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Review

Review of the Water–Land–Food–Carbon Nexus Focused on Regional Low-Carbon and High-Quality Agricultural Development

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Abstract: To overcome the multiple challenges of water scarcity, agricultural land conversion, food security, and carbon emissions, an optimal collaborative management scheme for food production is urgently needed, especially in high food-production and food-consumption countries such as China. The water–land–food–carbon (WLFC) nexus provides a new perspective, but its interactions are complex, dynamic, and spatially heterogeneous; the coupling mechanism is not fully understood; and the driving forces and regulation strategies remain uncertain. Therefore, in this study, the WLFC nexus centered on low-carbon and high-quality agricultural development was systematically reviewed. The main contributions are as follows: (1) A framework of the regional agricultural WLFC nexus was proposed based on bibliographic analysis. (2) The main internal and external factors influencing the WLFC nexus in agriculture were identified by reevaluating meta-analysis review studies. The results showed that changes in the amount and type of irrigation water, the amount and planting activities of agricultural land, and climate change (temperature, precipitation, and CO_2 concentration) affected food (rice, wheat, and maize) yields and carbon emissions to varying degrees. Moreover, population, technological innovation, trade, and polices were important external factors impacting food production and carbon emissions. (3) The common methods and tools for assessing, simulating, and optimizing the WLFC nexus in agriculture were summarized from the perspectives of its status, physical links, and embodied links. Integrated indices, complex system thinking, and process-based and data-driven methods were applied in the studies of the WLFC nexus. (4) Strategies and programs for collaborative WLFC management in agriculture within 10 global river basins were compiled. These findings could help us better understand the WLFC nexus in agriculture and identify the optimal cooperative management scheme, thereby realizing low-carbon and high-quality agricultural development.

Keywords: water–land–food–carbon nexus; framework; drive forces; technologies and tools; collaborative management; agriculture

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1. Introduction

It is challenging to ensure food security against the background of limited water and land, a rapidly increasing population, and changing climate, which has become a global concern [1–3]. Food security impacts the national economy, people's livelihood, social stability, and economic development, and it is an important part of achieving sustainable development goals [4]. However, the contradiction between the food supply and demand has increased in recent years and is influenced by numerous factors, e.g., resource and environmental constraints, population growth, climate change, and regional geopolitical conflicts. Currently, approximately 820 million people worldwide are threatened by food shortages [5]. By 2050, the global population will reach 10 billion [6,7]. Population growth and dietary structure changes have led to higher food-quantity and -quality requirements [8]. Notably, enormous challenges will be faced in agricultural sustainable development over the next few decades.

As a country with high food production and demands levels, the food supply and demand in China exhibit a fragile balance, although the food field has increased in recent years [9]. Therefore, safeguarding a food supply and demand balance is the top priority for governance. "Paying close attention to ensuring stable production and the supply of grain and important agricultural products" was emphasized in the No. 1 document of the Central Committee in 2023 after the overall deployment and implementation strategy of food security were enacted in the 14th Five-Year Plan. However, the shortage of water resources, cropland loss, and mismatch of the spatial distributions of land and water are important agricultural issues in China and represent bottlenecks that must be overcome to achieve sustainable agricultural development [10–13]. Agriculture is the main water-consuming sector in China. According to the 2020 Water Resources Bulletin, food production accounts for approximately 61% of the total water extraction and 74.9% of the total water consumption, while approximately 30 billion m^3 of water are still lacking annually in agriculture. The scale of grain transport from water-scarce northern regions to water-rich southern regions continues to increase, and the contradiction between water shortage and food production is considerable [14–17]. Cropland decreased at a rate of 800 km^2/a from 2009 to 2019 according to the Ministry of Land and Resources. Moreover, the mismatch between water and arable land is notable, as 80% of the total water resources in China serves approximately 23% of the potential arable land [11]. With the acceleration in population growth, economic development, and urbanization, food production in China will face long-term pressure from shortages of arable land, water resources, and labor, and will be threatened by global climate change, agricultural nonpoint source pollution, and industrial exogenous pollution. Additionally, the double carbon goal has been proposed by the Chinese government within the context of global carbon reduction. Therefore, there is an urgent need for an optimal collaborative management scheme to achieve low-carbon and high-quality agricultural development under the dual pressures of resources and the environment. Resolving the contradiction between water and land resource constraints, carbon sequestration, emission reduction, and food security has become a critical problem and a research hotspot [13,18–23].

Existing studies have indicated that there are close links among water, land, food, and carbon emissions. In agriculture, water and land are the two basic elements for food production, and the sustainable management of these two resources is the premise of ensuring food security [18,24,25]. Water scarcity and arable land loss will increase the pressure on food security. In particular, water scarcity threatens effective irrigation in non-rain-fed agriculture, thus affecting food yields [18]. Agricultural water pollution during food production exacerbates agricultural water shortages. The rapid increase in cultivated lands loss and population has resulted in a significant decrease in the per capita cultivated land area [26]. Moreover, high-yield land loss due to urbanization increases the risk to food security [27]. Irrational land use affects the temperature and runoff, and thus influences food production [28]; notably, the mismatch between food production and consumption also results in soil erosion [29], as well as agricultural soil pollution, thereby affecting cropland loss.

Climate change caused by greenhouse gas (GHG) emissions is an important factor influencing food production [3,30,31]. Generally, climate change affects the food yield and quality through notable changes in precipitation, temperature, humidity, wind speed, and sunshine hours [32]. Moreover, the agricultural sector serves as an important carbon emission and sink. The food system constitutes one-third of the global anthropogenic GHG emissions [33]. More than 13% of the global anthropologic GHG originates from agriculture [34]. Approximately 15–20% of the global CH_4 emissions can be attributed to paddy rice cultivation [35]. On the one hand, carbon is not only directly emitted in crop growth and soil microbial activities but also in agricultural activities, including fertilizer and pesticide inputs, ploughing, and irrigation [36,37]. In China, the GHG emissions attributable to agriculture account for 17% to 20% of the total GHG emissions, of which irrigation accounts for nearly 22% of the total agricultural emissions, and groundwater pumping for irrigation accounts for approximately 3% of the total agricultural emissions [23,25,38,39]. On the other hand, crops and soil can capture large amounts of carbon. According to Lal [40], the estimated annual carbon sequestration potential of global cultivated land ranges from 0.75 to ~1.0 Pg. Overall, the coupling mechanism among water, land, food, and carbon remains unclear because of the complexity, nonlinearity, and dynamics of the relevant links.

