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COMMENTS

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Operationalizing food-energy-water nexus toward carbon neutrality

1 Introduction

Reaching carbon neutrality by 2050 facilitates limiting warming to 1.5°C (IPCC, 2018). Many countries, including the European Union, the United States, and the UK, have pledged and included carbon neutrality in their development agenda toward 2050. Carbon emission mitigation in energy-intensive sectors is a widely adopted approach in national documents. Power generation, transportation, and construction are considered as prioritized sectors in China's programmatic document for achieving carbon neutrality. The interconnections among these prioritized and related sectors (e.g., power generation and coal mining) are also important for emission reduction, as the complex nexus relations between sectors could shift carbon emission from the prioritized carbon abatement sectors to other connected sectors, resulting in inaccurate carbon measurements and hindering global carbon neutrality. Therefore, cross-sectoral integration and governance are essential for achieving the total carbon neutrality goal of China (Wei et al., 2022). Among numerous inter-sector resource management practices, integrating food, energy, and water (FEW) sectors is a typical case of complex networks frequently discussed since 1990s (Hoff, 2011; Roidt and Avellán, 2019). Each of the FEW sectors emits a large quantity of carbon, while the nexus of the FEW sectors induces huge uncertainties in carbon abatement in the siloed sector. Lack of cross-sectoral collaboration in operation would result in invalid carbon abatement efforts and cause unexpected consequences. For example, the development of water-intensive coal mining industry in Inner Mongolia, China, secures the energy supply in the Beijing-Tianjin-Hebei (BTH) region but threatens local water and agriculture security (Tao et al., 2015), increases local carbon emission, and even shifts the carbon emission from BTH region to Inner Mongolia. Considering the huge carbon emission and the complex coupling characteristic of FEW sectors, it is unreliable to use a siloed approach to evaluate and optimize the potential of the carbon abatement in the nexus scenario. Therefore, this paper aims to provide a comprehensive understanding of the interactive carbon abatement across the highly interdependent FEW sectors, mitigating the negative impacts of carbon emission transfer, and addressing the trade-offs within the FEW nexus to support global carbon neutrality. Two key contributions are presented: first, developing a methodology with leverage points and actionable steps to transition the FEW nexus from concept to carbon neutrality practice; second, defining carbon status and carbon profits to reframe FEW nexus practices toward the nexus facilitated carbon neutrality.

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2 Complexity and barriers of engineering practice on FEW nexus

Understanding FEW systems in a holistic and integrated manner is the cornerstone to address the security, efficiency, and governance issues in carbon mitigation actions. This section reviews and defines the FEW nexus, analyzes the complexity of FEW nexus, and identifies barriers on implementing FEW nexus practices for carbon neutrality.

2.1 The definition of FEW nexus

FEW nexus emerged from concerns over scarcity and sustainability in the late 2000s (Weitz et al., 2017). Since then, the nexus approach has been widely used to frame the cross-sector and cross-scale interactions. Interactions among FEW attained great attention in the international community during 2007–2009, in the context of growing concerns about economic growth and the food and energy security crisis (Allouche et al., 2014). Some representative FEW policies and their corresponding nexus descriptions are presented in Table 1. Beddington (2009) regarded the relationship between FEW and climate as ‘a perfect storm’, because of the increasing demand for FEW resources by 2030 and simultaneous mitigation and adaptation to climate change. The FEW nexus was formally proposed as a cluster of risk management by the World Economic Forum in 2011. The concept recognizes the dependence between FEW sectors over time at the Bonn conference in 2011 and the 2014 Stockholm Water Week. In China, the *Engineering Fronts 2018*, issued by the China Academy of Engineering, selected the FEW nexus as one of the annual top 10 engineering research fronts in engineering management (PGGEF, 2018). The word ‘nexus’ is the Latin word ‘nectare’, meaning ‘to connect’, which has been widely used in philosophy, economics, and the natural resource realm (Liu et al., 2018). Compared to other similar words (e.g., interdependence, connection, relation), the nexus is frequently used to indicate a group of focused linkages across multiple distinct nodes, highlighting the equal importance of each node and the interactions between each node; that is, integrating between FEW nodes not within them (Roidt and Avellán, 2019). Hence, a widely accepted FEW nexus concept can be defined as a set of linkages between FEW nodes, including all visible and hidden linkages within and across sectors, regions, and scales.

All of these representative policies are based on siloed FEW sectors, although some incorporate cross-domain interactions. Some aspects of these policies focus on bioenergy and enhancing FEW resources conservation to address carbon and climate change issues. However, FEW nexus policies in practice remain scarce for two reasons. First, current FEW governance systems are silo-based and strongly path-dependent. Second, the understanding of the FEW nexus, particularly its complexity, is still insufficient. Therefore, comprehending the complexity of the FEW nexus is a critical step in advancing FEW nexus practices toward carbon neutrality.

