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Transboundary Environmental Footprints of the Urban Food Supply Chain and Mitigation Strategies

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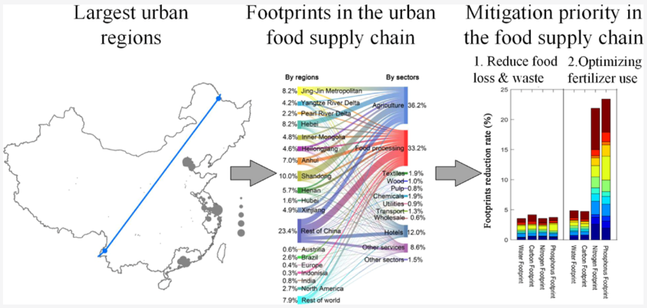
ABSTRACT: Food supply has been the central issue of human development for millennia and has become increasingly critical in an urbanizing world. However, the environmental footprints and associated mitigation strategies of food consumption have rarely been comprehensively characterized at urban or regional scales. Here, we analyze the water, carbon, reactive nitrogen, and phosphorus footprints of food consumption in Chinese urban regions and demonstrate how such information can help to formulate tailored mitigation strategies. The results show that in three of the largest urban regions of China, 44−93% of the four footprints are embodied in transboundary food supply. The size of the footprints and the effectiveness of mitigation measures in food supply chain vary across the environmental footprints and urban regions. However, targeting agriculture and food processing sectors in Hebei, Shandong, and Henan provinces can reduce these footprints by up to 47%. Our findings show that the analysis of the environmental footprints along the transboundary food supply chains could inform individualized and effective mitigation targets and strategies.



■ INTRODUCTION

More than half of the world population is now living in cities. In China, more than 580 million people became urbanized between 1985 and 2018,[1] resulting in profound environmental, social, and economic impacts.[2−4] Urbanization shifts the dietary structure, where urban residents routinely consume more animal and aquaculture products,[5] which are much more impact-intensive.[6] Multiple environmental stresses that challenge the stability of the Earth system[7] are primarily caused by food production and consumption, such as climate change because of greenhouse gas (GHG) emissions, water scarcity because of over withdrawal, transgressed biogeochemical flows because of nitrogen, and phosphorus discharge. However, cities have little capacity to meet their food demand through local production and need to import food from their hinterlands and beyond.[4] Food imports in urban regions contribute up to 20−50% of total environmental pressures in these hinterlands[8] and lead to some serious environmental problems, for example, global warming, particulate matter formation, soil acidification, and water eutrophication. Urban food system is uniquely critical compared to water, energy, and transportation systems, owing to its transboundary footprints that will not only cause local environmental stress but also affect the outside regions. Managing the multiple and broader environmental impacts in the food supply chain is the key to achieving a smart, sustainable, and healthy urbanized world[9] as well as ensuring cleaner production in hinterlands. However, the impacts associated with complex interactions among regions and sectors of urban food supply are still not systematically understood, which constrains the capacity in prioritizing the mitigation efforts along different supply processes.

Current research studies require inclusion of a wider range of critical environmental impacts and a complete food supply chain. Previous studies have provided insightful analysis of environmental footprints. For instance, studies show that over 88% of the physical carbon in global cities comes from elsewhere[10] and that China's interprovincial food trade saves green water but losses blue water.[11] The design of the research is built on standalone analyses on transboundary environmental footprints of water,[12] carbon,[13,14] nitrogen,[15] and phosphorus[16] at national or subnational scales and the modeling of multiple environmental impacts related to food production.[6,17−19] Most previous studies on environmental impacts of the food system have tended to be a model part of the food supply chain and focused on limited or specific environmental aspects. For example, on one hand, many

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national or subnational research studies did not precisely differentiate the environmental performance of different food sources in the supply chain[20−23] or only considered the domestic supply chain.[24] Because of the complexity of the urban food supply chain, the modeling of interconnected regions and sectors is required to characterize the holistic environmental impacts.[25] On the other hand, the carbon footprint of food consumption has been evaluated extensively in previous studies; similarly, water and land impacts have also been examined in many studies, yet the nitrogen and phosphorus impacts of food consumption have been less studied.[22,23,26−30] However, more than 80% nitrogen and phosphorus come from food production and caused several regional and global environmental stresses.[18,19,31] Other research studies have included limited (or single) aspects of direct environmental issues of an individual city,[32] a country, or larger scales.[33] As for the evaluation of mitigation strategies, recent research studies have provided evidence-based data on environmental effects of optimizing fertilizer application,[34,35] reducing food loss and waste[36] and other efforts from both producers and consumers.[37] New data sets and more sophisticated models are required for more detailed and in-depth analysis of environmental footprints of food consumption. More research is needed to comprehensively evaluate the various environmental impacts and the mitigation potentials on different stages and processes of the urban food supply chain.

