REVIEW

Water-Food-Carbon Nexus Related to the Producer–Consumer Link: A Review

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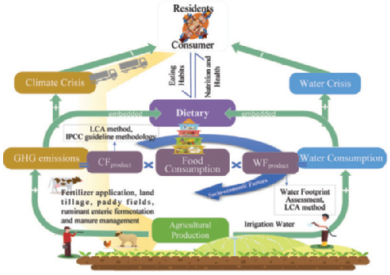
ABSTRACT

Clarifying the water-food-carbon nexus is key to promoting the harmonious development of human society and environmental resources. The sustainable development of agricultural production systems is being challenged by water scarcity and climate change. Crop growth and irrigation consume large amounts of water, and greenhouse gases are generated due to processes such as fertilizer application and enteric fermentation. These environmental impacts accompany the agricultural production process and are thus embedded in the entire life cycle of diverse food items; in turn, consumers' food choices indirectly impact water consumption and greenhouse gas emissions. Reducing agricultural water consumption and greenhouse gas emissions during food production have become crucial issues in mitigating the projected water, climate, and food crises. From the consumer's perspective, diets vary regionally due to different natural conditions for food production and varying socioeconomic and income levels. This review delves into the interactions between diet and its potential environmental impacts, including water consumption and greenhouse gas emissions, in order to support further development of the water-food-carbon nexus. *Adv Nutr* 2022;13:938–952.

Statement of Significance: This review delves into the interactions between diet and its potential environmental impacts, including water consumption and greenhouse gas emissions, in order to support further development of the water-food-carbon nexus.

GRAPHICAL ABSTRACT



Keywords: food consumption, agricultural production, sustainable diet, water resources, water footprint, greenhouse gas emissions, carbon footprint, life cycle assessment

Introduction

Sustainable food production is key to guaranteeing food security and environmental sustainability (1). As income levels rise worldwide, growing demand for increased "quantity" and "quality" of diets is stressing the sustainability of agricultural systems, thereby rendering the water-food-carbon nexus more complicated (2). In the process of agricultural production, crop growth and irrigation consume a large amount of water resources. Meanwhile, greenhouse gases (GHGs) are emitted through the production processes, including

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chemical fertilizer application, land tillage, livestock enteric fermentation, and rice growing. These agricultural inputs and potential effects are embedded in the cradle-to-grave life cycle of the production processes of various foods (including planting, tillage, irrigation, fertilization, animal husbandry, and retail transportation). Therefore, different food items exhibit differences in water consumption and GHGs. From the consumer's perspective, there is also spatial and temporal variability in dietary changes between regions. As agricultural products are transported and consumed globally through trade, water resource consumption and GHG emissions embedded in local dietary patterns have also changed. In other words, food consumption indirectly uses natural resources and changing global diets are further aggravating its negative impact on resources and the environment.

Water scarcity and climate change have become the 2 crises limiting the sustainable development of agricultural systems. Growing demand for food is challenging the sustainability of natural resources (3). Freshwater is one of the most important natural resources, but 80% of the global population faces a water crisis due to human activities (4). Population growth results in increased food demand, thereby requiring greater agricultural water resources (5). Similarly, increasing GHG emissions are leading to irreversible climate change, an enduring global crisis for the next thousand years. The production of food for human consumption accounts for 20% of GHG emissions (6), and agricultural irrigation accounts for approximately 70% of the water withdrawals (7). Therefore, heeding the potential environmental effects of food consumption is essential given the competition for water resources between agricultural development and the needs of the natural environment.

Furthermore, there is an interaction effect between the water and climate crises in agricultural production. Neither exists independently, nor affects the sustainability of agricultural systems separately, but rather they affect agricultural production activities through a combination of factors. On one hand, climate change leads to higher temperatures, drier soils, and erratic precipitation, which affect the availability, quality, and quantity of agricultural water. On the other hand, soil moisture is the dominant factor affecting the terrestrial carbon cycle at low latitudes, and inappropriate water management exacerbates GHG emissions from farmland (7, 8). Taking rice as an example, with intermittent irrigation the alternating cycle of aerobic and anaerobic processes has a significant depressive effect on methane (CH_4) emissions and a significant stimulatory effect on nitrous oxide (N_2O) emissions; thus, appropriate irrigation management can mitigate farmland GHG emissions (9).

Due to its high water consumption and GHG emissions per unit, the production of animal-based foods, especially meat, has a greater potential environmental impact (10). Studies have shown that 80% of agricultural GHGs come from animal husbandry (11), a process that also indirectly consumes irrigation water through feed conversion. Simultaneously, global meat consumption is growing rapidly (12), and dietary changes vary in different regions significantly, indirectly affecting the sustainable environmental development in each country.

Although existing studies have highlighted the water-saving or emissions-reducing effects of dietary changes, achieving an environmentally sustainable diet is influenced by multiple factors, and there is a lack of systematic analyses of the interactions of the environmental impacts and drivers of dietary changes. Therefore, taking agricultural production as the keystone, this review analyzes the research on the potential environmental impacts of dietary change, clarifies the water-food-carbon nexus interactions, and raises awareness of the dual concerns of the health of consumers and that of the natural environment. A further understanding of these aspects could facilitate sustainable management decisions related to agricultural production systems and ensure global food security.

We identified papers on diet types as well as their water consumption and GHG emissions from all Web of Science databases by searching for the following keywords: (water footprint OR water resource) AND (carbon footprint OR greenhouse gas emissions OR GHG) from the results "food consumption OR diet OR agricultural production". In total, 2885 articles were collected (by March 2021) and the top 1000 relevant articles were analyzed. **Figure 1** shows the keyword mapping of diet, water consumption, and GHG emissions, using VOSviewer software developed by the Center for Science and Technology Studies of Leiden University in the Netherlands to analyze the frequency of relevant search words in the titles, keywords, and abstracts of the available literature. The keywords consist of 3 parts. First, in the double challenge of environmental sustainability and soaring food demand, water-food-carbon-energy is inextricably linked, and 3 energy types (i.e., electricity, biofuels, and fossil fuels) are highly correlated with food consumption. Footprint indicators are often used to assess the environmental impacts, with the life cycle assessment approach dominating in accounting for GHGs and the water footprint assessment approach in water consumption. Second, studies on food-related GHG emission types and pathways are more numerous than those on food-related water consumption, with the United States, India, and China as the hotspots. Third, food types are concentrated on staple foods, such as wheat and rice, and animal-based foods with higher resource consumption, such as red meat and dairy products.

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Supplemental Tables 1 and 2 are available from the "Supplementary data" link in the online posting of the article and from the same link in the online table of contents at https://academic.oup.com/advances/.

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Abbreviations used: AWARE, Available WAter REmaining; CO_2eq, carbon dioxide equivalent; FBS, Food Balance Sheet; GHG, greenhouse gas; GLEAM, Global Livestock Environment Assessment Model; IPCC, Intergovernmental Panel on Climate Change; ISO, International Organization for Standardization; LCA, life cycle assessment; LCI, life cycle inventory; Tg, teragram; WF, water footprint; WFA, water footprint assessment; WFN, Water Footprint Network.