2.2 The complexity of FEW nexus

The FEW nexus is regarded as an open dynamic system. Understanding its complexity is the prerequisite to minimize the tradeoffs of FEW nexus. von Bertalanffy (1950)

Table 1 Representative FEW policies and their nexus descriptions

FEW nodes	Name of regulation	Nexus descriptions	Countries/Regions
Water	EU Water Framework Directive	F-E-W: further integration of protection and sustainable management of water into other Community policy areas such as energy, transport, agriculture, fisheries, regional policy and tourism is necessary	Europe
	Commission Notice Guidelines to support the application of Regulation 2020/741 on minimum requirements for water reuse 2022/C 298/01	W-E: reclaimed water can be used for the agricultural irrigation of: Non-food crops (fodder): crops cultivated not for human consumption but for pastures and forage or in other sectors (industrial, energy and seeded crops)	Europe
	Clean Water Act (2018 version)	F-E-W: encourage waste treatment management methods, processes, and techniques which will reduce total energy requirements; develop a comprehensive agricultural monitoring and evaluation network for all major drainages within the Lake Champlain basin	USA
	Regulations on Water Conservation	W-F: implement the water quota of crops; promote the water-saving irrigation techniques	China
Energy	The European Green Deal	F-E-W: emissions reduction targets across a broad range of sectors; a target to boost natural carbon sinks	Europe
	The Federal Sustainability Plan	E-W: increase facility energy efficiency and water efficiency	USA
	Implementation Plan for Promoting the High-quality Development of New Energy in the New Era	E-W: promote the development of hydropower	China
Food	EU Common Agriculture Policy	F-E-W: investments may concern, inter alia, infrastructures related to the development, modernisation or adaptation to climate change of agriculture and forestry, including access to farm and forest land, land consolidation and improvement, agro-forestry practices and the supply and saving of energy and water	Europe
	Agriculture Improvement Act of 2018	F-W: protect and improve water quality and quantity F-E: encourage investments in alternative energy technology and production of renewable biomass for biofuel	USA
	The Action Plan for Saving Food	F-E: regulate and control the development of food-consuming bio-fuel processing industries	China

and Qian et al. (1993) focused on the elements, relations, boundary, and external environment for understanding the open complex giant system. The complexity of an open complex system exists in the internal structure, relations of system elements, the external environment interacting with the system, and the generating dynamic input-output feedback mechanism. Besides, the complexity of FEW nexus includes the dynamic boundary, the interactions between systems with the same or different levels of granularity, the interactive mechanism between acute and chronic external factors (Zhang et al., 2018), and those uncertainties and complex interconnections within physical (e.g., climate change, hazard) and social domains (e.g., human behavior, and policy) (Zhang et al., 2018). These complexities can be summarized as follows.

First, the linkage complexity of FEW nexus originates from numerous internal linkages, which can trigger a series of chain reactions. These internal linkages are widely located along the life cycle processes (i.e., production, consumption, distribution, and waste disposal) of FEW resources, which are categorized into input–output relations, physical relations, and feedback relations. For example, approximately 70% of freshwater and 30% of electricity are consumed in agricultural activities to produce commercial food, with these demands rising due to population growth and the application of automated technologies (Zhuang et al., 2023), thereby contributing to increased carbon emissions. These numerous internal linkages can shift carbon emissions between nodes, increasing trade-offs between different sectors and regions, and reducing the effectiveness of siloed, sector-based carbon abatement policies (Fankhauser et al., 2021; He et al., 2022).

Second, the element complexity of FEW nexus exists in those interactive systems with various granularity located at different scales from individual to community, region, nation, and the globe. These multiscale interactions are sometimes telecoupled (Liu et al., 2018). For example, household food consumption behaviors can influence water and energy usage, as well as carbon emissions, at both the community and regional scales. Since varying levels of granularity represent different endowments, goals, and authorities of FEW elements, the complexity of these elements increases the difficulty of developing a widely accepted carbon action plan. Moreover, coordination between these FEW elements raises the implementation costs of current carbon policies (Wei et al., 2022).

Third, the interactive complexity of FEW nexus is located at the interactions between the FEW networks and the changing environment. FEW nexus is place-specific (Guillaume et al., 2015), but the internal mechanism of FEW nexus varies with specific context (e.g., place, scale, time). The changing environment exerts differentiated influences on the internal mechanism of FEW nexus. Furthermore, the co-occurrence of acute-chronic and physical-social external factors under the changing environment causes spatio-temporally compound extremes, challenging the understanding of the FEW nexus and leading to unexpected consequences. For example, the Sichuan-Chongqing spatio-temporal compound extremes of 2022 (Hao et al., 2023) increased energy demand, decreased hydropower capacity, damaged crops due to a lack of irrigation, and negatively impacted the implementation of local carbon action plans and economic activities in both the local and eastern coastal regions. These significant uncertainties in interactive complexity can trigger even greater uncertainties within the socio-economic system (Rising et al., 2022), highlighting the need to revise current carbon abatement policies and carbon neutrality roadmaps (Zickfeld et al., 2023).

The above complexities lead to the scalability of FEW nexus (Table 2) and the difficulty in defining the boundaries of FEW networks. In practice, the interwoven chains in FEW nexus are much longer and more invisible, which are identified only after detecting certain unexpected consequences. The openness of FEW nexus would lead to an unlimited expansion of system boundary and aggravate the difficulty in defining the boundary. Therefore, it is necessary to explore the complexity of specific FEW nexus cases from a global perspective, and provide solutions to local FEW nexus problems.