This study addresses these gaps by modeling food supply chain with new environmental inventory data. The modeling includes 30 Chinese provinces and 40 world countries or aggregated regions. We aim to answer two questions: (1) how environmental footprints of urban food are allocated to the transboundary and intersectoral supply chain? (2) where the mitigation strategies lie in the supply chain, and how effective are the strategies? Answering these questions will help to find the most effective regions and processes to initiate mitigation strategies. We quantify the provincial green, blue, and gray water footprint, GHG, nitrogen and phosphorus emissions of year 2010 for all sectors with the national analytical framework and regionally differentiated parameters[18,19] (see the Methods section). Supporting household food consumption involves each sector directly or indirectly in the supply chain. Thus, "food-related" environmental impacts group together agriculture, food processing and production, hotels, and other services (Supporting Information, Figure S1). Thus, the quantification includes detailed food categories, industrial, and service sectors (Supporting Information, Tables S1 and S2 and Figure S2).

This study evaluates the regional and sectoral patterns of environmental footprints and explores the mitigation effectiveness at different stages of the urban food supply chain through modeling of two selected strategies: reducing food loss and waste and optimizing fertilizer application (see the Methods section and Supporting Information, Figure S3). We analyze the footprints for two levels: on eastern China and western China and on the three largest urban regions (Supporting Information, Figure S4). Eastern China, located on the eastern side of the Hu Huanyong line,[38] supports 94.4% of the total population with only 43.2% of the total territory.[39] The Hu Huanyong line, which was first proposed in 1935, runs from northeastern through southwestern China and virtually divides China into two parts with significant differences in population density and urbanization level. The three largest urban regions—the Yangtze River Delta (Shanghai, Jiangsu, and Zhejiang), the Jing-Jin Metropolitan (Beijing and Tianjin), and the Pearl River Delta (Guangdong)—have the highest urbanization rate (60.6−89.3%[1]) and the highest per capita GDP (10.8−17.2 thousand dollars[1] in China, in 2015. See Supporting Information, Figure S5). The household consumption in these three urban regions make up 38.6 and 33.2% of total household consumption in eastern China and the whole mainland China, respectively (Supporting Information, Figures S5 and S6).

■ METHODS

Summary. In this study, we quantify four environmental footprints of urban food consumption, namely, water, carbon, reactive nitrogen and phosphorus and explore ways to reduce the footprints by looking at interlinkages among different urbanized regions and their upstream food supply chain. We divided China into eastern and western parts along the Hu Huanyong line (see Supporting Information, Table S6) to examine the pattern of footprints in these two parts with distinct demographical, geographical, and economic disparities.[40] The food supply chain impacts of household consumption were assessed using the multiregional input−output (MRIO) method by extending the merged MRIO table with environmental accounts. First, we collected activity data from statistics and emission factors in each activity process from the literature, and we compiled four environmental satellite accounts using various methods such as the inventory method,[6] modeling,[25] and material flow analysis (MFA).[32,33] Many previous studies also provide similar environmental emissions,[19,41−43] but they are not openly accessible with sectoral and regional details that match the MRIO table or they lack attention on emissions from different agricultural products. For all environmental indicators, we set a sectoral resolution of 30 sectors, for the 30 regions in mainland China, and 35 sectors for the 40 regions in the rest of the world, following the resolution of the Chinese MRIO table and the world MRIO table. Second, we merged the Chinese MRIO table with the world MRIO table by estimating intermediate and final flows between each province in mainland China and each region in the rest of the world, thus formulating a world MRIO model. This research considered all the embodied environmental impacts of household food consumption in one region that comes from all outside regions. Third, two selected strategies were tested to indicate the potential and criticality in the supply chain. (1) Reducing food loss and waste is designed according to the Sustainable Development Goals from United Nations, which aims to halve the current food loss and waste in postharvest processes including handling, storage, processing, distribution, and consumption. (2) Optimizing fertilizer application is to decrease reactive nitrogen or phosphorus emission intensity with a medium reduction (half of the potential) of avoidable fertilizer application identified from the field experiment and a medium increase (half of the potential) of reuse of straw and manure as a replacement for chemical fertilizer.