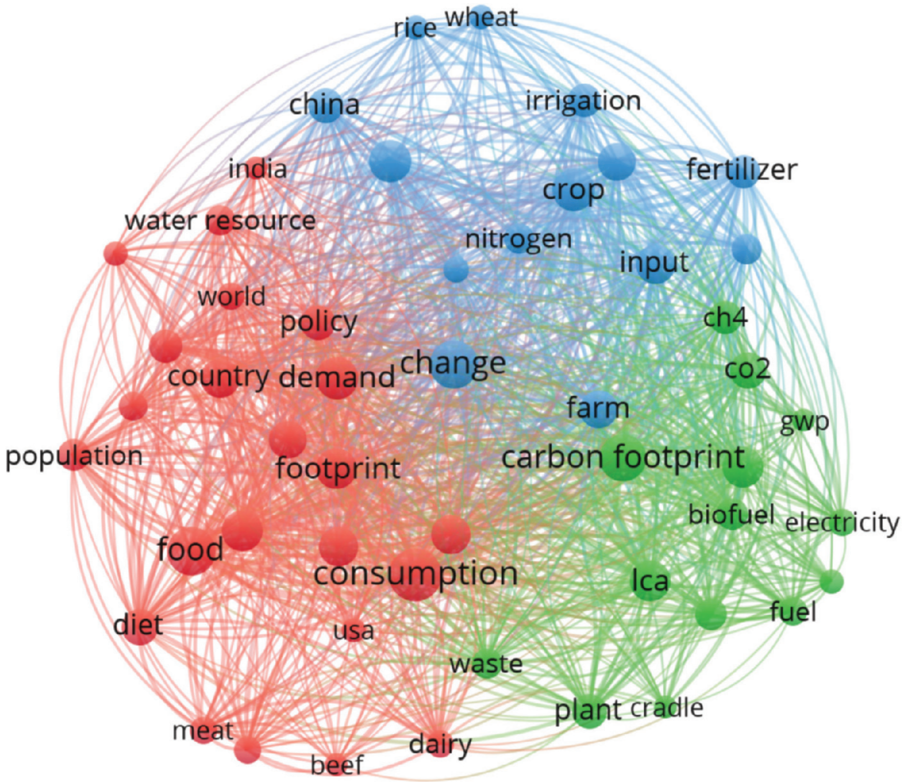


Figure 1 Keyword mapping of research on diet-water consumption-GHG emissions. The figure was made using VOSviewer, developed by the Center for Science and Technology Studies of Leiden University. GHG, greenhouse gas.

Assessment Methods and Indicators

The relevant hotspots on identifying the characteristics of changing diets of consumers from different regions are in the field of nutritional health and medical hygiene. Water and carbon footprint indicators are subsequently widely used to measure human consumption and possession of natural resources, and to gauge the prospects for sustainable societal development, especially sustainable agriculture. The concepts of carbon and water footprints, formally introduced around 2005 (13, 14), have become the 2 most important derived indicator systems for ecological footprints.

Food consumption and dietary characteristics

Food consumption is an important quantifier for defining the "quantity" and "quality" of the diet. There are 2 main data sources for food consumption. The first is the statistical database from nations, regions, or international organizations—for example, the Food Balance Sheet (FBS) in FAOSTAT (15). The advantages of these datasets include the suitability of the total value that accounts for the region as a whole, the consistency of the food classification criteria for better system integrity, and the ability to obtain dietary changing-trend data within long-term series (**Figure 2**). It is worth noting that the FAOSTAT database only provides data on food supply, which is generally equal to the sum of food consumption, food waste (subjective waste), and food loss (unavoidable losses during transport, cooking, etc.). Therefore, it is important that the scope of primary food data is consistent with the accounting of the related environmental footprint. For example, Vanham et al. (16) used correction factors to quantify the process from the farm to the consumer table to extend the food supply data from the FBS.

The second source is interview data on participant food intake in the study area of interest through sample questionnaire surveys or 24-h dietary recalls extrapolated to represent overall food intake levels. These methods are suitable for subnational regions with similar food and cultural habits; individual diet preferences or other factors are likely to disturb estimates of the average (Figure 2). The sampling surveys can cover a limited number of samples of hundreds to thousands of people, and their available food types are specific and appropriate for exploring dietary differences among consumers of different ages and genders. The time series generally is limited to within the last 3 y (17, 18) (Figure 2).

Furthermore, the balanced diets advocated by various countries or regions have also become hot topics, such as the Eatwell Plate (2016) in the United Kingdom (19), the Dietary Guidelines (2015–2020) in the United States (20), and the Balanced Diet Pagoda (2016) in China (21). As the nutritional reference value for consumer food intake,

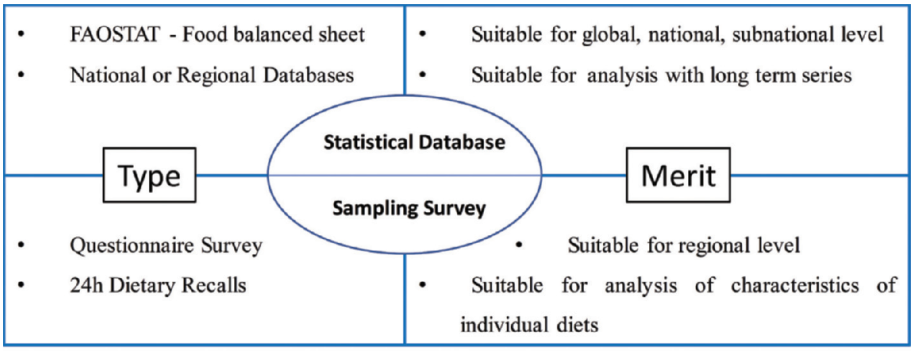


FIGURE 2 Comparison of types and merits of dietary data sources.

balanced dietary guidelines are formulated in the context of local eating habits and agricultural production conditions. A healthy and rational diet transition is also an expectation of policymakers, so the dietary guidelines can be regarded as an optimization of the actual food consumption. Nevertheless, from a long-term perspective of policy decisions and environmental impact assessments, the recommended diet is the closest option to the future dietary trends of the region.

Water footprint for food

Water footprint assessment.