2.3 Barriers of conducting engineering practice on FEW nexus for carbon neutrality

A few barriers prevent the development of FEW nexus engineering practices. The first barrier is the inefficiency in research collaboration within FEW nexus modeling, which neglects the feedback interactions across disciplines, thereby hindering progress toward global carbon neutrality (Wei et al., 2022). The FEW nexus is a transdisciplinary research topic (Zhuang et al., 2021a), relating to more than 42 disciplines from natural science and social science (Liu et al., 2018; Zhang et al., 2020). Hence, FEW nexus modeling works put forward higher requirements on the ability to digest knowledge from other disciplines. In practice, knowledge exchange and mutual learning of experiences are relatively easier than performing actionable collaborations, which are mainly limited by the unclear individual research stewardship and the widespread disciplinarily siloed research viewing from one discipline to another (Zhuang et al., 2021a). Inefficient research collaboration weakens the scientific and technological capabilities to capture the feedback and coupling mechanisms that facilitate carbon neutrality within the FEW nexus, further hindering the advancement of technologies and policies aimed at carbon neutrality.

The second barrier is the unclear policy coherence mechanism in FEW nexus governance, which would intensify tradeoffs among FEW sectors. For example, China's agricultural policies, designed to improve food

Table 2 The complexity of the FEW nexus and its relationship to carbon emissions

	Stylized characteristics	Research priorities	Research methods	Relation to carbon emission
Linkage complexity	• Numerous causal, input–output, physical linkages (Hoff, 2011) • Linkages locate along the life cycle of FEW resources (Hoff, 2011) • Linkages intertwine together with chain reactions (Estoque, 2023)	◆ Defining the boundary of the FEW nexus (Liu et al., 2018) ◆ Quantifying the structure of the FEW nexus (Scanlon et al., 2017) ◆ Modeling the dynamic FEW nexus (Van Vuuren et al., 2019)	• Data mining (Scanlon et al., 2017) • Life cycle anlaysis (Ali and Acquaye, 2024) • System dynamics (Li et al., 2016) • Participative approaches (Bois et al., 2024)	Shifting carbon emissions from one sector or region to another through the complex linkages would: ➢ increase trade-offs in carbon abatement between sectors and regions (Fankhauser et al., 2021) ➢ decrease the effectiveness of current carbon abatement policies (He et al., 2022)
Element complexity	• The elements vary in granularity (Bois et al., 2024) • The elements are positioned across spatial, temporal, organizational scales (Liu et al., 2018) • Elements are engaged in telecoupling with interactions across multi-scales (Huntington et al., 2021)	◆ Establishing the hierarchy structure of the FEW nexus (Li et al., 2019) ◆ Disclosing telecoupling mechanisms across multi- scales (Li et al., 2024) ◆ Establishing a fair and efficient profit allocation mechanism (Huntington et al., 2021)	• Multi-agent modeling (Namany et al., 2019) • Game theory (Namany et al., 2019) • Multi-objective optimization (Mannan et al., 2018) • Participative approaches (Bois et al., 2024)	The varying granularity of elements representing different endowments, goals, and authority would: ➢ increase the difficulty of forming a widely accepted carbon action plan (Wei et al., 2022) ➢ increase the implementation costs of current carbon policies (Wei et al., 2022)
Interactive complexity	• The FEW nexus interacts with the changing environment (Guillaume et al., 2015) • The FEW nexus is impacted by compound risks (Hao et al., 2023)	◆ Conducting case studies in various locations (Leck et al., 2015) ◆ Understanding the evolving nature of compound risks (Jones-Crank et al., 2024) ◆ Quantifying cascading effects (Zhang et al., 2020)	• System dynamics (Li et al., 2016) • Integrated models (Estoque, 2023) • Data mining (Scanlon et al., 2017) • Case study (Leck et al., 2015)	The significant uncertainties stemming from external shocks would: ➢ cause uncertainties within social-environment systems (Rising et al., 2022) ➢ revise the current carbon abatement strategy and carbon neutrality road-map (Zickfeld et al., 2023)

security and self-sufficiency, have led to the over-exploitation of local groundwater and the excessive use of energy-intensive chemical fertilizers (Ghose, 2014; Xu et al., 2020), resulting in unintended excess carbon emissions in both the water and food sectors. The FEW nexus governance requires the negotiation among stakeholders relating closely to socio-economic activities. These stakeholders have distinct perceptions, interests, and practices (Weitz et al., 2017), posing great challenges to policy coherence. In practice, FEW-related policies are widely implemented from various sectors with unequal power, asymmetric information, and conflicting interests. The effectiveness of local policies is also impacted by policies implemented in adjacent or distant regions. Since these related sectors are located in different regions, scales, and industries, it is difficult to achieve effective cross-sector coordination and collaboration. Challenges also arise in evaluating whether the optimization achieved by a specific policy is partial or holistic, and failing to identify partial optimization may lead to conflicts between sectors. This barrier would increase the implementation and coordination costs of carbon policies, and could even threaten the security of FEW resources. For example, uncoordinated policies during the net-zero transition may exacerbate threats to energy and food security as variable renewables and bioenergy expand (Zhang et al., 2024).