Environmental Accounts. The term "water footprint" was used to account for direct and indirect water consumption by including green, blue, and gray water of each sector.[44,45] For each sector in each region, we calculated the direct water consumption, which is water that cannot be returned to its origin. For the agricultural water footprint, we calculated the green, blue, and gray water volumes from crop and animal production data and the coefficients from the reports of

Mekonnen and Hoekstra (2010).[46,47] We obtained the activity data from the China Agriculture Yearbook[48] and the China Statistical Yearbook[1] and considered 68 categories of crop products and 10 categories of animal products. For the industrial and service water footprints, we collected industrial and domestic water withdrawals from the provincial water resource bulletins and detailed industrial sectoral water from the China Economic Census Yearbook 2008.[49] The industrial sectoral water withdrawals were then scaled by the total industrial water withdrawal of 2010 from the provincial water resource bulletins. The sectoral blue water footprint is the consumed portion of the total withdrawal and was gained by multiplying a so-called consumption coefficient[50] for each sector (see details in the Supporting Information, ref 40), and the gray water was assumed to be the same as the amount of blue water by setting a dilution factor of 1.[17] The blue water footprints of the service sectors were assumed to equal a consumptive portion of 10%,[17] and the gray water was calculated by the same method as for the industrial sectors.

GHG inventories were compiled using the IPCC[51] and national GHG inventory[52] method, by multiplying various activity data (e.g., energy consumption volumes) by the emission factors. We considered three main GHGs—carbon dioxide, methane, and nitrous oxide—in this research. For GHG from nonenergy sources, we include methane and nitrous oxide from the crop, livestock, waste treatment, and industrial process. The related activity data were obtained from Chinese statistics on agriculture and the environment. For GHG from energy use, we included 27 types of primary energy, according to the national energy statistical yearbook,[53] which contains sectoral energy consumptions, and the provincial statistical yearbook, with detailed industrial energy consumptions. We did not include secondary energy consumption such as heat and electricity, to avoid GHG double counting, because these were generated from primary energy such as coal and gas.[25,54] Electricity may trade across provinces within China, and here, we attributed the emissions in electricity to the province where it was generated, to compile a production-based GHG inventory. We excluded energy used as raw materials in the chemical industry—such as coal combusted in ammonia production—because little GHG is generated in these processes. For the 40 regions in the rest of the world, we adopted sectoral GHG emissions from the data sets in the WIOD database.[55]

The reactive nitrogen and phosphorus of the agricultural sector were calculated using the MFA method, by modeling cascade flow and balancing the material input and product output of the subsystems. Generally, the nitrogen or phosphorus emission (F) for food type f in region r was calculated by multiplying activity data (D) by emission factors (R) in all the production processes (p)

$$F_{f,r} = \sum_{p} D_{f,r,p} \times R_{f,r,p} \tag{1}$$

The detailed calculating process could be found in Supporting Information, Figure S13 and Supporting Information, Tables S1 and S7. The emissions of other sectors (i.e., nonagriculture) were calculated directly using the inventory method. Our calculations included the same amount of food categories as for the water footprint calculation, but subcategories of vegetables and fruits were not explicitly detailed because of the limits of the coefficients from the literature; however, further information regarding data collection and calculation boundaries can be found in the refs.[17,32,33] Reactive nitrogen and phosphorus denote the mass loss to the environment, to gain nitrogen or phosphorus in products, and can be quantified within the boundaries of the sectoral production process. Reactive nitrogen contains nitrogen potentially emitted to water bodies (mainly by the nitrate radical, i.e., NO_3^{-1}) and to the air by nitrous oxide, ammonia, and nitrogen oxide (NO_x). Phosphorus denotes phosphorus loss to water bodies or to soil because of crop production, livestock, aquaculture, chemical production, food processing, and wastewater treatment. Nitrogen and phosphorus have similar, yet distinctly different, fates of cycling in soil (in the cropland subsystem). Both nitrogen and phosphorus inputs come from fertilizer, irrigation water, atmospheric deposition, seeds, and reused crop residue and animal manure, while the main outputs are harvested crops, crop straw, leaching and runoff, and accumulation (termed "sediment" for phosphorus) in soil. Both the nitrogen accumulation and the phosphorus sediment in soil were calculated by balancing the flows in the cropland subsystem,[19,56] but the difference lies in the forms in which nitrogen and phosphorus exist in the soil. Nitrogen accumulates in soil as organic or inorganic nitrogen content. It could be in various and complex forms and could be further absorbed by plants through mineralization in the next harvest or emitted into the air (mainly nitrogen, i.e., N_2) through nitrification and denitrification. However, phosphate ions in solution from various fertilizers will gradually react with elements within the soil, especially in tropical soils.[57,58] For example, the reaction will be dominated by calcium in alkaline soils and by aluminum in acid soils (and then transformed into crystalline variscite and strengite), and all these phosphates are highly insoluble and generally are not available to crops. Although croplands in northern China have weaker phosphorus retention capacity,[59] the residue phosphorus can lose to water bodies through runoff and leaching, and phosphorus over-application continues to be a problem.[60] Therefore, we did not treat nitrogen accumulation in soil as a type of contaminant to the environment, but we did treat residue phosphorus in soil as a loss of resource and a threat to aquatic ecosystems. Because human consumption does not belong to any sector in the MRIO model, the related reactive nitrogen and phosphorus losses to the environment were attributed to wastewater treatment in the "Other Services" sector in the MRIO model.