The methodological system for water footprint accounting is outlined in **Figure 3** (22). The water footprint of growing a crop includes 3 components: blue, green, and gray water. The blue water footprint refers to consumption of surface and groundwater along the supply chain of a product. The green water footprint refers to consumption of rainwater, excluding components that form runoff. The blue water

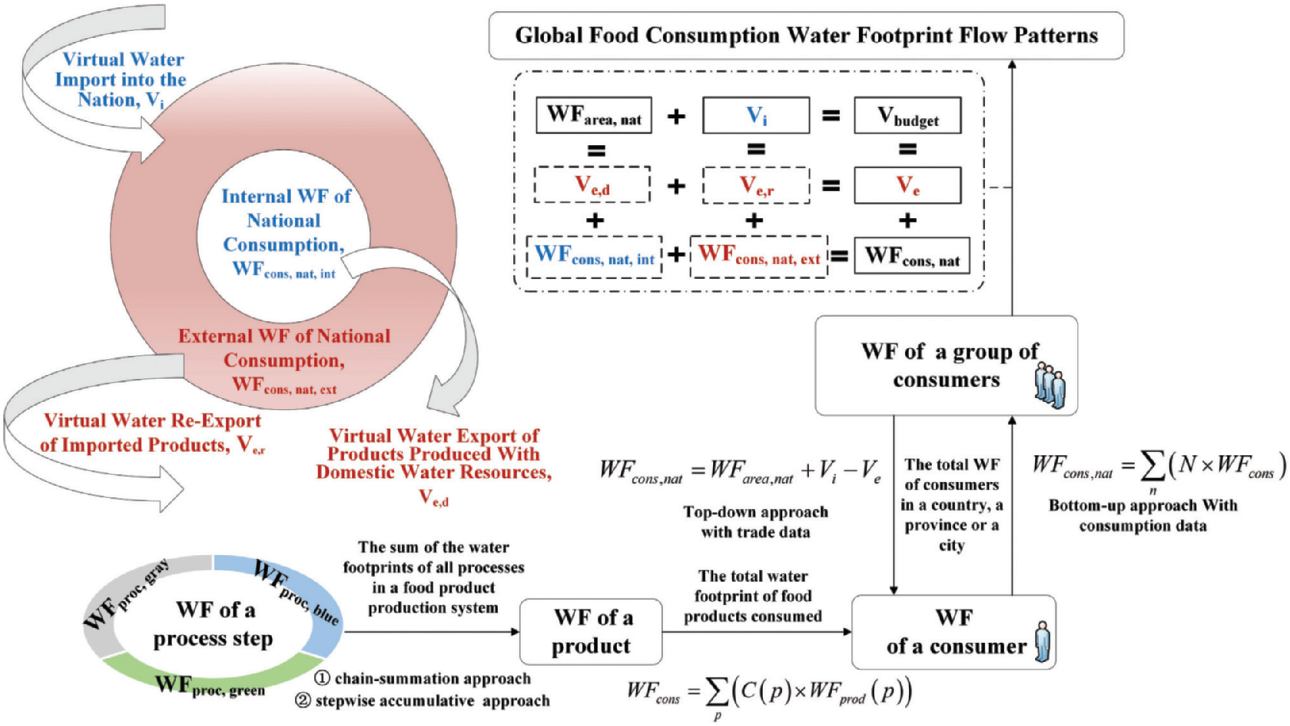


FIGURE 3 Accounting system of WFA. Based on data from reference 22. C(p), consumption of product; n, subnational area n; N, population; V_{budget}, budget of virtual water; V_e, gross export of virtual water; $V_{e,d}$, virtual water export of products produced with domestic water resources; $V_{e,r}$, virtual water re-export of imported products; V_i, virtual water import into the nation; WF, water footprint; WFA, water footprint assessment; $WF_{area, nat}$, water footprint within the area of the nation; WF_{cons}, water footprint of a consumer; $WF_{cons, nat}$, water footprint related to national consumption; $WF_{proc, blue}$, blue water footprint of a process step; $WF_{proc, gray}$, gray water footprint of a process step; $WF_{proc, green}$, green water footprint of a process step; $WF_{prod}(p)$, water footprint of a food product.

footprint ($WF_{proc,blue}$) and green water footprint ($WF_{proc,green}$) are directly linked to crop evapo-transpiration, which can be estimated indirectly through empirical equations or the CROPWAT or AQUACROP models (23, 24). The gray water footprint ($WF_{proc,gray}$) refers to pollution and is determined by the difference between the existing ambient water quality standards of the receiving water body and the natural background concentration (22). The water footprint of a process and its three components are calculated as follows:

$$WF_{proc,blue} = \frac{CWU_{blue}}{Y}[\text{volume/mass}] \tag{1}$$

$$WF_{proc,green} = \frac{CWU_{green}}{Y}[\text{volume/mass}] \tag{2}$$

$$WF_{proc,gray} = \frac{(\alpha \times AR)/(c_{\max} - c_{nat})}{Y}[\text{volume/mass}] \tag{3}$$

$$WF_{proc} = WF_{proc,blue} + WF_{proc,green} + WF_{proc,gray} \tag{4}$$

where CWU_{blue} is the blue water component in crop water use (m^3/ha); CWU_{green} is the green water component in crop water use (m^3/ha); Y is crop yield (ton/ha); c_{max} is the maximum acceptable concentration (kg/m^3); c_{nat} is the natural concentration for the pollutant considered (kg/m^3); AR is chemical application rate to the field per hectare (kg/ha); α is the leaching-run-off fraction; and WF_{proc} is the water footprint of a process such as crop growth.

The water footprint of a food product [WF_{prod} (p)] refers to the total amount of fresh water consumed in food production, including water consumption and pollution from all processes in the supply chain—for example, on-farm production, feed conversion, transportation, and retail. For plant-based food products, the accounting method focuses on crop water requirements and crop yields; for animal-based food products, water used for livestock drinking and service is also counted in addition to the water footprint of the fodder used. There are 2 approaches for calculating the product water footprint: the chain-summation approach, which is only suitable for some specific case studies, and the stepwise accumulative approach, which is generally applicable [for detailed calculation formulas, see (22)]. Currently, the Value of Water Research Report Series No. 47 and No. 48 (25, 26) published in the Water Footprint Network (WFN), are widely accepted (27–29). These reports provide the water footprint for approximately 400 food items from more than 200 counties and regions during 1996–2005.

The water footprint for consumer food (WF_{food}) is defined as the water consumption and pollution of water that can be associated with the production of the diverse food items used by the consumer. The water footprint for the food of a group of consumers is equal to the sum of the water footprints for the food consumed by each consumer, which is influenced by population structure and size.

$$WF_{food} = \sum_{p} (C(p) \times WF_{prod}(p))[\text{volume/time}] \tag{5}$$

where $C(p)$ is consumption of food product p per year (kg/y); $WF_{prod}(p)$ is the water footprint of this food product (m^3/kg); and WF_{food} is the water footprint for the food of consumers per year (m^3/y).

There are 2 approaches for water footprint accounting at the national or regional level. The top-down approach is based on product trade data, and is suitable for research on virtual water trade in countries or regions. The bottom-up approach is based on product consumption data, and is suitable for research on regional total water footprint accounting.

Life cycle assessment for water footprint.

The water footprint in life cycle assessment (LCA) is a comprehensive metric that quantifies the potential environmental impacts related to water. This LCA framework of water footprint accounting by the International Organization for Standardization (ISO) (30–32) consists of 4 main phases (**Figure 4**) (33). In contrast to water footprint assessment (WFA), the water footprint in LCA can only be used after impact assessment modeling (phases 3 and 4) and is not applied to water footprint inventory results or other virtual water calculations (phase 2) (34).

Both the LCA and WFN communities debate the accounting scope and evaluation indicators for the water footprint. First, WFN determined that green water is an essential part of the 3 components of the water footprint (35) because green water is inextricably linked to blue water and plays an important role in plant growth even though it is not directly consumed by humans. As global resources, consumption of either blue or green water impacts water scarcity between water-abundant and water-scarce areas. However, green water in LCA is considered integral with land-use impact assessments, in which land pollution and water quality indicators are applied to avoid double-counting of environmental impacts in LCA (33).