These barriers result in inefficient integration of multiple disciplines, hindering a comprehensive understanding of the FEW nexus complexity. They also obstruct the promotion of multi-agent collaborative governance, ultimately preventing global carbon neutrality. To overcome these barriers, methodologies that facilitate transdisciplinary knowledge collaboration and enhance cross-sector cooperation are essential.

3 Methodologies on operating FEW nexus toward carbon neutrality

3.1 Leverage points of operating FEW nexus towards carbon neutrality

FEW nexus research is complicated with multiple levels of intertwined nodes and linkages. It is critical to identify leverage points and use them as the keys to detangle the complexity of FEW nexus. In practice, these problems often arise from focusing too much on one node or system while neglecting others, ultimately leading to unintended consequences. These unexpected trade-offs are commonly encountered in the process of operating the FEW nexus toward carbon neutrality. For instance, while a carbon tax may improve the energy structure, it could negatively impact the economic output of the water and food sectors (Zhang et al., 2024). Therefore, life cycle assessment is critically important after defining the leverage points, as life cycle tracking provides the foundation for avoiding the hidden shifting of carbon emissions between nodes and reaching a holistic optimization of carbon neutrality within the FEW nexus. Any currently focused FEW systems with independent functions can work as leverage points to address FEW nexus issues; that is, focusing on specific FEW sector and integrating other sectors simultaneously (i.e., F-EW, E-FW, and W-EF). Toward carbon neutrality, it is inevitable to calculate the carbon emissions of all FEW nexus practices on any FEW systems with independent functions, and using positive, zero, and negative net carbon emission to categorize them into carbon positive, carbon neutral, and carbon negative FEW nexus practices, respectively, is needed. Experience mining is employed to promote carbon negative and neutral FEW nexus practice, while reducing carbon emissions holistically is the most important task in carbon positive FEW nexus practice. Three illustrative cases (F-EW, E-FW, and W-EF) are used to explain the leverage point issue as follows.

In the F-EW case, optimizing crop planting patterns based on crop suitability evaluation is often used to reallocate water and land resources (He et al., 2022). This kind of optimization could reduce EW consumption by selecting EW-saving crops during the cultivating phase, while increasing carbon emissions and even harming reaching carbon neutrality. This is because the carbon sequestration capacity and energy consumption vary by crops. For example, the carbon sequestration capacity of wheat is higher than vegetables, and vegetables consume more energy than wheat (Zuo et al., 2023). Therefore, when the food subsystem servers as the leverage point, a comprehensive investigation of its carbon cycle and precise measurement of its carbon emissions are essential. Both aspects should focus on horizontal crop selection as well as the entire life cycle from crop planting to food waste disposal. Additionally, it is important to focus on the interconnections between FEW and carbon emission (C), considering all relations, such as F-E-C, F-W-C, F-W-E-C, and F-E-W-C.

In the E-FW case, energy subsystem is the leverage point, and the selection of the type of energy is a classical issue toward carbon neutrality. Electricity generation and consumption relate closely to the consumption of water (e.g., thermal power) and food (e.g., bio-energy), emitting large quantities of greenhouse gases (GHG). Using green energy to substitute fossil fuels and bio-energy can secure local FW resources and reduce carbon emissions (Næss et al., 2021). Additionally, the characteristics of local FW resources should be connected to the energy production and consumption, which has significant impacts on shaping the carbon emission of FEW nexus. For example, the net-zero emission solar-powered irrigation system could theoretically establish a carbon negative FEW nexus, but this cheap, green energy provides a template for farmers to change local agricultural practices (e.g., crop choice, cropping intensity). Such shifts in food node might lower the emission reductions that were originally assumed (Balasubramanya et al., 2024). While the fossil fuel extraction, consuming EW resources and destroying local arable land, would induce a carbon positive FEW nexus at the larger scale. In addition, investigating various carbon emission roots (e.g., E-F-C, E-W-C, E-F-W-C, E-W-F-C) is a key focus in this E-FW case.

In the W-EF case, water subsystem is the leverage point. Distributing water resources efficiently to secure the production of EF resources at the regional scale and to satisfy water demand at the urban scale are important issues. The equations being used to quantify the coupling relations amid the water distribution process are the core components. For example, China's Yellow River catchment with limited water resources is an important energy basin in China (Sun et al., 2024), facing high levels of carbon emissions and significant water demand conflicts between energy production, food production, and urban livelihoods. Distributing water resources among various demand nodes is a holistic optimization problem with a carbon constraint. Because without the carbon constraint, carbon emission in FEW sectors would increase through the optimized crop planting pattern and the energy-intensive water sources to address insufficient water resources. Hence, the water distribution scheme could result in carbon negative, carbon neutral, and carbon positive FEW nexus practices. Finally, in the processes of water distribution and management, checking all related carbon emission roots of W-E-C, W-F-C, W-E-F-C, and W-F-E-C is another core component.

