	3.11	86.95
	8.9	8.9.1	67	27	Positive	735	24.6	80.98	41.15	8.71	29.64	66.57
12	12.2	12.2.1	0.5	68.3	Negative	544	0.28	64.47	16.85	12.48	1.03	56.54
		12.2.2	0.29	3.45	Negative	480	0.14	27.15	1.18	1.42	0.29	3.34
	12.4	12.4.2	0.88	140	Negative	605	0.12	848.94	28.00	79.04	0.94	141.20
	12.5	12.5.1	100	20.9	Positive	602	1.52	136.06	63.14	22.41	20.67	99.15
15	15.1	15.1.1	63	2.9	Positive	480	2.9	66.8	30.15	17.67	4.20	63.00
		15.1.2	93.92	0.22	Positive	308	0.2	97.16	28.32	25.29	0.22	94.78
	15.2	15.2.1	88.99	1.7	Positive	310	1.34	90.5	47.70	25.15	1.78	86.91
	15.3	15.3.1	0	46.64	Negative	465	0	46.69	7.93	11.65	0.00	46.64
	15.4	15.4.1	100	1.47	Positive	300	0.84	100	21.67	20.71	2.31	100.00
	15.5	15.5.1	92	15	Positive	256	5.04	97	59.91	19.72	15.47	92.63
	15.a	15.a.1	4.9	—	Moderate	256	0.04	6.93	0.80	0.99	0.06	4.95
	15.b	15.b.1	59.291	—	Moderate	256	2.39	100	59.29	27.85	4.69	100.00

Table A3. Unit root test of panel data

Variables	LLC test on raw data	LLC test on first order differential data	IPS test on raw data	IPS test on first order differential data
SDG2	-6.878	-16.173***	-1.362	-2.822***
SDG6	-10.185***	——	-1.872***	——
SDG7	-8.871***	——	-1.462	-3.155***
SDG8	-11.533***	——	-1.911***	——
SDG12	-7.224	-17.984***	-1.283	-2.976***
SDG15	-6.795***	——	-1.234	-2.208***

Note: * * *, * *, and * indicating significance at levels of 1%, 5%, and 10%, respectively.

Table A4 GMM (Generalized Method of Moments) results of PVAR model

Independent variables	Dependent Variables					
	h_dSDG2	h_dSDG6	h_dSDG7	h_dSDG8	h_dSDG12	h_dSDG15
L. h_dSDG2	0.577***	-0.0294	-0.110	-0.0743	0.00613	0.113*
	(6.05)	(-0.42)	(-0.72)	(-1.57)	(0.11)	(1.81)
L. h_dSDG6	0.391***	0.788***	-0.480***	0.0447	-0.0306	-0.0215
	(6.64)	(19.94)	(-5.27)	(1.48)	(-0.89)	(-0.61)
L. h_dSDG7	-0.0708	0.0508	0.0387	-0.144***	-0.0524	0.00693
	(-1.57)	(1.31)	(0.49)	(-5.57)	(-1.64)	(0.23)
L. h_dSDG8	-1.110***	0.277***	1.622***	0.634***	-0.0155	-0.0284
	(-9.58)	(3.64)	(9.24)	(11.26)	(-0.22)	(-0.38)
L. h_dSDG12	-0.300***	0.126*	0.292**	-0.101*	0.911***	-0.121**
	(-2.84)	(1.77)	(2.13)	(-1.88)	(12.05)	(-2.28)
L. h_dSDG15	-0.112***	0.0495**	0.0794	-0.0263	0.0679***	0.866***
	(-2.93)	(1.98)	(1.37)	(-1.48)	(3.15)	(19.84)
Observations	403	403	403	403	403	403

Note: t-statistics in parenthesis; L. is first-period lag; h_ means that the variable is “Helmert” transformed; d means that the original variable is first-order differential; * * *, * *, and * indicating significance at levels of 1%, 5%, and 10%, respectively.

SUPPLEMENTARY FIGURES

Fig. A1. Stability check of the PVAR model in this study.