Although numerous studies have focused on qualitatively and quantitatively exploring the relationships between two or three elements, namely, water, land, food, and carbon [22,24,41–43], it remains difficult to fully represent the interaction among the joint use of multiple resources, food production, and carbon emissions. In multihead decentralized management practices, it is also difficult to solve the supply and demand contradiction among multiple resources without a water–land–food–carbon (WLFC) nexus. Therefore, understanding the WLFC nexus is a priority. However, the WLFC nexus is affected by the regional resource endowment, topographic conditions, climate change, soil and water use modes, planting management modes, and other factors, and it is spatially and temporally heterogeneous. Therefore, clarifying the agricultural WLFC nexus, revealing its driving forces, and identifying the optimal WLFC collaborative management scheme are important but difficult topics.

This study mainly aimed to (1) propose a framework for the agricultural WLFC nexus based on a systematic overview of relevant studies; (2) identify and quantitatively analyze the driving forces of the agricultural WLFC nexus; (3) summarize common methods and tools for assessing, modelling, and optimizing the agricultural WLFC nexus; and (4) explore optimal WLFC management by evaluating collaborative WLFC management in global river basins. This review aimed to identify the notable areas and gaps in WLFC studies, enhance the understanding of the connections among the various elements, and help major Chinese grain-producing regions obtain collaborative WLFC solutions, thereby realizing regional low-carbon and high-quality agricultural development.

2. Materials and Methods

2.1. Literature Identification and Screening

In 2008, Siegfried et al. [44] proposed enhancing the understanding of the interaction among water, energy, and food after the conflict between groundwater depletion and power resources caused by agricultural irrigation in India attracted widespread attention [45]. In 2011, conflicts between water, energy, and food were described and the water–energy–food (WEF) nexus was first proposed at the Bonn Conference in Germany [46]. Thereafter, many WEF-related projects, conferences, and studies have gradually increased and become popular research topics. The WEF nexus is well understood and the WEF nexus approach has been widely utilized from the perspectives of households, communities, urban settings, basins, regions, nations, and the world. Currently, the nexus among water, land, food, energy, ecology, environment, and carbon is being widely studied.

Therefore, in this study, a systematic approach and bibliographic analysis were employed via VOSviewer_1.6.20 software, which is developed by the Center for Science and Technology Studies of Leiden University in the Netherlands, to investigate the research progress of the WLFC nexus for sustainable agricultural development. The keywords "water–food," "land–food," "water–land–food," "carbon–food," "water–food–carbon," "land–food–carbon," "water–land–food–carbon," and "water–land–food–GHG" were searched on the Web of Science Core Collection, Chinese Science Citation Database^{SM}, and the China National Knowledge Infrastructure (CNKI). A total of 398 related papers were collected in 2008–2024. Therefore, 309 relevant papers were collected from January 2008 to December 2023 from the Web of Science Core Collection, Chinese Science Citation Database$^{\text{SM}}$. We performed co-occurrence analysis of these papers, and the results showed that WEF nexus management and resource optimization are hot research issues, especially in China, the largest irrigation country. The nexus among water, land, food, energy, and their cooperative security is another topic of increasing concern in recent studies (the green nodes and links in Figure 1). Additionally, sustainable agricultural development and food security under climate change are global concerns. Further analysis is provided in Section 3.

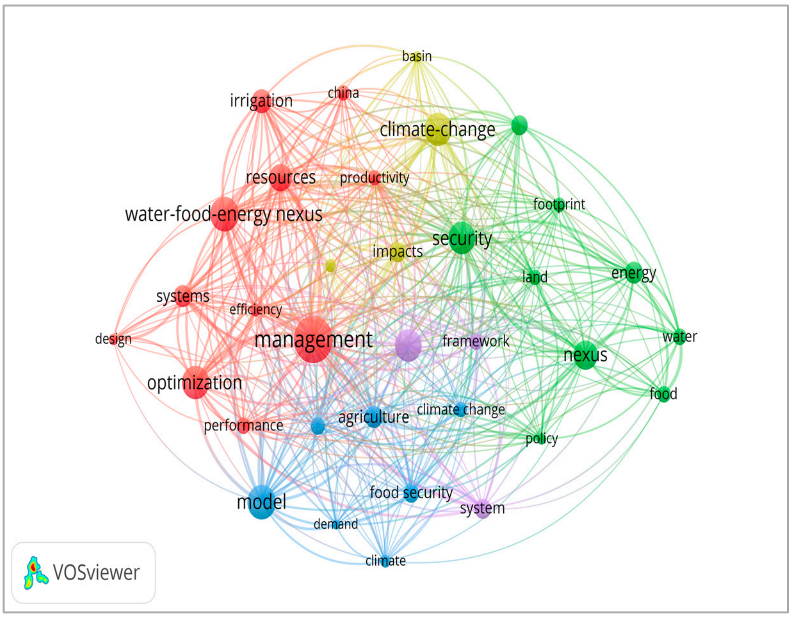

Figure 1. Keyword mapping of studies on the WLFC nexus.

2.2. Data Collection and Analysis

We collected peer-reviewed studies to identify and quantitatively analyze the diving forces of the agricultural WLFC nexus worldwide. Notably, 66 related papers were obtained. We then extracted related data from 20 meta-analysis papers (details in Supplementary Material S1) to quantitatively analyze the diving forces of the agricultural WLFC nexus. Data in graphical format were extracted using the GetData Graph Digitizer tool (http://getdatagraph-digitizer.com/). We quantitatively analyzed the main factors of the agricultural WLFC nexus in the production of three typical crops (rice, wheat, and maize). Details are presented in Section 4.

We extracted and summarized related information on common methods and tools applied in WLFC nexus assessment, simulation, and optimization from the collected papers. Details are provided in Section 5. We searched for studies on collaborative WLFC management in global river basins and obtained 23 related papers. Based on these cases, we reviewed the collaborative WLFC management experiences in 10 typical river basins worldwide. Details are introduced in Section 6. Overall, a flowchart of the data collection and analysis approach is shown in Figure 2.