3.2 Implementation steps of operating FEW nexus toward carbon neutrality

To operate the complex FEW nexus toward carbon neutrality, a powerful methodological framework is required to enhance transdisciplinary knowledge collaboration and integrate various sectors. Combining the empowered methodological framework with specific implementing steps is an effective way to deepen our understanding of advancing FEW nexus toward carbon neutrality, and provide support for cross-sectors integration and decision making. In Fig. 1, the methodology of complex systems science is the preferred choice for three reasons. First, methods from complex systems science can be used to investigate phenomena across both natural and social science domains (Siegenfeld and Bar-Yam, 2020), aligning with the transdisciplinary nature of the FEW nexus and carbon neutrality. Second, complex systems science focuses on the behaviors of both subdivided systems and the overall system, emphasizing the visualization of complex systems in modeling. This approach helps in understanding the operating logic of advancing FEW nexus toward carbon neutrality, monitoring policy effects, and promoting synergies between engineering practices and policies. Third, the subdivided system is scalable, and the interfaces between these systems are identifiable, providing the capacity to address the issue of varying granularity within the FEW nexus and carbon neutrality.

Based on the methodology of complex systems science, 6 steps are proposed to operate FEW nexus toward

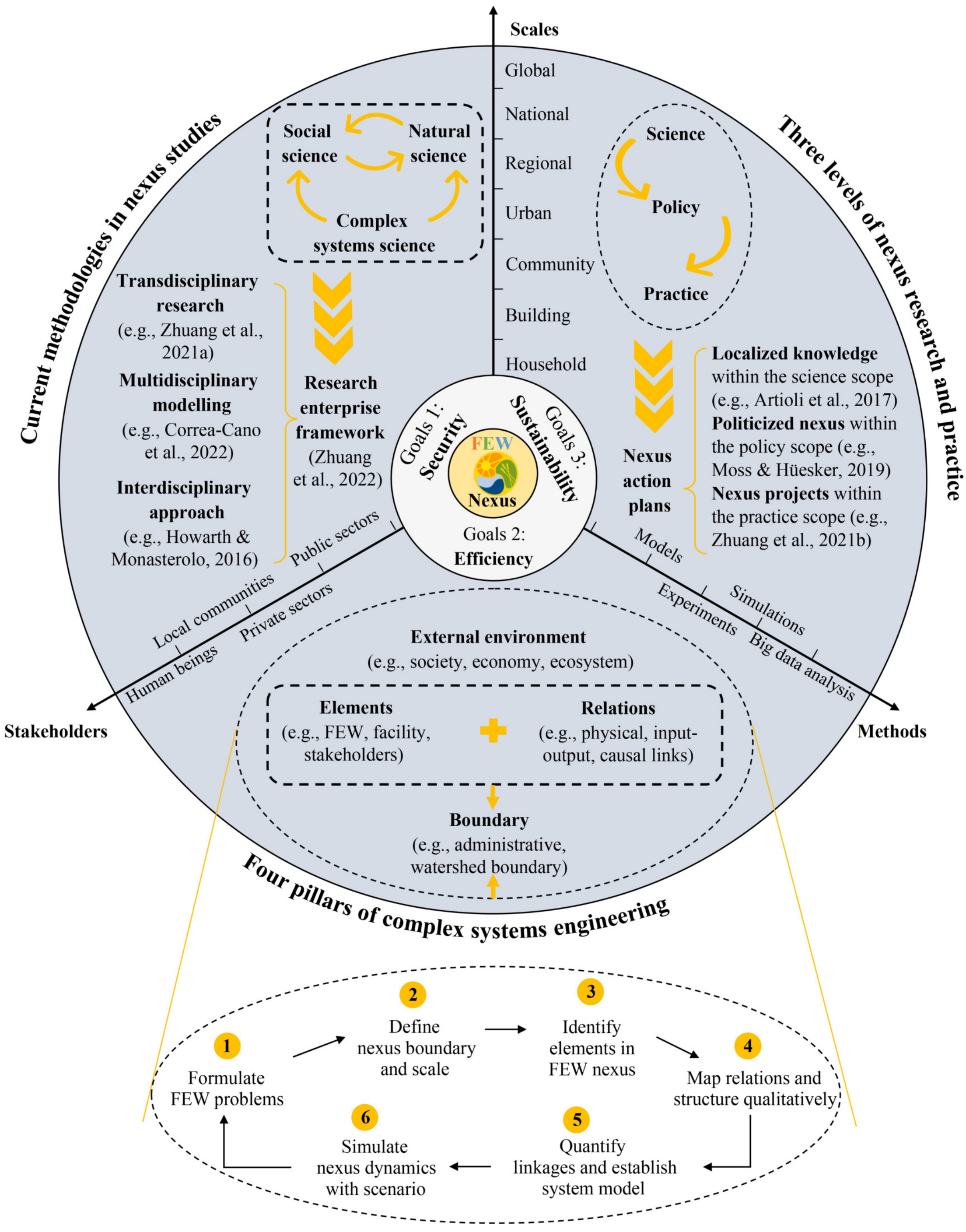


Fig. 1 Methodologies of FEW nexus research and practice.

carbon neutrality (Fig. 1). The first step is formulating FEW nexus problems by visible phenomena and development goals. The formulated problem list could be used to identify the leverage point and label the FEW nexus practice with carbon positive, neutral, or negative. Second, the boundary and scale of FEW nexus are defined, together with the stakeholder group. Third, system elements are identified within the boundary, and the place-specific characteristics can be extracted from local practices and further expressed with parameters and functions. Fourth, the FEW nexus is qualitatively mapped with the relations between internal elements, and the linkages between the element and external environment. While the causal loop schematic for operating FEW nexus is established. Fifth, quantify the causal loop schematic with equation set, and build the FEW nexus complex system model. Sixth, simulate the influencing mechanisms of acute, chronic, and social-physical factors on FEW nexus through scenario analysis, and monitor the variations in system behaviors and carbon status under enacted FEW- and carbon-related technologies, policies, and management activities.