MRIO Modeling. The China MRIO compiled by Liu et al. (2015)[61] provided relationships among 30 regions in China, with a total of 900 sectors, with one column of total exports to other regions and one row of intermediate and final imports from other regions. The 30 regions include 22 provinces (e.g., Hebei), four municipalities (e.g., Beijing), four autonomous regions (e.g., Xinjiang) in mainland China. Tibet autonomous region is not included because of the lack of input−output data but should be included in future modeling. The world MRIO table from WIOD contains 40 regions (excluding China) and a total of 1400 sectors. We coordinated the sectoral classification norms of these two data sets, and the intermediate and final flows between provinces in mainland China and regions in the rest of the world were estimated by splitting provincial total trade volume by a matrix generated from the trade relationship between China as-a-whole and other regions in the world MRIO table. Thus, the flow from sector i in Chinese province p to sector j in region s is given by

$$T_{ij}^{ps} = \frac{T_{ij}^{ps}}{\sum_s \sum_j T_{ij}^{ps}} \sum_s \sum_j T_{ij}^{ps} \tag{2}$$

where T_{ij}^{Cs}, taken from the world MRIO table, describes the monetary flow from sector i in mainland China to sector j in region s. This method has also been applied similarly in the previous studies.[14,62,63] Hence, we get the linked MRIO table with 70 regions containing 2300 sectors and 70 columns of aggregated final consumption from household.

We applied the approach of economic input−output analysis for assessing the transboundary impacts of food-related household consumption (i.e., excluding capital) of Chinese provinces. In particular, the MRIO method is a well-established technique that is widely used in interregional trade and consumption-based environmental assessment. The fundamental input−output equation could be presented as $X = (I - A)^{-1}y$, where X is total output, I is the identity matrix, and $A = T\hat{X}^{-1}$ is the direct requirement matrix. $L = (I - A)^{-1}$ is the Leontief Inverse and describes all direct and indirect relationships between sectors. Household food consumption was obtained from the purchase of agricultural sectors in the final demand (y) of the MRIO table, and thus, consumer waste was included in our analysis.[64] We extended this basic input−output equation by involving four environmental satellite accounts (E) identified as water, GHG, reactive nitrogen, and phosphorus. We defined the sectoral direct environmental intensity as the amount of impact caused by one unit of total output, shown as $e = E\hat{X}^{-1}$. Then, the life-cycle environmental impacts (footprints) of final household consumption could be calculated with the equation $F = eLy$. The footprints for water, carbon, reactive nitrogen, and phosphorus had quite different attributions and orders of magnitude. Hence, we normalized them separately with the min−max scaling method[65] by the following function, to make different environmental indicators comparable.

$$f = \frac{F - \min(F)}{\max(F) - \min(F)} \tag{3}$$

We integrated the embodied flow of four environmental indicators by summing up each of the normalized flows (f) with equal weight, to analyze the embodied environmental impact of the food supply chain, in the main text.

Measuring Environmental Stress. To quantify the environmental and resource stress for different environmental elements, we used different indicators. To characterize the regional water scarcity we used the water stress index,[12] which is the ratio of local water withdraw over total available water resource. We used the per capita terrestrial GHG emissions to indicate the carbon mitigation stress in different regions. For the reactive nitrogen and phosphorus emissions, we mainly considered the water pollution effects and used the pollutant load of surface freshwater as the indicator to measure the environmental stress. All the environmental and resource inventories for different regions around the world are derived from the calculation of this research. The values of the indicators are shown in Supporting Information, Table S8.

Strategy Settings. First, we defined reduced food loss and waste strategy in the three urban regions. Based on the survey and estimates from literatures,[66,67] we took average postharvest loss rates of 23.2, 17.2, and 32.3% for grain, meat, and vegetables, respectively. We calculated the overall loss rate of final consumption by multiplying each of the loss rates of a food type by the corresponding share of the expenditures and summed them up; they totaled a 20.7% loss in the final consumption (Supporting Information, Tables S9 and S10). We assumed a medium (half)-reduced food loss and waste (final consumption of the agricultural sector) in the consumption (postharvest) stage in the three urban regions, checked the environmental mitigation effects and distributed the changes of demand to all regions proportionately.