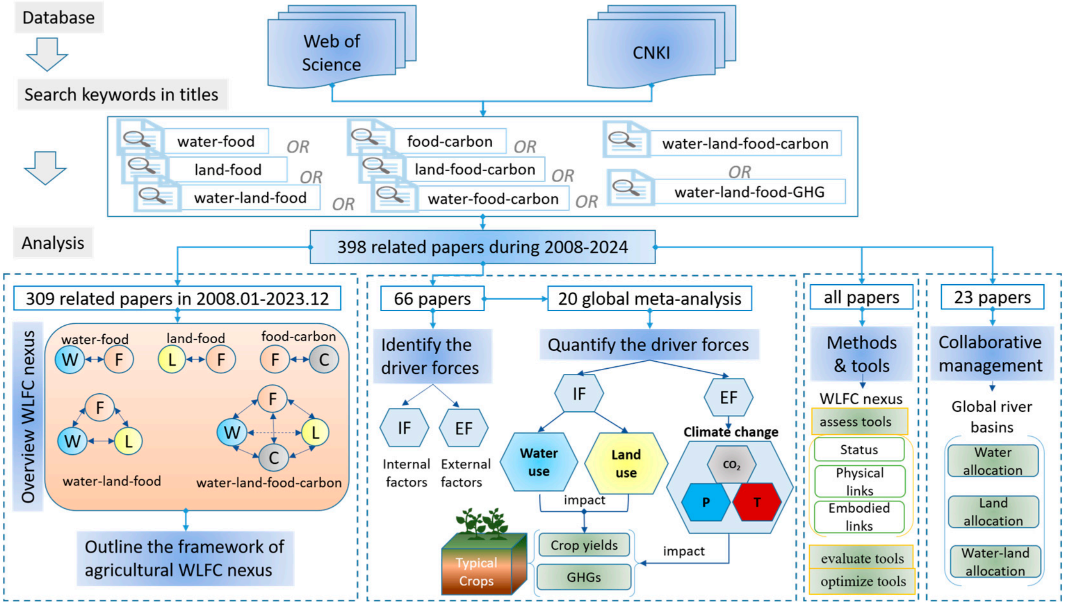

Figure 2. Flowchart of this study.

3. Overview of the WLFC Nexus

3.1. Water–Food, Land–Food, and Water-Land–Food Relationships

Previous studies focused on the impact of water on food production and the impact of food production on water. Therefore, food security was used as the entry point, with a focus on the following aspects: the impacts of water resource quantity (water scarcity and floods) and quality (water pollution), and the spatial–temporal mismatch of water resources on food production [12,47,48]. Some studies also concern on the impact of water use behaviors, i.e., the irrigation model, unconventional water use, and economic water scarcity, on food production [49–51]. Moreover, the water–food relationship was explored by calculating virtual water and blue, green, and grey water footprints [14,15,52–54]. For instance, Mekonnen et al. [55] constructed a grid-scale dynamic water balance model and quantified the water footprint of global crop production. The blue, green, and grey water footprints of rice production in major producing countries have also been quantified [56]. Sun et al. [57] calculated the total water resource consumption considering the green water consumption in 42 sectors in China via an input-output table and relevant meteorological data. Additionally, the effects of water governance (water price, water pollution taxes, and water-saving policies) on food production has primarily been considered. With water security as the entry point, studies have mainly focused on the direct and indirect effects of food production on water resources, including the impact of the water use efficiency on food production, and the influences of planting structures and patterns, food demand changes, and food trade on water resources [2,14,58].

Notably, in existing land–food relationship studies, the coordination between changes in the quantity, quality, and pattern of cultivated land, land use mode, intensive land use level, and food yield has mainly been examined. For instance, some studies have been devoted to the effects of urban expansion, land abandonment, land pollution, cultivated land conversion, and the policies of returning farmland to forestland or grassland on food production [59–61]. To quantify the relationship between cultivated land and food, models and concepts such as the cultivated land pressure index, gravity center model, and virtual land have been widely applied [62,63]. Most scholars have indirectly analyzed agricultural land use by studying the ecological footprint, land-carrying capacity, and sustainable development. Other studies have showed that changes in food consumption and demand can cause land use alteration and affect the soil quality [29].

Water, land, and food exhibit complex interrelations [20,63]. The implementation of water conservation irrigation measures has promoted an increase in the food yield per unit area [64,65]. Otherwise, rapid urbanization and industrialization have caused a sharp decrease in the area of cultivated land, which has affected the total food output [27]. Additionally, the quantity and utilization level of water resources directly affect the production capacity of cultivated land [35,66], while the degree of land reclamation restricts the development and utilization of water resources [67]. Shortages of land and water resources and their spatial mismatch directly affect the sustainable development of regional agriculture and food security [68]. At present, most studies focus on the relationships between water and land resource use efficiency, spatial–temporal patterns of water and land resources, and food security [25,69,70].

3.2. Food–Carbon Relationship

Food systems constitute the main source of anthropogenic carbon emissions [33]. Therefore, the number of studies on carbon emissions in food production is gradually increasing. Existing studies on agricultural carbon emissions have been conducted from the perspectives of source analysis, quantity measurement, driving factor assessment, etc. The main sources of agricultural carbon emissions are agricultural inputs (e.g., chemical fertilizers, pesticides, agricultural film, and agricultural diesel), methane from rice cultivation areas, animal intestinal fermentation, and tillage [71–75]. Agricultural carbon sinks mainly originate from the increase in the soil carbon pool caused by fertilizer input, straw returned to fields, and no-tillage measures [37].

Accurately assessing carbon sources and sinks remains difficult but is key to formulating emission reduction measures and rationally promoting regional carbon reduction processes. At present, carbon effect assessment studies have mainly been conducted from the microscopic perspectives of agricultural production activities [71,76], industry sectors [77,78], and the carbon cycle in terrestrial ecosystems. The methods employed to assess carbon emissions largely include the life cycle assessment (LCA) method, Intergovernmental Panel on Climate Change (IPCC) emission factor method, carbon emission coefficient method, modelling method, input-output (IO) method, mass balance method, and measurement method [79,80]. The carbon footprint refers to the direct and indirect GHG emissions generated by a product or a service throughout its whole life cycle or geographical scope and can represent the carbon emissions of different functional units [81,82]. In some studies, the agricultural carbon footprint has been calculated to measure the level of carbon emissions, applying an IO model, the LCA method, and the carbon footprint theory [78,83]. At present, there are several challenges. First, the results of different calculation methods greatly vary because of the distinct calculation methods, data sources, and carbon emission coefficients. Second, the differences in research boundaries and scales make it impossible to compare the research results horizontally. Third, in most studies, only carbon emissions from food production have been considered while ignoring the overall carbon fixation effect of crop–soil systems, which limits the understanding of the net carbon emissions from food production. Moreover, the carbon emission measurement objects mostly comprise single crops at the provincial or irrigated area scale. Therefore, accurately assessing agricultural carbon emissions is essential for clarifying the food–carbon-coupling relationship.