Second, in terms of the assessment indicator system, fewer indicators in WFA include the blue water footprint (WF_{blue}), green water footprint (WF_{green}), gray water footprint (WF_{gray}), or water footprint of consumers (WF_{cons}). Because the ISO standard formulates assessment principles for the water footprint, but not the specific indicators and calculation process, the selected indicators should depend on the research aim. For example, various indicators exist on measures such as water scarcity [e.g., the water scarcity footprint and Available WAter REmaining (AWARE)] (36); stress (37), quality (eutrophication, acidification, and toxicity), and endpoints (human health, ecosystem quality, and resources) (38). Taking milk production as an example, Ridoutt and Hodges (34) compared the water resource evaluation by the AWARE indicator with other scarcity footprint indicators and concluded that AWARE is unsuitable for use in the water scarcity footprint due to its larger value and comparison difficulty.

The LCA and WFA methods for water footprints have their own points of focus. On one hand, LCA aims to quantify the potential impacts on anthropogenic environmental issues (e.g., climate change, human respiratory impacts, and land use). The LCA water footprint focuses on assessing the

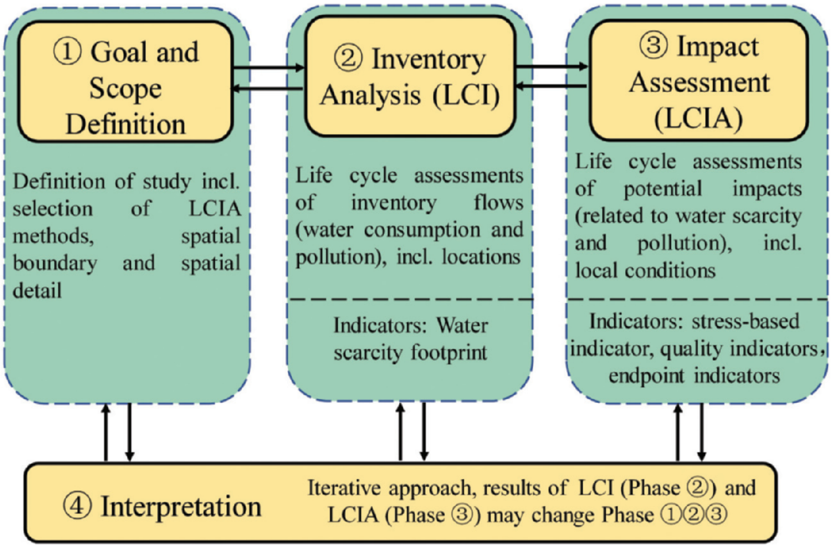


FIGURE 4 Main phases and indicators of the LCA framework for water footprint. incl., including; LCA, life cycle assessment; LCIA, life cycle inventory assessment. Reproduced from reference 33 with permission.

environmental effects associated with water consumption after defining the boundaries of land, air, etc., where water use is considered one of the causes of these potential environmental impacts. Generally, the environmental issue of consideration is the environmental impacts of water use, not water use in itself. On the other hand, WFA aims to support sustainable water management, including volumetric accounting of water use and allocation. When limited freshwater resources are embedded in the food production cycle through agricultural production and economic activities and ultimately reach consumers' tables, it is worth highlighting the specific amount of water consumed in that food, the distribution patterns of limited water resources within the region, and the rational allocation for environmental sustainability (33, 35, 39).

Nevertheless, water footprint indicator is also caught in a synergistic dilemma between the 2 methods. Boulay et al. (40) considered both methods complementary for accounting inventories and assessment indicators. For instance, WFA can use the more well-developed inventory database in LCA for reference. Indicators such as the blue water footprint and blue water scarcity footprint are important in WFA and LCA, and the development of consensus indicators allows for a more thorough assessment of freshwater resource sustainability.

To date, the LCA method for water footprint often focuses on industrial products or a single type of agricultural product, such as cotton (41). The WFA method is used more widely in accounting for the water footprint for diets.

Carbon footprint for food

The carbon footprint for food refers to the total amount of GHG emissions directly and indirectly generated during production in farmland, processing, transportation, retail activities, use, and waste. For plant-based foods, the carbon footprint is mainly attributed to GHG emissions from farmland during crop growth and maturation, such as CH_4 from paddy fields and N_2O from fertilizer application. Compared with plant-based foods, animal-based foods have a higher carbon footprint per product unit (42) for several reasons, the first being that plant-based food (e.g., maize and beans) is required as fodder to produce animal-based food. The lower the feed conversion, the higher the water footprint per unit of animal-based food product. The second main emission sources are CH_4 from enteric fermentation in livestock and CH_4 and N_2O emissions from manure management. Enteric fermentation refers to the process of herbivore digestion, which releases CH_4; this depends on the type of digestive tract, age, and weight of the animal, and its feed quality and quantity. Ruminant livestock (e.g., cattle, sheep) are major sources of CH_4; moderate amounts are generated from nonruminant livestock (e.g., pigs, horses) (43). During manure (including dung and urine) storage and management, the anaerobic decomposition of manure produces CH_4 (43). The main emission source of the carbon footprint for food after leaving the farm is the energy used for transportation, retail activities, and cooking.

LCA for carbon footprint.

The British Standards Institution first implemented *PAS 2050:2008 Specification for the assessment of the life cycle greenhouse gas emissions of goods and services* (44) for accounting of the carbon footprint of products at the enterprise level. Subsequently, ISO updated and issued *ISO 14067:2018 Greenhouse gases—Carbon footprint of products—Requirements and guidelines for quantification*, which defines the principles, requirements, and guidelines for the quantification of the carbon footprint of products. This document aims to quantify GHG emissions associated with the life cycle stages of a product, beginning with resource extraction and raw material sourcing, and extending through the production, use, and end-of-life stages of the product (45).

The Global Livestock Environment Assessment Model (GLEAM) by the FAO is based on LCA. It is used to evaluate the carbon footprint along the supply chain of ruminants, pork, poultry, eggs, and dairy products beginning from land use and feed production, continuing through animal production, processing, and transportation of products, and finally, to the retail distribution point (46–48). The system boundary of GLEAM is divided into 2 parts: cradle-to-farm gate and farm gate-to-retail. GLEAM consists of 5 modules: the herd, feed, manure, system, and the allocation modules (49) (**Figure 5**). In addition, there are software platforms such as SimaPro, GaBi, and Umberto embedded with well-developed databases that quickly and easily calculate the carbon footprint for a product based on LCA for industrial enterprise products. Agri-footprint 5.0 is a life cycle inventory (LCI) database focused on the agriculture and food sector containing approximately 11,000 agricultural products (50).

Intergovernmental Panel on Climate Change guideline methodology.