Second, we defined the strategy of optimizing fertilizer application by reducing over-application of chemical fertilizer and substituting chemicals by increasing crop straw residue and animal waste reuse across China. Defining the avoidable fertilizer application leads to the largest possible reduction of fertilizer without lessening the yield. Additionally, the contribution of fertilizer reduction will be outweighed by the production of the three grains. A reduction of 20−70% of nitrogen and 10−30% phosphorus fertilizer utilization will not sacrifice food production, according to previous studies (see Supporting Information, Table S11). We assumed an additional potential increment from returning 50% of the crop straw/residue and all manure to cropland, based on the current situation (i.e., 20% of manure is currently unmanaged). The weights of nitrogen and phosphorus provided by straw and manure were, respectively, about 20 and 29%,[68] and we assumed the increased amount of straw and manure being returned/reused would weigh the same as the avoided amount of chemical fertilizer. Every 1% reduction of fertilizer will result in an average reduction of 0.8% of nutrient loss.[69] Ultimately, we defined the strategy for reducing nitrogen and phosphorus emissions intensity by aggregating these parameters together (see Supporting Information, Tables S12 and S13). As the reactive nitrogen is reduced, the amounts of N_2O and GHG will fall accordingly. Based on the percentage of N_2O emissions in the total agricultural GHG emissions of different regions, we can reduce the percentage of overall GHG emissions by reducing the nitrous oxide.

Limitations and Uncertainty Analysis. The sectors provided in MRIO data are highly aggregated, making it difficult to depict the impact from the consumption of different food types or to recommend specific changes in the dietary structure. However, this issue is beyond the scope of this research. Furthermore, our rough aggregation of the regions in China misrepresents the actual situation, to some extent. For example, the Jing-Jin Metropolitan area should also include many coastal cities in Shandong and Hebei provinces, but we took Beijing and Tianjin city as a proxy. These problems can be addressed in future studies with more disaggregated data and more finely developed methods.

The main uncertainties in this study came from environmental accounting and the MRIO table because of various input variables of parameter settings and statistical data. Uncertainties in the four environmental accounts and in the values in the MRIO table were separately quantified by Monte Carlo (MC) simulation, presented with mean value (μ), standard deviation, (σ^2) and range of $\mu \pm 2\sigma$ (with 95% confidence). Estimations of errors in the footprints (F) in the MRIO calculations were carried out using the standard error propagation method based on Taylor series expansion, which is much less time-consuming than MC simulation.[15,70] The standard deviation of F is calculated as