3.3. Water-Land–Food–Carbon Nexus

Explaining the relationships among water, land, food, and carbon is essential to realizing sustainable agricultural development. The Earth System Science Consortium (ESSP) proposed food, carbon, water, and human security as research priorities for joint programs after the concept of the food–energy–water (FEW) nexus was proposed in 2011. Since then, studies on the FEW nexus have been widely published and have mostly focused on regional characteristics, driving mechanisms, coordination, and coupling. However, few researchers have investigated the water-land–food or water–energy–food nexuses in the agricultural sector [25,69,70,84]. Multielement coupling studies have also been performed, such as studies on the water–energy–food–ecology (WEFE) and water-land–energy–carbon (WLEC) nexuses [19,21,23]. At present, the WEFE nexus at the watershed scale has been examined, especially in large basins and international transboundary river basins, e.g., the Yangtze River Basin, the Yellow River Basin, and the Syr River Basin [85–87]. Moreover, a few studies have started to focus on exploring the WLFC nexus [88]. Overall, the WEF and WEFC nexuses have been widely investigated from multiple perspectives. These findings have significantly contributed to WLFC nexus investigations. However, there remains a lack of qualitative and quantitative studies on the WLFC nexus. Therefore, the feedback and interactions of the WLFC nexus remain to be explored, especially in agriculture.

3.4. Framework of the Agricultural WLFC Nexus

To better understand the mechanism of the WLFC nexus in the agricultural sector, the synergy and trade-off relationships among water, land, food, and carbon were investigated, as shown in Figure 3. In the crop production process, water, land, food, and carbon are inextricably interrelated, and shortages and irrational use of water and cultivated land seriously affect food yields and carbon emissions. In particular, crop planting is one of the main agricultural water sources used for crop irrigation and food production. Notably, fluctuating water availability and poor water quality can affect food production both in rain-fed and in irrigated agriculture. Crop growth requires water, and rapidly increasing food demands may increase the risk of regional water shortages. Moreover, fertilizer and pesticide inputs for crop growth may cause nonpoint water pollution. Additionally, the food trade is accompanied by virtual water transfer. Crops grow on land, and land quality and quantity changes affect food yields and food quality. As food demands increase and food types change, the accounts of different land types will also change. Mismatches between food production and consumption can also cause cropland soil erosion aggravation [29]. Carbon emissions are discharged through crop production processes, including chemical fertilizer and pesticide application, agricultural machinery use, water intake, pumping, irrigation, land tillage, and crop respiration [71–75,88]. Thus, various irrigation and tillage methods and agronomic activities can reduce or increase carbon emissions [51,71,72]. Harvested straw and grain are also a carbon fixation. In addition, carbon is captured and sequestered in water and land layers, while CO_2 dissolves in water and is transferred to soil organic carbon through roots, microbes, and soil inorganic carbon by irrigation leaching on land [37,40]. Overall, carbon exchange accompanies the food production process. However, carbon emissions increase with increasing CO_2 and temperature levels, which are generally referred to as climate change, and cause crop yields to decrease. Climate change also negatively affects land and water resources, thereby impacting food production [32,89–91]. Globalization can alleviate shortages of regional water and land resources and enhance food security [88]. Population growth results in increased food demands, thereby requiring greater agricultural water and land resources [8]. A changing lifestyle may require more meat, which results in greater land and water use for feed grain growth [73]. Urbanization leads to decreased arable land and limited agricultural water resources, thereby threatening food security [18]. Overall, these core elements and natural, economic, and social factors and their non-liner interrelationships render the WLFC nexus more complex. Thus, quantitative studies on the driving forces and mechanisms of the agricultural WLFC are necessary.

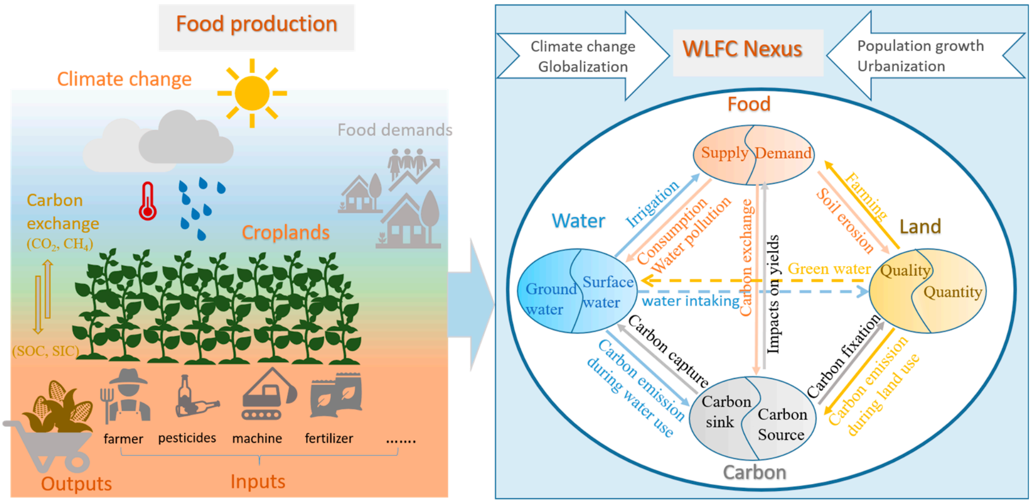

Figure 3. Main interactions within the regional agricultural WLFC nexus.

4. Driving Forces and Mechanism of the Agricultural WLFC Nexus

4.1. Water and Land Affecting Agricultural Yields

Water stress and limited land resources are the two greatest internal challenges for sustainable agricultural development. Water conditions such as effective precipitation and irrigation water are closely related to crop growth [92,93]. In China, a 10%~30% reduction in precipitation causes a 6.4%~19.3% decrease in winter wheat yields and a 4%~15% decrease in summer maize yields at the watershed scale [92]. Irrigation contributes 29%~33% to reducing the risk of agricultural drought, and the combined contribution of irrigation and nitrogen fertilizer to the food yields in China ranges from 44% to ~50% [93]. Globally, each 1% increase in precipitation leads to an average of 0.69%, 0.43%, and 0.06% increases in rice, wheat, and maize yields, respectively (Figure 4(a3) [32]). The yields of these three crops worldwide increase when the irrigation amount increases, while their yields reduce to varying degrees under deficit irrigation and noncontinuous flooding practices (Figure 4(a1)) [64–66,94,95]. Theoretically, cultivated land expansion leads to an increase in food yields, but there are differences in the quality, utilization mode, natural conditions, and location of newly added cultivated land. Compared with continuous monoculture, rotation also affects crop yields, accounting for approximately 20.1% ± 3.5% of the crop yield increase [96]. Specifically, global rice, wheat, and maize yields increase by 18.8%, 14.6%, and 28.9%, respectively, under legume-based rotation practices (Figure 4(a2)) [97]. In addition, tillage is an important factor influencing crop yields, and no tillage has been reported to negatively affect rice (−7.5%), wheat (−2.6%), or maize (−7.6%) yields (Figure 4(a2)) [98]. Additionally, fertilizer inputs, which cause soil fertility alterations, obviously positively influence crop yields (Figure 4(a2)) [65,71].