The Intergovernmental Panel on Climate Change (IPCC) guideline methodology, according to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories (43), provides principled schemes for greenhouse gas accounting in countries. Chapters 5 and 10 of volume 4 focus on GHG emissions from farmland and livestock, providing references on the carbon footprint for plant- and animal-based foods, respectively (Figure 5). To calculate GHG emissions from farmland, the first step is to classify farmland systems and to distinguish between annual and perennial crops, as well as temporary fallow land. The second step is to estimate GHG emissions from all carbon sinks and sources (i.e., biomass, dead organic matter, soil carbon) in different farmland systems by multiplying corresponding emission factors. To calculate GHG emissions from livestock, first the livestock population and feed characterization are identified; then, emissions are estimated (i.e., CH_4 emissions from enteric fermentation, and CH_4 and N_2O emissions from manure management) based on emission factors. Since suitable options of emission factors play an important role in accounting accuracy, the IPCC Guideline Methodology is also called the IPCC Emission Factor Method.

Figure 5 compares the IPCC Guideline Methodology with the LCA method in accounting accuracy, applicable scope, and system methodology for carbon footprint assessment.

It is noteworthy that most existing studies have only considered the water or carbon footprints for food during the farmland phase and ignored the water or carbon footprints from the farm-to-consumer table (including transportation, retail, cooking fuel, and food waste) due to their negligible percentage contribution. Recently, however, as pressure on resources and environment increases, and amidst the growing urgency to save water and reduce emissions, the post-farm water and carbon footprints have gradually gained attention. Mohareb et al. (51) reported that home delivery of different grocery options and reduction in post-distribution food waste by 50% in cities in the United States would reduce ~1% and 11% of total food sector emissions, respectively. Moult et al. (52) concluded that different methods of food waste handling at food retailers result in GHG emission differences, and recommended that food waste unfit for human consumption can be converted to animal feed or anaerobic digestion, because the highest GHG emissions come from the landfill disposal of food waste.

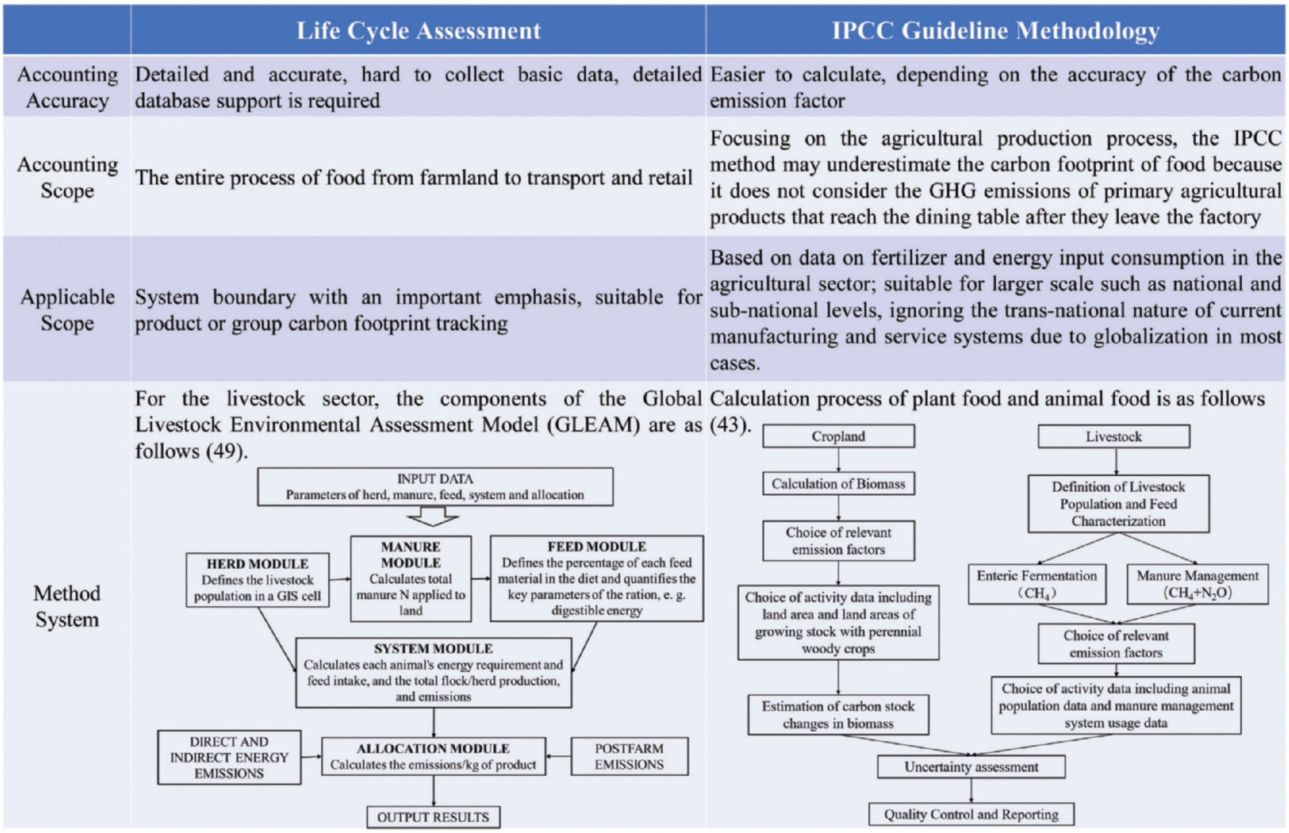
The Environmental Impact of Dietary Change

The main characteristics of the current dietary changes are 3-fold: *1*) the average food intake in high-income developed countries far exceeds the recommendations, with a high proportion of animal-based foods (mainly meat) consumed in North America, Asia, the Pacific, and Western Europe; *2*) increasing consumption of animal-based foods in upper-middle-income developing countries is lower than that in developed countries; and *3*) malnutrition, hunger, and obesity still coexist in developing countries (53, 54). Meanwhile, dietary choices influenced by socioeconomic factors, such as income level, eating habits, and health factors, indirectly affect water consumption and GHG emissions embedded in changing dietary trends.

The impact of dietary changes on water resources consumption

Supplemental Table 1 compares the data sources and global representative research results of the water footprint for different diets. Due to the rapid increase in meat consumption, the water footprint for food is growing to varying degrees. For example, Liu and Savenije (29) concluded that the water footprint for food in China increased from 255 m^3/y^{-1} per capita in 1961 to 860 m^3/y^{-1} per capita in 2003. Food-related water consumption varies considerably between developed and developing countries, with the per capita water footprint for food in developing countries generally being lower than that in developed countries. For instance, from 1997 to 2001, the water footprint for food was 1459 m^3/y^{-1} per capita in the United States, 1067 m^3/y^{-1} per capita at the global average, 921 m^3/y^{-1} per capita in India, 810 m^3/y^{-1} per capita in the United Kingdom, and 605 m^3/y^{-1} per capita in China (10), with variance among countries ranging from −43% to +37% of the global average.