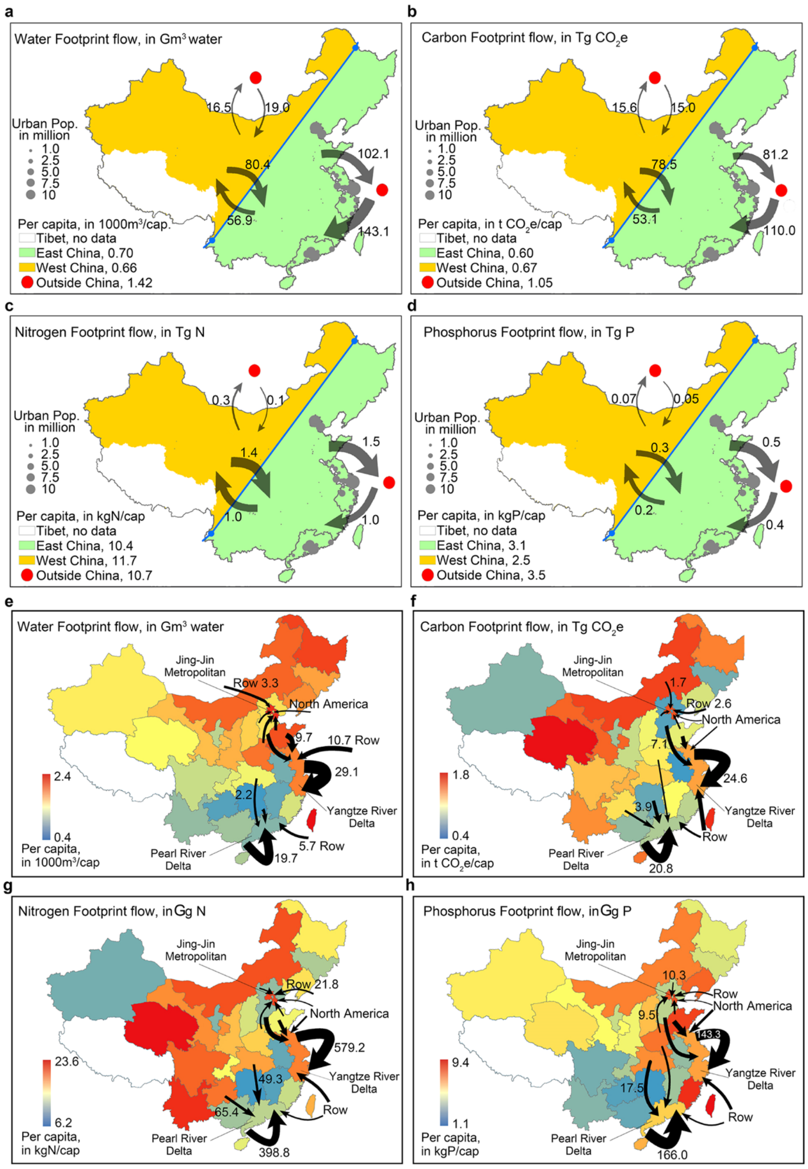

Figure 1. Environmental footprints flow of food-related household consumption in western and eastern China (a−d) and three urban regions (e−h). Total environmental footprints flow in the direction of the arrow. The boundaries of the regions are delineated with lines and colors or labeled (e.g., Row, USA). Units for total footprints flow are in gm^3 (water footprint) and Tg or Gg (carbon, nitrogen, phosphorus footprint). Units for per capita footprints are in 1000 m^3/cap (water footprint), t/cap (carbon footprint), kg/cap (nitrogen and phosphorus footprint). Gray dots on maps (a−d) indicate cities in the three urban regions with urbanized populations larger than 1 million, and the size of the dots is set to show the scale of the population; unit is one million people.

$$\sigma_F = \sqrt{\sum_{i=1}^{n}\left(\frac{\partial F}{\partial e_i}\right)^2 \times (\sigma_{e_i})^2 + \sum_{i=1}^{n}\sum_{j=1}^{n}\left(\frac{\partial F}{\partial L_{ij}}\right)^2 \times (\sigma_{L_{ij}})^2 + \sum_{j=1}^{n}\left(\frac{\partial F}{\partial y_j}\right)^2 \times (\sigma_{y_j})^2} \tag{4}$$

In the calculation of uncertainty, we set e as a single row vector ($1 \times n$), $\boldsymbol{L}$ as a square matrix ($n \times n$), and $\boldsymbol{y}$ as a single column vector ($n \times 1$). Mean value (μ), standard deviation (σ^2), and range of $\mu \pm 2\sigma$ (with 95% confidence interval) of footprints were calculated, and the uncertainties were presented as relative standard deviations given by σ_F/F (see Supporting Information, Figure S14). Our results show that the footprints of eastern China fall within 11.1−18.7% of their mean values and those of the three urban regions fall within 13.6−21.2% of their mean values, both with 95% confidence.

■ RESULTS

Transboundary Supply Chain of Food-Related Footprints. We compare the national footprints with the national environmental limits which are downscaled from the planetary boundaries of the food system[71,72] to show the sustainability levels of the four environmental aspects. While carbon footprint is about 28% below the national limits, water, nitrogen, and phosphorus footprints are 2.4−10.1 times larger than their national limits. The environmental footprints of food consumption in eastern China and three largest urban regions are largely embodied in the transboundary food supply. Figure 1a−d shows that eastern China, where most cities are located, transferred 19.0−28.5% of its total food-related environmental footprints to western China (8.5−12.3%) and abroad (8.6−18.3%) in 2010. Western China, with more vulnerable ecosystems,[73] produced 12.5% of the total pork, 16.5% of

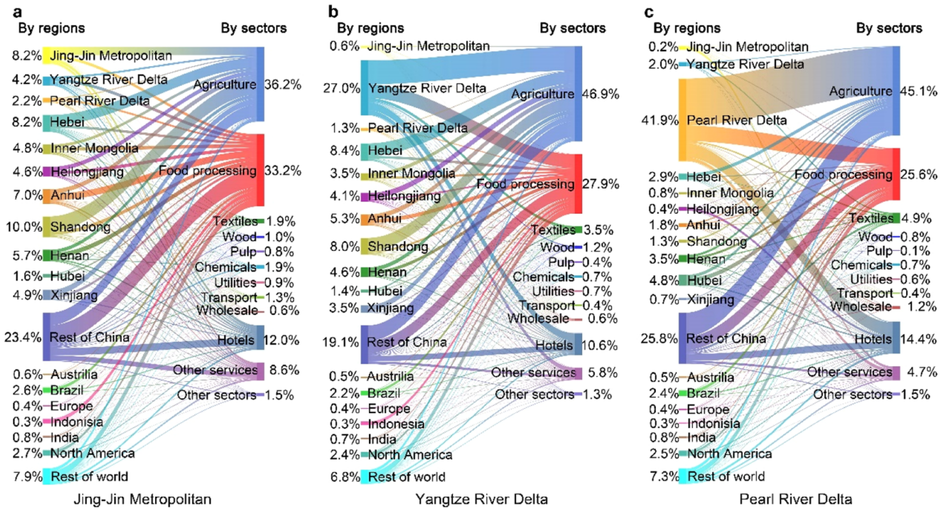

Figure 2. Footprint supply chain of household consumption related to food by region/country and sector, for the three urban regions. Sankey diagrams show a network of normalized footprints and capture the impact of each sector in each region driven by food consumption in the (a) Yangtze River Delta, (b) Jing-Jin Metropolitan, and (c) Pearl River Delta. The ratios on the left sides of each diagram show the regional sources of food-related footprints, while those on the right sides show the decomposition of sectors that require direct and indirect input from food sectors.

the total beef, and 36.5% of the total mutton[48] in China: about 45.6−49.1% of the total food-related environmental footprints there are embodied in food exported to eastern China. Eastern China has larger per capita water and phosphorus footprints, but smaller carbon and nitrogen footprints, than those of western China because of different diets and production efficiencies of various food types across regions.