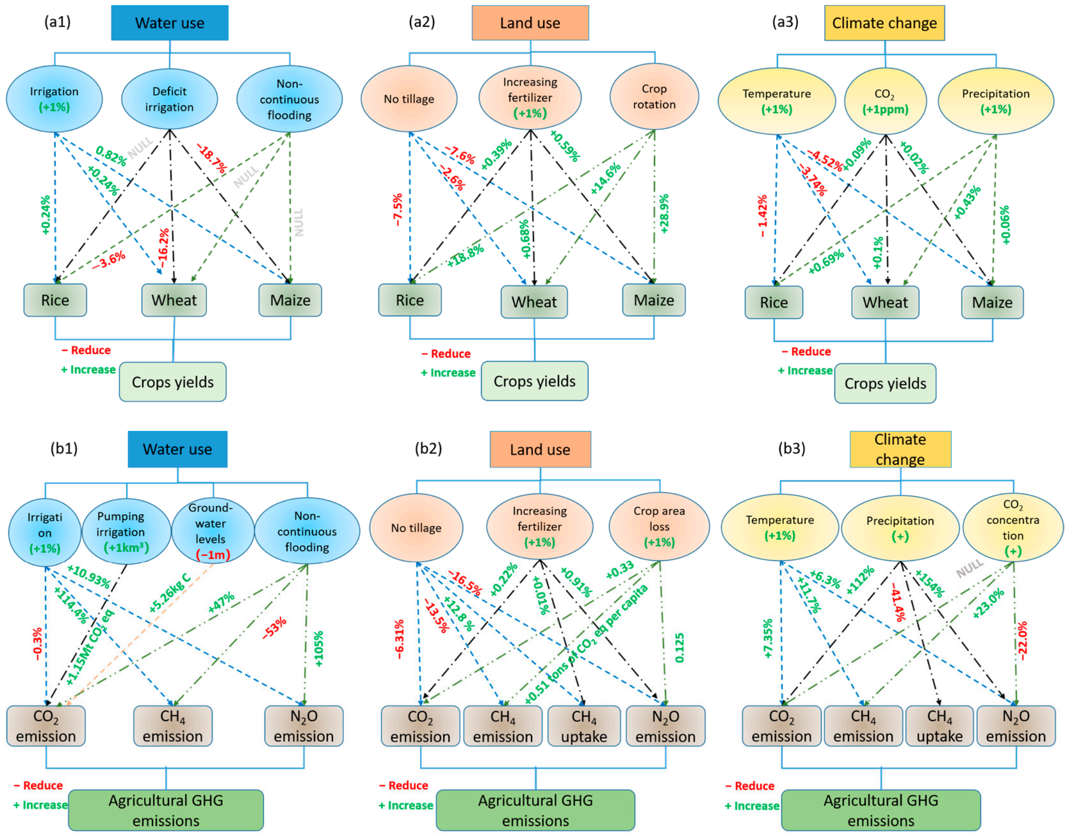

Figure 4. Contributions of various factors to food yields and carbon emissions. (**a1**–**a3**) The effects of water, land use, and climate change on the yields of the three main crop. (**b1**–**b3**) The effects on agricultural greenhouse gas emissions. Note: Figure 4 was constructed based on a selection and reanalysis of data from more than twenty meta-analysis studies (Supplementary Material S1). The data in the figure represent changes in the variables as average values.

4.2. Effects of Water and Land Use on Agricultural Carbon Emissions

Water and land use are two important factors impacting agricultural carbon emissions. Studies have shown that differences in agricultural water extraction and irrigation amounts and methods all affect carbon emissions [51,99]. Notably, CH_4 and N_2O emissions increased by 114.4% and 10.93%, respectively, while CO_2 emissions decreased by 0.3% when irrigation was increased by 1% (Figure 4(b1)) [72]. In particular, each 1 km^3 of groundwater pumping irrigation caused the emission of 1.15 Mt carbon dioxide equivalent (Figure 4(b1)) [100]. The groundwater level also affects carbon emissions during water extraction, as a 1 m drop in the groundwater level results in approximately 5.26 kg C of additional emissions resulting from pumping, but this value varies with energy consumption level (Figure 4(b1)) [101]. Noncontinuous flooding irrigation imposes an obvious positive effect on CO_2 and N_2O emissions but exerts a negative effect on CH_4 emissions in rice paddies (Figure 4(b1)) [102]. Compared with flood irrigation, deficit irrigation causes a notable decrease in N_2O and CO_2 emissions from summer maize cultivation [51]. Most studies on the effect of land use on agricultural carbon emissions have focused on changes in land use types, tillage methods, and plant structures [103–106]. A 1% increase in agricultural land conversion could lead to varying increases in CO_2 (0.33 tons of CO_2 equivalent), CH_4 (0.51), and N_2O (0.125) emissions per capita (Figure 4(b2)) [107]. The influence of tillage on agricultural carbon emissions generally depends on tillage implementation, depth, and frequency. No-tillage and minimum-tillage practices have been demonstrated as beneficial for mitigating soil carbon emissions, whereas deeper tillage results in higher carbon emissions [37,104,105]. An increase in nitrogen fertilization inputs could led to an increase in CO_2, CH_4, and

N_2O and emissions (Figure 4(b2)) [71]. Adjusting the planting structure can also cause a reduction in carbon emissions from food production [106,108]. Moreover, diversifying crop rotation can not only reduce net GHG emissions but also increase food yields [76]. Few studies have focused on investigating the degree to which spatial–temporal matching between water and land impacts agricultural carbon emissions [23,109].