Researchers have developed dietary scenarios based on historical characteristics of dietary patterns and the current national dietary guidelines to model and quantify the respective water consumption. Liu and Savenije (29) modeled 3 diets of low, medium, and high levels of modernization based on technological changes, food consumption, and baseline annual growth rates of crop production. They separately considered the growth rate of the water footprint for plant- and animal-based foods according to the baseline annual growth rate of crop production and maize production. They concluded that food consumption patterns were a



	Life Cycle Assessment	IPCC Guideline Methodology
Accounting Accuracy	Detailed and accurate, hard to collect basic data, detailed database support is required	Easier to calculate, depending on the accuracy of the carbon emission factor
Accounting Scope	The entire process of food from farmland to transport and retail	Focusing on the agricultural production process, the IPCC method may underestimate the carbon footprint of food because it does not consider the GHG emissions of primary agricultural products that reach the dining table after they leave the factory
Applicable Scope	System boundary with an important emphasis, suitable for product or group carbon footprint tracking	Based on data on fertilizer and energy input consumption in the agricultural sector; suitable for larger scale such as national and sub-national levels, ignoring the trans-national nature of current manufacturing and service systems due to globalization in most cases.
Method System	For the livestock sector, the components of the Global Livestock Environmental Assessment Model (GLEAM) are as follows (49).	Calculation process of plant food and animal food is as follows (43).

FIGURE 5 Comparison of life cycle assessment and IPCC guideline methodology for accounting for carbon footprint. Based on data from the IPCC (43) and Gerber et al. (49). GHG, greenhouse gas; IPCC, Intergovernmental Panel on Climate Change.

determinant of virtual water consumption, and dietary changes contributed more to the growth of the total water footprint for food than did population growth; therefore, water requirements can be effectively reduced by reducing the intake of animal-based foods with a high product water footprint. Hess et al. (27) modeled 4 diets in 2031 based on political, economic, social, technological, and environmental factors, and concluded that changes in the UK diet will lead to blue water scarcity in externally relevant trading countries such as Spain and South Africa, and suggested that increasing the proportion of imported products from regions with higher blue water productivity (tonnes/m^3) and lower water stress could alleviate water stress in the United Kingdom and reduce the vulnerability to water-related risks in the food supply chain. Vanham et al. (16) adopted 3 diets: the current diet (REF; average of 1996–2005), a healthy diet (HEALTHY; based on the Food-Based Dietary Guidelines), and a vegetarian diet (VEG). They concluded that water footprints for VEG and HEALTHY were lower than REF, which also supports the environmental benefits from plant-based foods. Although VEG was poorest in nutrition, if it were adopted the study area would be transformed into a virtual water net-positive export area for agricultural products. Vanham et al. (28) also compared the water-saving effect of a healthy meat diet (HEALTHY-MEAT), a healthy pescatarian diet (HEALTHY-PESC), and a healthy vegetarian diet (HEALTHY-VEG) with the actual diet. Results showed water savings of 10–33% of blue water and 11–37% of green water in the HEALTHY-MEAT, 33–55% of the total water footprint in the HEALTHY-PESC, and 35–55% of the total water footprint in the HEALTHY-VEG diets.

The impact of dietary changes on climate change

Supplemental Table 2 compares the methods and global representative research results of the carbon footprint for different diets. Similar to the water footprint trends for food, the carbon footprint for food is also increasing in parallel to the rising consumption of animal-based foods, especially ruminant meat. The total GHG emissions from China's livestock sector increased from 233 $TgCO_{2e}$to 520 $TgCO_{2e}$ (1 Tg = 1 teragram) as the livestock population increased from 142 to 441 million from 1980 to 2010 (55). The environmental impact of ruminant meat is 100 times higher than that of plant-based foods (56). Unless unprecedented technological advances appear, reducing consumption of ruminant meat and dairy products is essential to meeting emissions reduction targets (57–60).

The scenario-based methodology is also the main tool for analyzing the impact of dietary change on climate change. Bernerslee et al. (42) maintained per capita energy supply of 3458 kcal/d and modeled 3 vegetarian and 3 vegan diets. Their results showed that each of the 6 diets has a different level of emissions reduction (18–31%) compared with the actual diet in 2007 in the United Kingdom, with an average reduction equivalent to 50% of the current transportation GHG emissions in the United Kingdom. Behrens et al. (61) quantified GHG emissions, eutrophication levels, and land use for the recommended diets in 37 countries (64% of the global population) and showed that the shift to a recommended healthy diet would be beneficial to the environment in high-, low-, and middle-income countries. Clark et al. (62) assessed the contribution of different diets to the growth of GHG emissions over time and showed that, even if fossil fuel emissions were to cease, current global food demand trends would make the 1.5°C reduction target unattainable and threaten the achievement of the 2°C reduction target toward the end of the century.

Even though considerable water-saving and emissions reductions can be achieved through proactive dietary optimization, it does not mean that animal-based food, which consumes a large number of environmental resources, must be completely abandoned. Macdiarmid et al. (63) used a linear programming model to obtain a sustainable diet at no additional cost to achieve a 36% reduction in GHG emissions, with only a 40% reduction in meat and a 5.3% reduction in high-fat dairy products.

Sustainable and Healthy Diets

As a bridge linking environmental sustainability and human health, diets are influential on sustainable development in countries that face growing pressure related to natural resources and the environment, on the one hand, and severe challenges in nutrition, hunger, and disease on the other. Thus, it is necessary to consider factors such as physical health and socioeconomics to construct a sustainable and healthy diet. A universal healthy reference diet taking planetary boundaries into account was introduced by the EAT-Lancet Commission based on the planetary boundary theory (64). This diet optimizes health without exceeding planetary boundaries associated with the 6 systems—namely, climate change, nitrogen cycling, phosphorus cycling, freshwater use, biodiversity loss, and land-system change (65). Shifting from the current diet to the planetary health diet would decrease agricultural GHG emissions in most countries, except for those with low- and middle-income levels (66).

Nutritional health factors

A reasonable consumption pattern of animal- and plant-based foods is not only a dominant factor in potential environmental impacts but also beneficial to physical health. Among plant-based foods, grains are rich in carbohydrates, an important source of physical energy; vitamin B (including thiamin, riboflavin, and niacin); minerals; protein; and dietary fiber (67). Fruits and vegetables are important sources of phytochemicals (phenolics, flavonoids, and carotenoids), vitamins (ascorbic acid, folate, and β-carotene), minerals (potassium, calcium, and magnesium), and fiber (68). Increasing the intake of fruits and vegetables can maintain good health and effectively reduce the risk of chronic diseases such as cardiovascular disease, lung cancer, and diabetes. Fresh animal-based foods are good sources of high-quality protein, fat, and fat-soluble vitamins and minerals (69); dairy products, which are rich in calcium, are good sources of high-quality protein, retinol, and cobalamin that promote bone health for children and adults (70).

Ruminants play an essential role in reducing harmful environmental impacts and promoting human health, as their stomachs are highly efficient in converting low-quality feed into high-protein foods such as dairy products and beef. While denouncing the "high emissions" and "high water consumption" of ruminant meats, most people still enjoy highly nutritious foods such as beef (12). As the living standard of the inhabitants in most countries continues to rise, except in extremely poor countries, the increasing amount and proportion of animal-based foods, along with energy intake, saturated fat, and cholesterol, have gradually exceeded healthy intake, resulting in an increased risk of obesity, type 2 diabetes, and cardiovascular diseases. The Global Burden of Disease Study noted that the diet is an important factor in predisposing people to malnutrition, obesity, being overweight, and other diseases (71, 72).