Western and eastern China import from overseas 5.3−13.3 and 8.6−18.3%, respectively, of their food-related footprints (Figure 1a−d). In 2010, China imported 140.4 Mt food, mainly beans and oil crops from North and South America and exported 40.1 Mt food, including fruits, vegetables, and chicken meat (e.g., from Henan and Shandong to overseas) according to FAOSTAT.[39] Producing one unit of these foods (such as chicken meat) in China causes much higher nitrogen and phosphorus emissions than producing the same amount of plant-based food in other regions.[6,33,74,75] Eventually, China is a net footprint importer of water and carbon but a net exporter of nitrogen and phosphorus (Figure 1). More imports of animal food in China will reduce the global agricultural impact, but this requires continuous development of international trade agreements[13] and design of policy synergies.[14]

In the three urban regions (Jing-Jin Metropolitan, Yangtze River Delta, and the Pearl River Delta), about 44.0−92.7% of their footprints are supplied by outside regions (amongst which, about 9.3−20.8% are supplied by foreign regions), with varying supply patterns among different environmental impacts (Figure 1e−h). Primarily, footprint supplying regions include Hebei, Shandong, Henan, rest of world (Row), and the urban regions themselves (see Supporting Information, Table S3 for the definition of aggregated regions). The transboundary sources of various footprints are spatially heterogeneous. Specifically, carbon and reactive nitrogen footprints of urban regions rely more on southwestern China, like Sichuan, but water and phosphorus are more relevant to northwestern China, such as Xinjiang. Compared to reactive nitrogen and phosphorus footprints, water and carbon footprints have larger importing proportions and thus depend more on outside regions. Jing-Jin Metropolitan imports more than 90% of the food-related footprints from outside regions, mostly from Row, Hebei, Shandong, and Anhui. However, Pearl River Delta imports relatively less footprints (44.0−63.7%) than the other two urban regions, primarily from Row, Hubei, Henan, and Hunan. Illustrating the source and destination of the environmental footprints means that we can identify the target regions for potentially reducing the food-related environmental footprints.

The regions with a higher urbanization level import a larger share (thus have a smaller in-boundary share) of their food-related footprints (Figure 1 and Supporting Information, Figure S7). They also have a larger per unit area of footprint (Supporting Information, Figure S8) but do not always have the higher per capita footprints (Supporting Information, Figure S9). Jing-Jin Metropolitan usually has larger per capita food-related footprints than other regions in mainland China (Figure 1), but Taiwan, despite its relatively lower urbanization rate (74.5%) than Jing-Jin Metropolitan, has an even larger per capita water, carbon, and phosphorus footprint. Pearl River Delta is one of the most urbanized regions in China, but the per capita water and carbon footprint are the smallest among Chinese regions, because of the more efficient and sustainable agricultural supply chain. For example, the Pearl River Delta converts about half (compared to just 10−20% in many other regions) of the agricultural products to final products for consumers, other than raw materials for other industries. Thus, the quantity of the per capita footprint is highly dependent on the efficiency of the supply chain and the green level of the food suppliers.

Intersectoral Supply Chain of Food-Related Footprints. The sectoral allocation of environmental footprints shows similar but also varied patterns among the three urban regions. In Figure 2, each of the four footprint flow networks was standardized and then added up with equal weight to evaluate the sources of food-related footprints at both regional and sectoral levels (see the Methods section and Supporting Information, Figure S10). In the life-cycle supply chain, every sector will require direct or indirect input from food sectors; thus, food products will be consumed through the demand of all sectors. The majority of the footprints of food-related consumption come from (or due to) the agricultural sector

Table 1. Priority Degree of Mitigating the Four Footprints in Top Ten Regions That Are Both Main Food Suppliers and Most Environmentally Stressed[a]

	water footprint	carbon footprint	nitrogen footprint	phosphorus footprint
Hebei	√√√	√√√	√√√	√√√
Shandong	√√	√√	√√	√√√
Henan	√√√		√√√	√√√
Jiangsu	√√	√	√√√	√√
inner Mongolia		√√√	√√	√√
row		√√√	√√√	
Xinjiang	√√	√√√		
Anhui	√		√√	√
Hubei	√	√	√	√
Heilongjiang	√√	√		

[a] The number of ticks (ranging from zero to three) indicates the number of urban regions that have critical priority of footprints mitigation from the supplying regions (such as Hebei, Shandong, etc.). The cell is left blank if the supplying region is crucial to none of the urban regions, while one tick means the supplying region is crucial to one urban region and so forth. The regions are ranked by the critical level.