4.3. External Factors Influencing Food Yields and Agricultural Carbon Emissions

The external factors include climate change, rapid population increase, diet change, technological innovation, trade, and policy implementation (Figure 4). Climate change generally causes variation in the hydrology cycle, land use, and farming conditions for food production [3,110]. Studies have shown that an increase in temperature under climate change leads to a decrease in rice, wheat, and maize yields but an increase in agricultural GHG emissions (Figure 4(a3,b3)) [32,89]. Increasing precipitation can increase both the yields of the three main crops and the agricultural carbon emissions (Figure 4(a3,b3)) [32,90]. The CO_2 concentration positively affects crop yields and CH_4 emissions but negatively affects N_2O emissions (Figure 4(a3,b3)) [32,91]. Moreover, there are greater land, water, and food requirements and carbon reduction challenges for satisfying the increasing population and changing diets [73]. Technological innovations, such as saving water, enhancing the soil carbon capture capacity, and planting high-yield resource-efficient crops, aim to improve the agricultural resource efficiency and reduce carbon emissions in the food production process, thereby promoting regional agricultural green production [111]. Food and water trade can alleviate food, water, and land shortages in import regions but increase the risks in export regions. Therefore, numerous studies have focused on one or two elements of the WLFC nexus in trade chains using the multivariate statistical input–output (MSIO) model, the multiregional input–output (MRIO) model, and the LCA method. Policies also affect the WLFC nexus, i.e., enhancing food variety was reported to impact water and energy requirements, while adopting renewable energy resulted in an increase in the land demand and a reduction in CO_2 emissions [112]. Regional carbon reduction has been shown to cause crop yield reduction under climate change [113]. These external factors negatively or positively influence the WLFC nexus. To date, the existing WLFC nexus interaction research is insufficient. Climate change has become the main research hotspot of studies on the external factors of the WLFC nexus. However, the interactions among water, land, food, and carbon emissions and their driving forces have rarely been quantified.

5. Technologies and Tools for Exploring the Agricultural WLFC Nexus

5.1. Common WLFC Nexus Assessment Methods

The common methods and tools for assessing, modelling, and optimizing the WLFC nexus were summarized. Notably, assessment studies generally focused on the status, physical links, and embodied links of the WLFC nexus. Status evaluation studies mainly focused on the spatial–temporal match, stress, resource use efficiency, security, sustainability, and resilience of the WLFC nexus [114]. The physical links of the WLFC nexus denote the relationships among water, land consumption, food yields, and carbon emissions. The embodied links indicate that the embodied flows in food supply chains vary and that the effects of economic changes are caused by certain subelements of the WLFC nexus. The main methods are shown in Figure 5.

In agriculture, the match between water and cultivated land affects their utilization efficiency and regional food security. Therefore, the matching coefficient, Gini coefficient, and data envelopment analysis (DEA) method have mainly been employed to evaluate the matching level between agricultural water and land [60,67,115,116]. However, the Gini coefficient is not effective when these two resources exhibit a state of shortage or abundance. To identify the status of the WLFC nexus, various indices have been constructed, i.e., the RAND Pardee index [117] and the water scarcity index (WSI) [118]. A comprehensive evaluation system has also been developed based on the pressure–state–response (PSR) model [119], driving force–pressure–state–impact–response (DPSIR) model [120], and coupling coordination degree model [87,121,122]. In addition, geographic information system (GIS), remote sensing, and machine learning techniques have been used to assess water, land, food, and carbon changes [123,124]. Specifically, an integrated index has been constructed based on a comprehensive evaluation system through a mathematical method, i.e., weighted and geometric averages, and widely applied to assess the security, security, sustainability, and resilience of the WLFC nexus. However, this index cannot be employed to reflect the complex interactions within the WLFC nexus. LCA, which is a typical top-town method, can be used to calculate agricultural water, land consumption, and carbon emissions [125,126]. The IO model is a common bottom-up method widely adopted to calculate material flows in the agricultural sector [127]. Complex system thinking and methods such as symbiosis theory, network models, and system dynamics (SD) models are preferred to assess the physical relationships within the WLFC nexus [25,128–130]. When identifying the embodied links within the WLFC nexus, virtual water, virtual land, carbon footprints, and water-land–carbon prices are widely applied [131]. Additionally, cost–benefit analysis has been considered based on service and value theory.

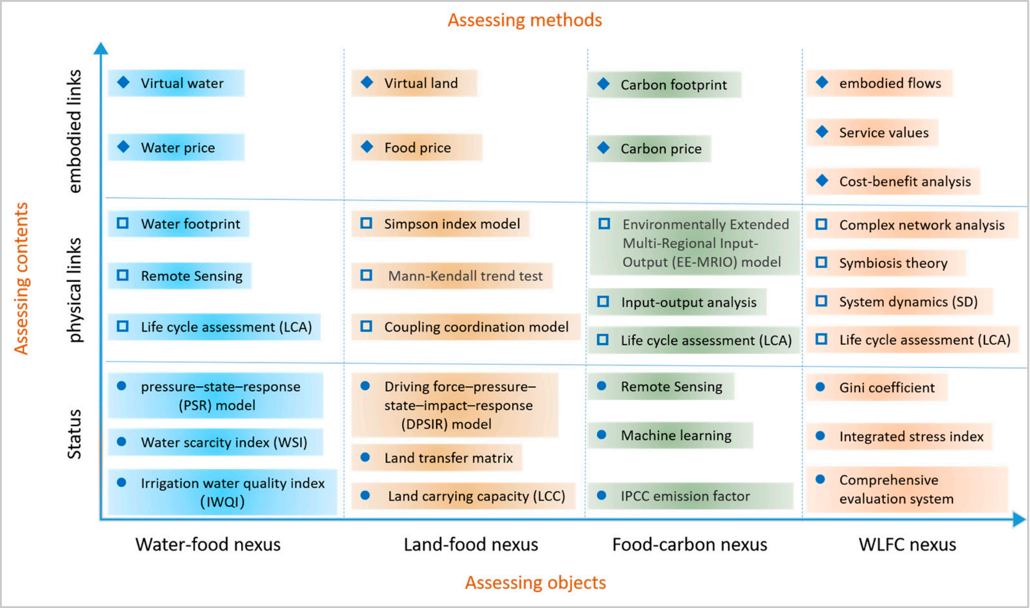

Figure 5. Methods for quantitatively assessing the WLFC nexus.