4 Reframing FEW nexus practices toward nexus facilitated carbon neutrality

In the FEW nexus practice, FEW nodes are indispensable with numerous interconnections, forming a community of interest. Some FEW nexus practices (i.e., the classical optimal planting pattern practice) reduce the regional net carbon sequestration capacity and increase regional carbon emission (He et al., 2022), being even harmful to reach the carbon neutrality goal. Hence, it is essential to reframe and operate FEW nexus practices from a carbon perspective, incorporating both bottom-up and top-down approaches. The bottom-up approach bases on complex system science, and is used to identify the carbon status (positive, neutral, negative) of FEW nodes at the subsystem scale and of FEW nexus at the overall system scale. The top-down approach views from the community of interest, and is used to allocate the generated carbon profits between FEW nodes. That is, building a fair and efficient allocation mechanism within FEW nexus to ensure the achievement of carbon neutrality.

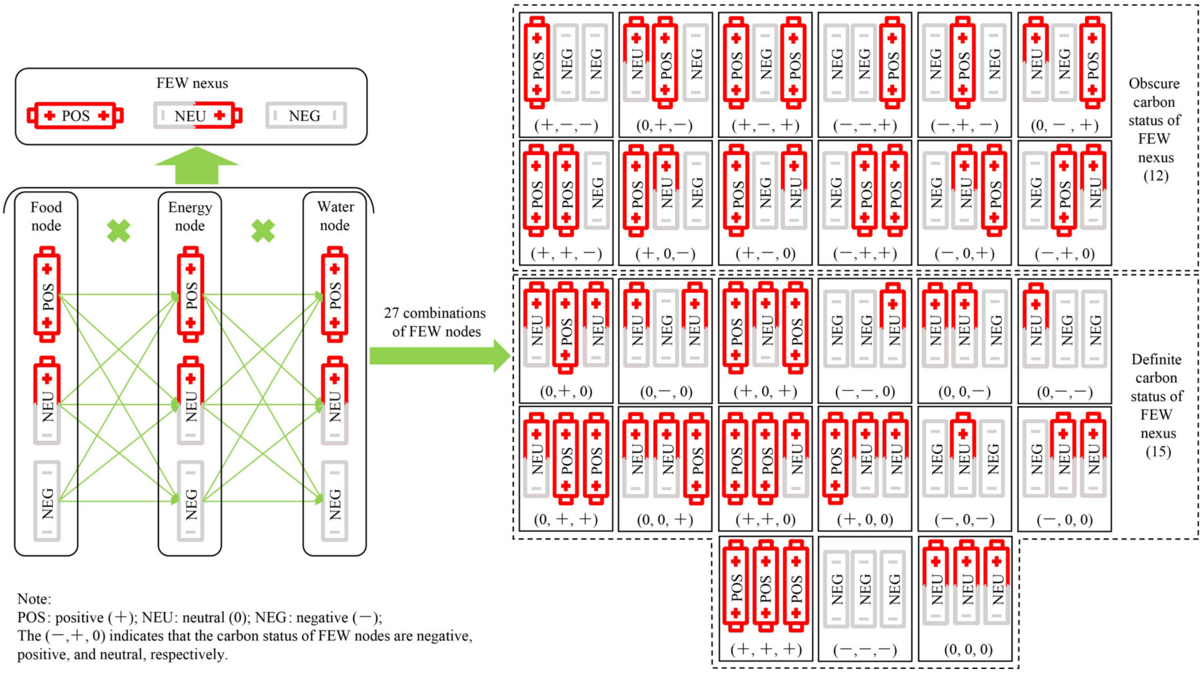
4.1 Label the carbon status of FEW nexus from the bottom up

An accurate calculation of carbon emissions of each FEW node is the cornerstone to operateing FEW nexus toward carbon neutrality. FEW nexus and each node (F, E, W) have three carbon statuses (Fig. 2); that is, positive (+), neutral (0), and negative (−). Under a carbon-negative FEW nexus, carbon sequestration exceeds carbon emissions from the FEW system. The carbon status of FEW nexus depends on the combination of carbon status of each node (F, E, W), and there are 27 combinations of FEW nodes (Fig. 2) calculated by three kinds of carbon status in each of the three nodes. 15 of the 27 combinations have definite carbon status of FEW nexus. That is, the carbon positive FEW nexus include the combination of (+, +, +), (+, +, 0), (0, +, +), (+, 0, +), (+, 0, 0), (0, 0, +), (0, +, 0), and the carbon negative FEW nexus are those combinations of (−, −, −), (−, −, 0), (−, 0, −), (0, −, −), (−, 0, 0), (0, −, 0), (0, 0, −), while the (0, 0, 0) is the definite carbon neutral FEW nexus. While the other 12 combinations contain both carbon negative and positive FEW nodes, leading to obscure carbon status of FEW nexus, which could be positive, neutral, or negative, depending on the quota and weight of each node. For example, the combination of (+, −, +) contains carbon positive FW nodes and carbon negative E node. This FEW nexus could be carbon positive, if the carbon emissions from positive FW nodes exceed that from the negative E node; and could be neutral, if both amounts from positive nodes and negative node are equal; and could be negative, if the carbon emission from negative node exceeds that from both positive nodes. Nevertheless, each node contributes to the carbon status of FEW nexus, and these contributions are non-synchronous and non-constant, because of the complexity of the FEW nexus. Therefore, the proposed methodology above should be employed to calculate the net carbon emission of FEW nexus and identify the carbon status of those 12 combinations, which could be addressed with a leverage point.