Promoting consumers' proactive choices to reduce excessive intake of animal-based foods not only contributes to environmental sustainability but also helps them develop healthy eating habits and focus on health issues. Friel et al. (11) modeled results showing that a 30% reduction in saturated fat derived from animal-based foods could reduce the risk of ischemic heart disease by 15% and 16% in the United Kingdom and Sao Paulo, respectively. Springmann et al. (73) coupled a region-specific global health model to analyze the environmental and health impacts of 4 diets, and concluded that changes in the consumption of red meat, fruits, and vegetables, as well as total energy intake, could reduce total mortality by 6–10% compared with the 2050 reference diet. Davis et al. (74) quantified that cereals such as maize, millet, and sorghum with the lowest blue water footprint can replace rice, resulting in a 33% reduction in irrigation water requirements and an increase in nutrients such as protein (+1%), iron (+27%), and zinc (+13%) with a modest reduction in energy intake.

Socioeconomic factors

Socioeconomic factors such as demographics, income level, trade flows, and food waste behavior directly influence dietary changes, thus indirectly contributing to potential environmental effects. In terms of population growth, Tilman and Clark (75) estimated that the synergistic effect of a 36% increase in global population by 2050 combined with dietary changes will lead to an 80% increase in GHG emissions associated with food production. In terms of economic costs to consumers and producers, there were significant regional differences in the increase or decrease of economic costs when shifting to an environmentally friendly diet with constraints on GHG emissions, economic costs, and nutrition (76). For example, most economic costs in the

Andes tended to decrease, whereas they increased by at least 20% in the northern coastal cities of Peru, Cajamarca (Andes), and Pucallpa (Amazon basin) (76). Hence, flexible communication should be advocated between consumers and producers along the food supply chain, such as the use of digital tools and incentivizing regional and sector-specific targets (77).

In addition, a tax on food with high resource consumption can indirectly promote environmentally friendly food purchases. Edjabou and Smed (78) assumed GHG emission taxes on 23 food items based on total emission reductions, cost-effectiveness, and health impacts, and the results showed that the potential cost of promoting a climate-friendly diet through consumption taxes is low. For example, a tax increase of \$0.017–0.190/kg CO_2eq (carbon dioxide equivalent) in the most economical scenario would reduce GHG emissions by 2.3–8.8% per household in Denmark, and a tax increase of \$0.388–0.759/kg CO_2eq in the highest reduction scenario would reduce GHG emissions by 10.4–19.4%. Springmann et al. (79) concluded that taxes on 11 major food groups in 2020 would lead to rising prices and reduced consumption, and that food-related global GHG emissions could be reduced by 9.3% under full tax coverage and 8.6% under a regionally optimal tax scenario. From the perspective of food trade, studies have focused on the environmental impacts of food trade flows among different regions. Dalin et al. (80) showed that Pakistan, the United States, and India exported 67% of nonrenewable groundwater use for irrigation through the international food trade. Wu et al. (81) found that inter-province crop trade in China had a savings effect on total land resource use, but consumed more water resources for agricultural production.

Reducing food waste is considered a major step toward ensuring food security. Food waste accounts for about one-quarter of the global food supply chain, which correspondingly wastes approximately 24% of total freshwater resources and approximately 23% of global arable land (82). A higher proportion of subjective food waste is observed in total food consumption. Garciaherrero et al. (83) quantified that approximately 20% of total food production in Spain was wasted or lost over its entire life cycle, with approximately 11% wasted in the agricultural production and processing stages and up to 50% wasted in households.

Agricultural land resources

Agricultural land resources are facing an increase in food demand, and increased pressure from urbanization and industrialization. As a crucial infrastructural resource for agricultural production, regional land resources vary across food production processes. Thus, food studies focus on agricultural resources not only in terms of transportable water consumption but also in terms of quantifying the nontransportable land resources behind food consumption. Tilman et al. (2) predicted that global food demand will increase by 100–110% from 2005 to 2050, requiring the reclamation of 1 billion hectares of land and emitting 3 billion tonnes of GHGs at the current agricultural technology level. If agricultural intensification in low-yielding countries was improved, 200 million hectares of land would need to be reclaimed and 1 billion tonnes of GHGs would be emitted. Bajželj et al. (84) simulated the links between global land use distribution and agricultural biomass flows in 2009, and calculated that a 50% reduction in food waste would reduce arable land by approximately 14% and GHG emissions by 22–28% based on scenario analysis. Compared with reducing food waste, adopting a healthy diet could reduce cropland by approximately 5% and grassland by 25%, and reduce GHG emissions by 45%. Aleksandrowicz et al. (85) calculated that GHG emissions, blue water footprints, green water footprints, and land use increased by 3–5% when the actual diet in India shifted toward the recommended diet, but for those whose energy intake was below the dietary guidelines, the shifting had greater environmental effects of an increase of 28%, 18%, 34%, and 41%, respectively. Consumer acceptance of a healthy recommended diet may also save corresponding land use resources, which implies that the balance between food supply and demand will actively adjust the proportion of land use to promote sustainable agri-environmental development. For example, Davis et al. (86) reshaped the global crop structure based on the differences in water use between rain-fed and irrigated agriculture, and obtained an optimal crop distribution pattern that could feed an extra 825 million people, and reduce the need for rainwater and irrigation water by 14% and 12%, respectively.

Discussion

Integrated footprint indicators to evaluate the sustainability of dietary patterns

The theoretical systems of carbon and water footprints are gradually evolving, and **Figure 6** shows the logical nature of the water-food-carbon nexus. Studies have quantitatively evaluated the embedded resources and environmental effects of dietary trends by applying both water and carbon footprint indicators (17, 87, 88), rather than studies that systematically evaluate dietary sustainability by integrated footprint indicators. However, in facing the sophisticated environmental issues and the intersection of research hotspots, several scholars have pointed out that future research directions will focus on integrated footprint indicators or multidimensional normative coordination indicators to quantitatively assess human occupation and consumption of natural resources. Galli et al. (89) first introduced the concept of a “footprint family,” a collection of indicators that integrates ecological, carbon, and water footprints to assess the impact of human consumption of ecological and water resources, as well as GHG emissions in the planetary environmental system. In order to integrate various environmental footprint concepts and related methods under 1 unified conceptual system, the first step is to coordinate footprint accounting methods and to develop the ecological and water footprints as complementary methods to assess the sustainability of human natural resources use. The quantification of vast and undefined environmental impacts into specific indicators could