5.2. Common WLFC Nexus Simulation and Optimization Models

WLFC nexus simulation and optimization models are important sectoral tools that support low-carbon and high-quality agricultural development. Common tools mentioned in the literature are listed in Table 1. The Water Evaluation and Planning System (WEAP) model, Soil and Water Assessment Tool (SWAT), and Soil, Water, Atmosphere, and Plant (SWAP) model are usually used to assess the water–food nexus under various scenarios [125]. For instance, Dehghanipour et al. [132] coupled the WEAP and MODFLOW models to simulate surface water and groundwater for optimizing agricultural and environmental water demands. Zhang and Ren [133] applied a modified SWAT model to simulate the effects of various seasonal fallowing schemes on the water–food–energy nexus. Wang et al. [114] applied the SWAP and World Food Studies (WOFOST) models to assess the effects of different irrigation strategies in a winter wheat–summer maize rotation system. However, there are several limitations to the above models: The WEAP model cannot separate groundwater and surface water demands. The SWAT model restricts the ability to simulate future scenarios. The SWAP model does not provide a graphical user interface. The cellular automata (CA) –Markov model, Conversion of Land Use and its Effects (CLUE)-S model, and Model of Agricultural Production and its Impact on the Environment

(MAgPIE) are widely applied in simulating the land–food nexus. The CA–Markov model can be used to predict long-term land variation and simulate spatial changes in complex systems, but it relies on historical data [134]. The CLUE-S model is a dynamic, multidimensional, spatially explicit and regional simulation approach [135]. The MAgPIE model is an open-source framework for modelling global land-systems, with a spatial resolution of 0.5° × 0.5° [69]. Process-based models such as the Denitrification Decomposition (DNDC) model, Daily Century (DAYCENT) model, and Agricultural Production Systems Simulator (APSIM) model are widely applied in simulating the food–carbon nexus [74,136,137]. These models can be employed to simulate the key physical processes, but the accuracy of the results depends on the precision of the many input parameters. The SD model [130,138], multiobjective optimization model [84,139], and Bayesian network model [86] have also been widely adopted to simulate and optimize the WLFC nexus. Overall, most previous studies have provided a theoretical basis and method reference, but most have focused on the WEF and WLF nexus. However, the corresponding technologies and tools must be further applied and validated in WLFC nexus simulation and optimization studies.

Table 1. Simulation and optimization tools for the WLFC nexus.

Nexus	Tools	Objects	Advantages	Limits	References
Water–food nexus	WEAP	Water resource assessment	Dynamic simulation of scenarios	Cannot separate groundwater and surface water demands	[125,132]
	SWAT	Water resources and hydrology	Simulation of the transport of nutrients	Restricted for simulating future scenarios	[125,133]
	SWAP	Use of water in crop growth	Simulation of water transport in crops	Does not provide a graphical user interface	[114,125]
Land–food nexus	CA–Markov	Agricultural land assessment	Prediction of spatial–temporal changes in land	Relies on historical data	[134]
	CLUE-S	Agricultural crop pattern prediction	A dynamic, multidimensional, and spatially explicit approach	Simulation on a small scale	[135]
	MAgPIE	Simulation of crop production and environmental impacts	Provides recursive dynamic solutions with a cost minimization objective function	Global land simulation model with a low spatial resolution	[69]
Food–carbon nexus	DNDC	Calculation of carbon and nitrogen cycles and trace gas emissions	Process-based model with an input interface, biogeochemical field, and core process	Depends on the accuracy of the input parameters	[74,136]
	DAYCENT	Simulation of plant production, soil organic carbon decomposition, soil hydrology and thermal regimes	Process-based model for simulating key growth processes	Depends on the accuracy of the input parameters	[74]
	APSIM	Simulation of soil–plant–atmospheric processes	Process-based model with soil, plant, and governance parameters	Depends on the accuracy of the input parameters	[137]

Table 1. *Cont.*

Nexus	Tools	Objects	Advantages	Limits	References
WLFC nexus	SD model	Simulation of complex systems to better understand interrelations between components	Can address the complex time-varying and nonlinear system problems	Many data are needed.	[130,138]
	Multiobjective optimization model	Optimization of irrigation water, land, carbon emissions, and agriculture yields	Can be used to design agricultural water and soil resource allocation schemes under different objectives and scenarios	The optimal solution considers multiple goals, but it cannot be obtained each time.	[84,139]
	Bayesian network	Prediction of the future WLFC nexus	Characterizing causality, simulating uncertainty, and reducing data requirements	The prediction results depend on prior knowledge.	[86]

6. WLFC Collaborative Management in Large Global River Basins

The increasing water and cropland shortages and global climate change pressures underscore the need for optimal collaborative WLFC management [12,140,141]. To address these issues, most early studies focused on water resources as the key object for collaborative optimization (Table 2). Studies on agricultural water resource allocation started in the 1940s when Masse proposed the problem of optimal reservoir operation. Liu and Du [142] calculated and analyzed the effects of agricultural water resource allocation, which was a pioneering domestic study. Overall, relevant research has encompassed the stages of considering only water resources themselves; considering macroeconomic, ecological, and generalized water resources; considering cross-basin complex water system regulation; and considering water quantity and quality integration. Currently, nonlinear, multiobjective, uncertainty programming and intelligent optimization algorithms have also been adopted for agricultural water allocation because of the increasing variables and objectives [143]. The allocation of surface water, groundwater, unconventional water, and other physical water has been considered. However, the optimization of virtual water and physical water allocation should be studied further to address uneven water resource distributions and food production demands, especially in water-scarce regions. Additionally, the WLFC nexus should be accounted for in agricultural water allocation.

Agricultural land characteristics, including the planting structure, land area, and spatial patterns, are also the main objects of collaborative optimization. Land optimization can facilitate balancing agricultural water use, food production, and carbon emissions. Therefore, adjusting the planting structure is a common method for agricultural land optimization (Table 2). For example, adjusting the ratios of commercial and grain crops could mitigate the water stress in the Syr River Basin [144]. The adoption of a corn–soybean–wheat rotation effectively improved the food yields and controlled agricultural nonpoint pollution in the Mississippi River Basin [143]. In addition, adjusting land use patterns is an effective way to optimize agricultural land. Studies have shown that increasing wetlands results in agricultural pollution reduction in the Mississippi River Basin and that preventing cultivated land expansion can balance food production and water shortages in the Syr River Basin [144,145]. Deforested croplands in the Congo River Basin can cause carbon sink reduction, which suggests that adjusting the ratios of forestland and croplands can cause an increase in carbon fixation [146,147]. Studies on planting structure optimization in China started later than those in other countries. With in-depth study, the aims of Chinese agricultural land optimization have also shifted from improving the total food yields to satisfying the food supply and improving agricultural economic benefits, balancing the water–food–economic demands, and even pursuing social equity and environmental benefits. Other studies have also focused on optimizing the coupling of water and land resources after accumulation with the Gini coefficient or water and land matching coefficient [112]. Overall, at present, there are relatively few studies on planting structure optimization and adjustment considering WLFC synergy.