4.2 Build a fair and efficient allocation mechanism for carbon profit

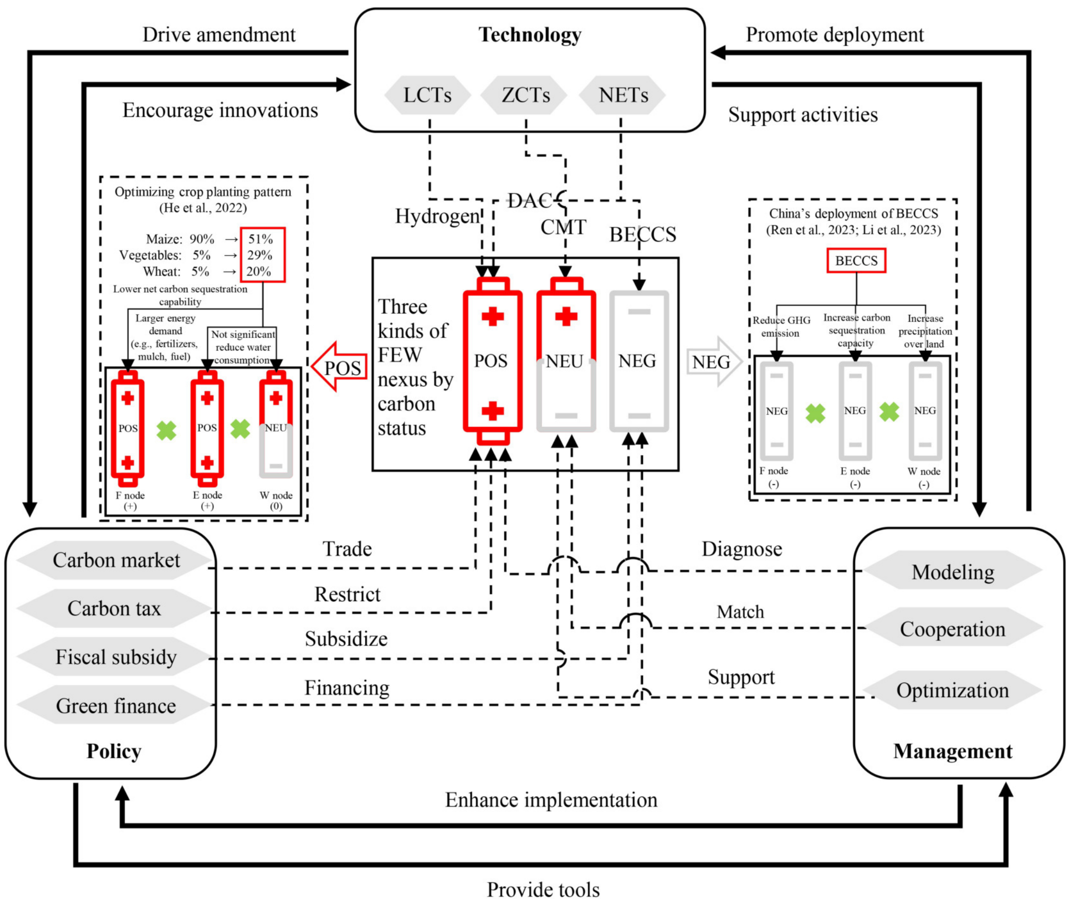
The carbon neutrality goal drives the FEW nexus toward sustainability by enhancing collaboration among FEW systems to mitigate the negative impacts of carbon emission transfer and advance global carbon neutrality. FEW systems work together to achieve carbon neutrality holistically, during which carbon profit is generated by applying a series of technologies, policies, and management activities (TPMs). Carbon profit refers to the social, economic, and environmental benefits generated from the adoption of TPMs and transboundary cooperation within the FEW nexus. The simplest form of carbon profit is the revenue (economic benefit) from carbon quota trading in the carbon market (Guo et al., 2020). Additionally, carbon sequestration on agricultural land can provide producers worldwide with additional revenues (social benefit), reduce economy-wide climate change mitigation costs (economic benefit), and contribute to achieving net-zero emissions in agriculture (environmental benefit) (Frank et al., 2024). Technologies (T) are the critical driving forces to achieving carbon neutrality, including low carbon technologies (LCTs; e.g., hydrogen), zero carbon technologies (ZCTs; e.g., carbon-neutral methane technology), and negative emission technologies (NETs; e.g., direct air capture). New technologies drive policy amendment, and are also promoted by policies and management activities. Policies (P) are powerful guarantees to achieving carbon neutrality, including carbon market, carbon tax, fiscal subsidy, and green finance. Policies could encourage innovations on new technologies, constrain emissions in carbon positive FEW nodes and FEW nexus, and further remedy the carbon market. Management (M) activities improve multi-agents collaborative efficiency through modeling, cooperation, and optimization, which could be used to facilitate collaborations between carbon negative and carbon positive agents across sectors, regions, and scales. The technology-policy-management (TPM) framework is presented in Fig. 3, exhibiting interactions between various FEW nexus practices and the related TPMs.