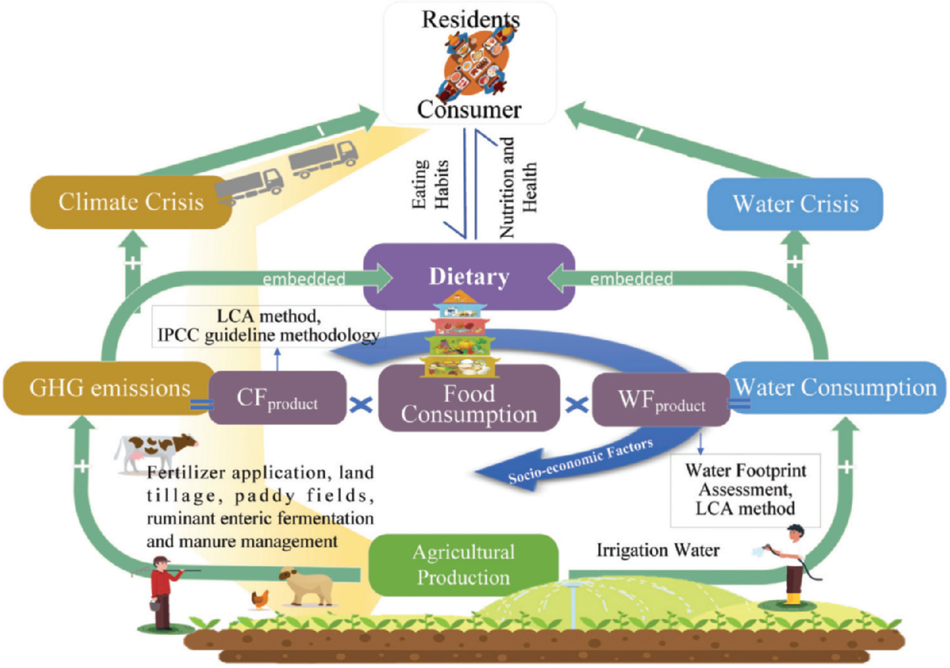


FIGURE 6 Flowchart of the water-food-carbon nexus. $CF_{product}$, carbon footprint of food products; IPCC, Intergovernmental Panel on Climate Change; LCA, life cycle assessment; $WF_{product}$, water footprint of food products.

provide evidence for policymakers and consumers, thus achieving the goal of living in harmony with the environment (22, 90).

As mentioned in the section on assessment methods, the LCA method has been applied to both water and carbon footprint accounting, and 2 major difficulties currently exist in accounting for water and carbon footprints within the same accounting boundary. First, the mechanism of the 2 effects is still unclear. The water-carbon coupling at the product level should be built on the basis of the mechanism of the interaction between the agricultural water cycle and the carbon cycle in order to explore the relation between water consumption and GHG emissions and comprehensively evaluate the agricultural impacts on the environment. Currently, researchers couple climate and hydrological models and continue to explore the interactions between the carbon and water cycles on a large global scale through machine learning (91, 92). However, at the product level, the coupling mechanism and interaction between the water and carbon footprints of products is unclear, and the integrated water and carbon footprint indicators are insufficient theoretically. Second, the water and carbon footprints of multiple foods require large and detailed underlying databases, and authoritative data are unavailable for LCI analysis.

The scenario analysis method is widely used to assume a shift in dietary trends toward healthy recommendations. Nevertheless, this method is only based on the assumption of nutritional expectations, but the actual situation involves individual behavioral options. In addition to physical health, socioeconomic factors, and land resources mentioned in the section on sustainable and healthy diets, measures can be taken from food processing, food retailing modes, and consumer attitudes, which can affect the dietary choices of individual behaviors.

Interdisciplinary research hotspots

Socio-hydrology is a popular emerging discipline for human-water relations that is still in the stage of conceptual framework construction, and as yet lacks a completely comprehensive evaluation system. In the economic-population loop, the water demand embedded in the diet is increasing along with population growth and rising income levels (**Figure 7**) (93). In the community sensitivity loop, the drivers of dietary choices involving food nutrients, consumer food choices, and water consumption behavior are not clear, and other environmental impacts such as land use and GHG emissions also influence system sensitivity. The study of the impact of the water environment embedded in dietary change can be used as a practical case of the natural environment-socioeconomic cycle in socio-hydrology. Further studies can therefore be conducted in conjunction with socio-hydrology developments on the interaction of dietary choices and potential environmental effects.

Energy also vitally interacts with food and its environmental impacts in agricultural production. More than one-quarter of the energy used globally is for food production and supply (94). Meanwhile, growing bioenergy crops may improve energy supply for irrigated agriculture, but may also result in increased competition for land use and water

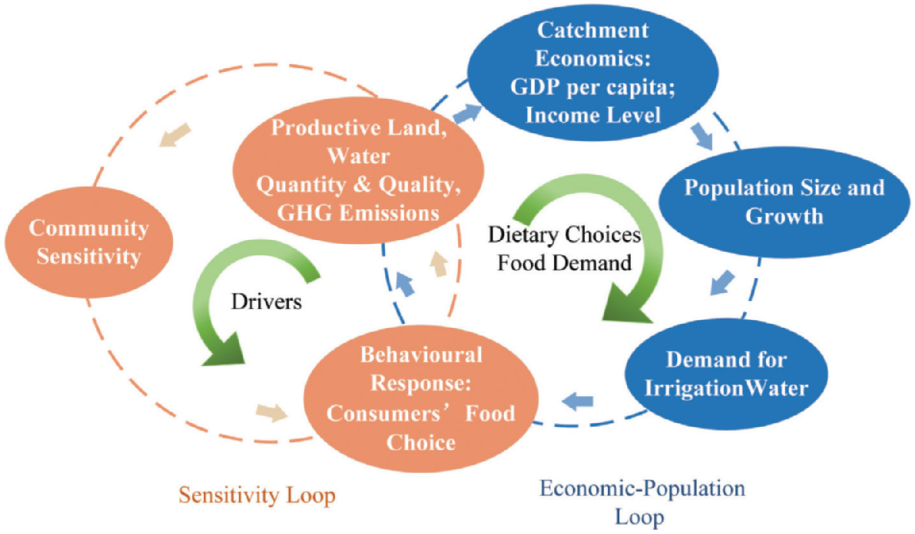


FIGURE 7 A socio-hydrological perspective on the potential environmental impact of dietary choices. GDP, gross domestic product; GHG, greenhouse gas. Reproduced from reference 93 with permission.

resources, which complicates the water-energy-food nexus (95). The nexus approach considers the multidimensional environmental impacts equally, and considers the interactions among different resource uses, such as the potential impacts of climate change on the food-water-energy nexus (95, 96). Hence, future research could develop the systematic food-impacts nexus model to explore synergies and trade-offs of potential impacts within the food system (97).

Conclusions

The water, climate, and food crises comprise the extent of the 3 major global aggravating crises. Research on the water-food-carbon nexus has advanced from single quantification methods to comprehensive evaluation, but the coupled mechanisms are still unclear. Water resources and climatic conditions are important in maintaining sustainable agricultural production. Clarifying the important role of food linking the water and carbon cycles promotes the development of sustainable agriculture. Different food consumption patterns, especially one involving a high proportion of animal-based foods, indirectly affect water consumption and GHG emissions. A diet with a high proportion of plant-based foods is confirmed to benefit the environment; reducing the current overconsumption of animal-based foods can both benefit human health and alleviate the climate and water crises. Furthermore, the implementation of an environmentally friendly diet requires consideration of nutrients, cost acceptability, and local food production conditions.

The footprint indicators have been a widely used research method to quantitatively evaluate the potential impacts of agricultural products on natural resources and the environment from the consumption side at global, national, or regional scales, as well as small-scale community groups and product supply chains. However, more research is required to evaluate the water-food-carbon nexus by comprehensive footprint indicators. Additionally, future research should integrate the social sciences, such as socio-hydrology, to elaborate on the water-carbon coupling mechanism.

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