Currently, regarding the integrated management of multiple environmental and resource elements, systems-based nexus thinking has been widely adopted. Most studies have emphasized partial elements of water, land, energy, food, and carbon. Among them, studies on agricultural water-land collaborative allocation have always focused on the water-land–food nexus or water–energy–food nexus (Table 2). For instance, scholars have optimized the allocation of scarce water and land resources for various crops in the Yellow River Basin considering the WLF nexus [70,148]. In the Yangtze River Basin, scholars have proposed the crop irrigation water productivity index from a WLF nexus for balancing water pollution, land change, and food production [149,150]. To ensure WEF synergy safety, researchers have recommended the option of double water–electricity cooperation in the Lancang–Mekong River Basin [151,152]. However, most existing studies have failed to consider carbon emissions from food production and the effects of agroecosystem carbon sinks on the allocation of water and land resources. Under the premise of considering carbon emissions, researchers have begun to search for optimal water and land resource allocation strategies for sustainable agricultural development from a water–energy–food–carbon nexus perspective, i.e., in the Yellow River Basin [84] and on the Indo-Gangetic Plain [75,153]. An agricultural high-quality development program is committed not only to achieving high resource utilization efficiency and economic benefits but also to achieving low-carbon emissions and a low risk to human health. However, at present, there are relatively few studies on coupling optimization and the adjustment of water and land resources considering the WLFC nexus. Additionally, all stakeholders in the upper, middle, and lower reaches of river basins should be considered in water-land resource optimization. Therefore, it is necessary to study agricultural collaborative management under multiple objectives with the WLFC nexus at a watershed scale.

Table 2. Cases of collaborative agricultural WLFC management in global river basins.

Basins	Main Conflicts	Optimizing Elements	Strategies	References
Mississippi River	Agricultural pollution	Land	Increasing wetlands	[145]
		Planting pattern Planting method	Corn–soybean–wheat rotation Cover crops and fertilizer reduction	[154]
Amazon River	Deforestation Agricultural expansion Flood- and drought-caused food loss Hydropower	Water Land	Manage blue and green water use Reduce deforestation Improve food productivity	[155,156]
Ganges River	Water scarcity Irrigation Energy Carbon emissions	Water-land	Basin-level water cooperation Adjust the use ratios of surface water and groundwater Adopt pressurized irrigation Fallow crop rotation	[75,153]
Amu Darya River	Water scarcity Cropland expansion Soil salinity	Water-land–food–ecology	Improve the irrigation efficiency Optimize water and land allocation Soil salinity control	[112,157]
Syr River	Irrigation water conflicts Land-water mismatch	Water-land	Improve water and land allocation Strengthen cooperative water networks among countries Optimize the crop-planting structure Control cultivated land expansion	[144,158]

Table 2. *Cont.*

Basins	Main Conflicts	Optimizing Elements	Strategies	References
Yellow River	Water-land stress Soil salinization Ecology stress	Water-land	Promote water-saving policies Optimize the allocation of water and land resources for diverse crops Adjust the planting structure	[70,148,159,160]
Yangtze River	Agricultural pollution Floods	Water-land–food	Optimize the allocation of limited resources and maximize irrigation water productivity	[149,150]
Lancang–Mekong River	Hydropower–irrigation conflicts	Water–energy–food	Double water–electricity cooperation Basin-level cooperation	[151,152,161,162]
Nile River	Water–food production Climate change	Water	Soil water conservation techniques, i.e., plastic film and straw mulching Basin-level cooperation	[163]
Congo River	Deforested croplands Carbon output Hydropower	Land–food–carbon	Promoting afforestation, reforestation, and conservation of natural forests Basin-level cooperation	[146,147]

7. Conclusions

In this study, a systematic review of the WLFC nexus for supporting low-carbon and high-quality agricultural development is presented. First, WLFC nexus studies were reviewed based on bibliographic analysis, and a framework for the agricultural WLFC nexus was proposed. Second, the main internal and external factors influencing the WLFC nexus in agriculture were identified through data reanalysis. The results showed that an increase in irrigation water can cause an increase in food yields (rice, wheat, maize) but cause a slight reduction in CO_2 emissions. Reduced irrigation water use (e.g., deficit irrigation and noncontinuous flooding) can reduce food yield and increase CO_2 emissions. Groundwater irrigation practices can also cause an increase in carbon emissions from energy consumption. Agricultural land loss results in reduced food production and increased carbon emissions. Agricultural land use activities also affect food production and carbon emissions. Notably, no tillage can cause reductions in both food production and carbon emissions, while increased fertilizer can cause increases in both food production and carbon emissions. Crop rotation can cause increases in food yields. Climate change affects food yields and agricultural carbon emissions mainly through changes in the temperature, precipitation, and CO_2 concentration. In particular, temperature increase can cause a reduction in food yields and an increase in carbon emissions, precipitation increase results in increases in both food yields and carbon emissions, and CO_2 concentration increase promotes increases in both food yields and CH_4 emissions but inhibits N_2O emissions. Other factors, such as population, technological innovation, trade, and polices, also influence varying degrees of food production and agricultural carbon emissions. Therefore, a comprehensive agricultural policy should be formulated based on reginal conditions, which can balance water and land consumption, food production, and carbon emissions. Third, the common methods and tools for assessing, simulating, and optimizing the WLFC nexus in agriculture were summarized from the perspectives of the status, physical and embodied links, and their advantages and disadvantages. An increasing number of integrated indices, complex system thinking, and process-based and data-driven methods have been applied to study partial elements of the WLFC nexus. Finally, strategies and programs for collaborative WLFC management in agriculture in global river basins were identified. Among them, water-land joint control is the key component of WLFC nexus studies. These cases provide us with favorable knowledge and optimization routes for realizing low-carbon and high-quality agricultural development. Overall, existing studies on the WLFC nexus are still their infancy, and there are many challenges to overcome. Most studies have focused on the coupling relationships, driving mechanisms, and optimal configurations of two or three elements—water, land, food, and carbon—but studies on the mechanism and regulation of the agricultural WLFC nexus are lacking. The WLFC nexus is complex, dynamic, and spatially diverse, and the coupling mechanism, evolutionary characteristics, and driving forces of the WLFC nexus in regional agriculture should be investigated further. Additionally, the optimal allocation of a single element or a single goal cannot meet the new practical needs of many countries, such as food security, the dual carbon strategy, cultivated land protection, and water resource protection. Therefore, it is necessary to determine the coupling mechanism of the WLFC nexus in major grain-producing areas and to explore optimal control measures based on multifactor coupling and multiobjective coordination to achieve low-carbon and high-quality agricultural development.

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