Fairly and efficiently allocating these carbon profits in



Note:
POS: positive (+); NEU: neutral (0); NEG: negative (−);
The (−,+,0) indicates that the carbon status of FEW nodes are negative, positive, and neutral, respectively.

Fig. 2 The carbon status of FEW nodes and FEW nexus.



Note: POS: positive; NEU: neutral; NEG: negative;
NETs: negative emission technologies; ZCTs: zero-carbon technologies; LCTs: low carbon technologies;
BECCS: bioenergy with carbon capture and storage; CMT: carbon-neutral methanol technology;
DAC: direct air capture

Fig. 3 The technology-policy-management (TPM) framework.

highly dependent FEW nodes is the key to facilitating collaborations in those combinations with obscure carbon status of FEW nexus. For example, in a carbon negative FEW nexus with the combination of (+, −, +), both positive FW nodes should participate in the allocation of carbon profits, rather than being punished. This is because both positive FW nodes contribute to the carbon negative E node and FEW nexus, and a restriction on carbon emissions of FW nodes could convert carbon negative FEW nexus into carbon positive one. Hence, the carbon profits should be allocated fairly and efficiently across sectors, regions, and scales from the top down, and all highly dependent agents should be regarded as a community of interest. The critical issue of the allocation mechanism is the measurement of individual contributions. Three potential ways to measure the individual contributions are proposed as follows.

First, the baseline scenario overlooks the nexus, focusing on individual rather than holistic scales, and the individual contributions are measured by the carbon status of FEW nodes; for example, in the combination of (−, +, −), the individual contribution of FEW nodes are negative, positive, and negative, respectively. This fragmented scenario neglects the co-benefits of carbon abatement actions in a highly interdependent community (Jiang et al., 2022), potentially leading to unexpected trade-offs by shifting carbon emissions across FEW domains.

Second, in the nexus scenario, individual contributions can be valued based on the weight of FEW nodes, such as the amount of carbon sequestration, or carbon profits could be distributed evenly among the FEW nodes. This kind of measurement could be used in the FEW nexus with definite carbon status, such as the combination of (+, +, +) and (−, −, −), because the carbon status of all nodes does not vary in an opposite direction.

Third, regarding combinations where some nodes vary in opposite directions, such as (+, −, +), individual contributions can be measured by their individual bargaining power in the carbon market, or could be dictated by mandatory documents (e.g., regulations, standards). The former relates to an X-player game, where players interact to maximize their individual benefits, ultimately reaching a stable equilibrium. In contrast, the latter can address the shortcomings of the carbon market and enhance the fairness of carbon measurement. For example, carbon tax (the latter), with its compound pass-through effect, proved superior to subsidies (the former) in achieving a responsibility-benefit balance in a highly interdependent community (Wang et al., 2025).

5 Summary

This paper explores the FEW nexus in the context of carbon neutrality, providing insights on mitigating the negative impacts of carbon emission transfer and achieving global carbon neutrality. Two barriers hindering FEW nexus practices are inefficient communications across sectors and unclear policy and governance mechanisms. The key to addressing the barriers is defining the leverage points (W-EF, E-WF, F-EW) of FEW nexus located in the identified FEW problem set. The complex system science should be employed to model the FEW nexus following six steps, that is, formulate FEW problems, define nexus boundary and scale, identify elements in FEW nexus, map relations and structure qualitatively, quantify linkages and establish system model, simulate nexus dynamics. Since some FEW nexus practices are harmful to the carbon neutrality goal, it is necessary to reframe and operate FEW nexus practices from a carbon perspective. The basic work is the identification of carbon status of FEW nodes and FEW nexus, which could be categorized into positive, neutral, and negative. The carbon status of FEW nexus depends on the combination of carbon status of FEW nodes, and 12 of the 27 combinations have unclear carbon status of FEW nexus. The applications of TPMs on FEW nodes could generate carbon profits on FEW nexus scale. These generated profits are contributed by all FEW nodes, and require fair and efficient allocations between FEW nodes. The core of the allocation mechanism in a highly dependent complex system, like FEW nexus, is the measurement of individual contribution. The individual contribution in FEW nexus could be measured by the carbon status in the baseline scenario without considering the nexus, by the weight of each node or dividing evenly in the nexus scenario with definite carbon status of FEW nexus, and by the bargaining power of each node or the mandatory documents in the nexus scenario with obscure carbon status of FEW nexus.

Competing Interests The authors declare that they have no competing interests.

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