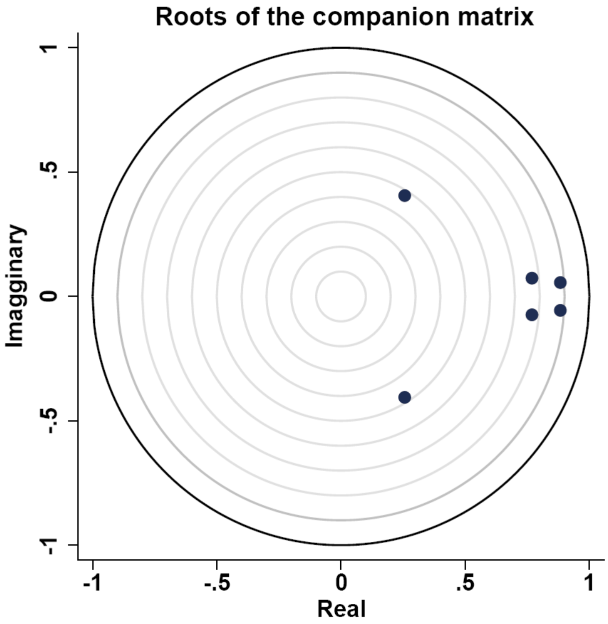
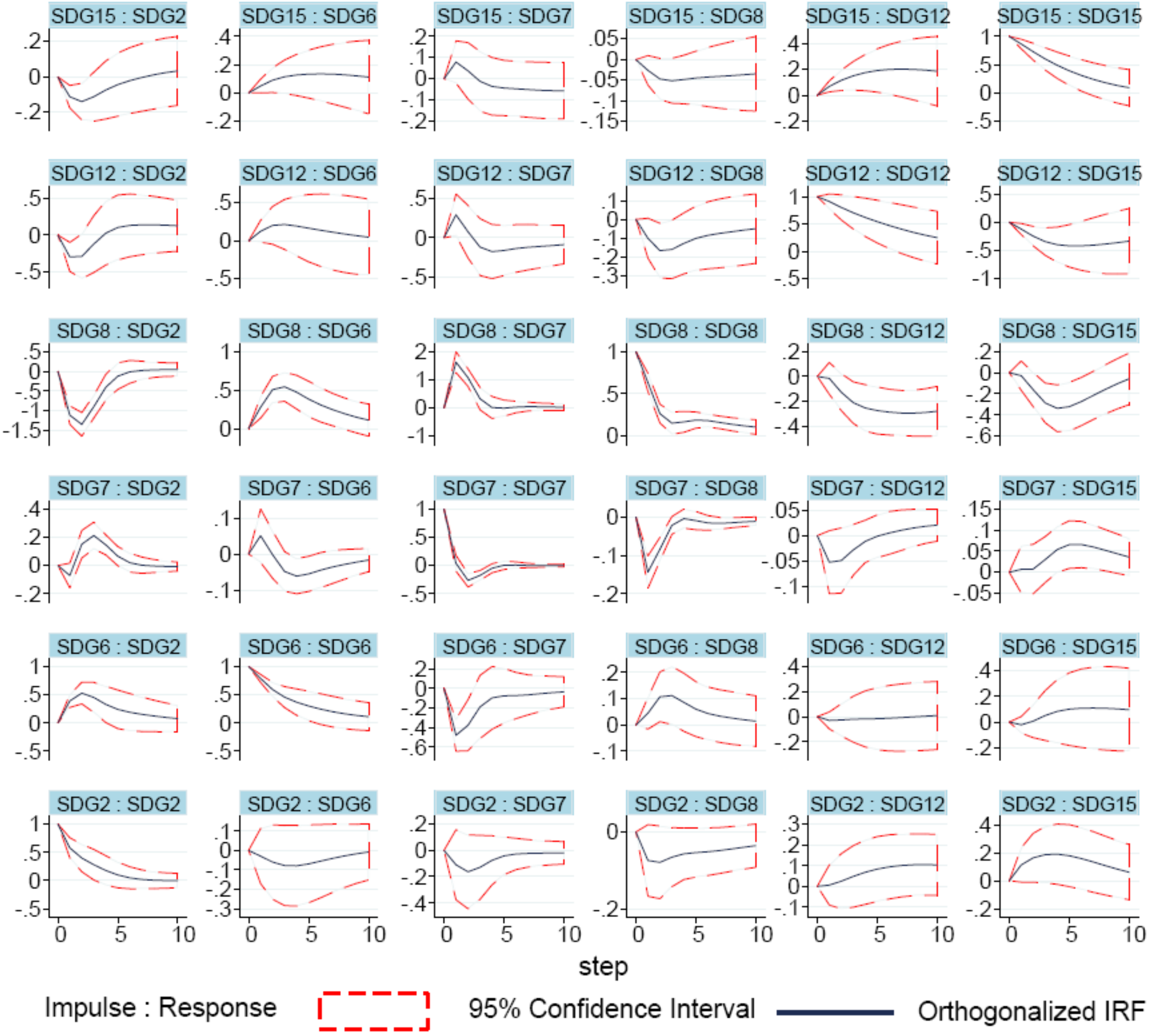


Fig. A2. The diagram of the orthogonalized impulse response function between the six sectors in the expanded food-energy-water nexus of China, including food (SDG2), water (SDG6), energy (SDG7), economic (SDG8), consumption and production (SDG12), and forest (SDG15) sectors. The SDG on the left represents the impulse variable, and the right one is the response variable. The solid black line in the middle represents the orthogonalized impulse response function (IRF). The vertical axis is the response value and the horizontal axis is the lag period. The red dashed line is the 95 percent confidence band constructed based on 500 replications.



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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.

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Junze Zhang: Conceptualization, Methodology, Writing - original draft. **Shuai Wang**: Formal analysis, Writing - review & editing. **Prajal Pradhan**: Formal analysis, Writing - review & editing. **Wenwu Zhao**: Formal analysis, Writing - review & editing. **Bojie Fu**: Conceptualization, Supervision, Funding acquisition.