(36.3–47.2%), food processing (25.6–33.1%), hotels (10.6–14.4%), other services (4.7–8.6%), and to a lesser extent, industrial sectors related to agriculture, such as textiles and chemicals. Different sectoral allocations are caused by differing consumption patterns and industrial mixes of the different regions. For example, because of the prosperous tourism and other tertiary industry in Jing-Jin Metropolitan, the service sector (8.6%) has a much larger impact than the other two urban regions (5.8 and 4.7%), but the textile sector has much less impact (1.9% compared to 3.5 and 4.9% in the other two urban regions). Additionally, food-related products imported from Hebei and Shandong allocate 60–80% of the environmental footprints to the agriculture sector, while those from Anhui, Henan, and most abroad regions allocate more footprints to food-processing, hotel, and other services (totaled 48–62%). These results indicate the need for differentiated policy pathways for different supply chains when regulating food-related footprints of urban household demand.

The different sectoral allocation among the four footprints helps to identify specific sectors that can be targeted for mitigation. More than one-third of water, nitrogen, and phosphorus impacts come from the agriculture sector, which is mostly located in rural regions (Supporting Information, Figure S11). However, the carbon footprint is more diversely distributed to other sectors, for example, the carbon footprint of agriculture takes about 5–10% smaller ratios than other footprints, and about 7–11% of food-related carbon footprints are because of the consumption of utilities in the urban regions, compared to less than 1% for other kinds of footprints. This means that rural regions that hold more agricultural production have larger potential and necessity to reduce water, nitrogen, and phosphorus impacts than carbon impact, through improvements in farming technology. Cities can reduce the life-cycle carbon emissions of food production by promoting production efficiency of electricity, petroleum, fertilizers, and pesticides because these factories are commonly located in urban regions. Additionally, given that food processing and hotel accommodation are typically located in cities, pursuing better performance in these sectors can simultaneously reduce all four footprints related to household consumption. These results identify the key sectors with mitigation potentials in the footprint supply chain. However, considering the variation in regional and sectoral allocation patterns of the footprints is also crucial to ensure effective environmental mitigation for the food system.

Mitigation Priority along the Supply Chain. Hebei, Henan, and Shandong are the pilots for mitigations of multiple environmental footprints in the three urban regions. We identify the regions with both severe environmental and resource stress and a large share of the environmental footprints in the supply chain as the most crucial focus to reduce the footprints of urban food consumption. Hebei is critical to simultaneously reduce all the four footprints in all the three urban regions (three ticks in Table 1) and should be top priority for reducing upstream food-related environmental impacts. Shandong and Henan are also the key regions to reduce the water, nitrogen and phosphorus footprints of the food consumption in the urban regions (see details in Supporting Information, Figure S12 and Table S4). Some regions, such as Inner Mongolia, take smaller shares in the footprints but also should be prioritized to mitigate impacts from there because of the highly stressed environment in these regions (Supporting Information, Table S8). Food production in these regions requires dedicated changes and a proper cut of production scale to simultaneously reduce environmental footprints.

However, some other regions are less synergetic for all the mitigation objectives and are related to either limited environmental aspects or only certain urban regions. For example, Inner Mongolia is critical for the carbon footprint mitigation in all the three urban regions but has no relationship to the water footprint in any of the urban regions; Hubei is one of the top regions for reducing footprints in Pearl River Delta but relates relatively less to other two urban regions (Table 1). As a result, the strategies will be varied when targeting different environmental footprints or different urban regions. For example, water footprint alleviation for three urban regions will largely rely on upstream supply chain of Hebei and Henan, while carbon footprint reduction will largely rely on Hebei, Inner Mongolia, and Xinjiang. These results illustrate a clear picture of the most urgent and effective supplying regions to reduce specific food-related environmental footprints of urban regions.

Halving food loss and waste and optimizing fertilizer application by reducing excessive chemical fertilizer and increase straw and manure reuse can effectively reduce footprints predominately in the above identified regions (Figure 3). The nitrogen and phosphorus footprints reduced by the combination of these two strategies are even 12–15% larger than the total footprints of food consumption in Pearl River Delta. These two mitigation strategies were selected because they well represent the main stages of the food supply chain. Many other environmental abatement strategies are either slow to realize or often deemed to be potentially harmful to food security and farmers' economic interests[42] and may have both positive and negative effects on different environmental goals.[43,44]

The identified top ten regions (Table 1 and Figure 3) can contribute 64–87% of the reduction efforts and the top three regions (Hebei, Shandong, and Henan) can support up to 47%. Halving food loss and waste within the three urban regions will reduce the environmental footprints by 3.5–5.3%,

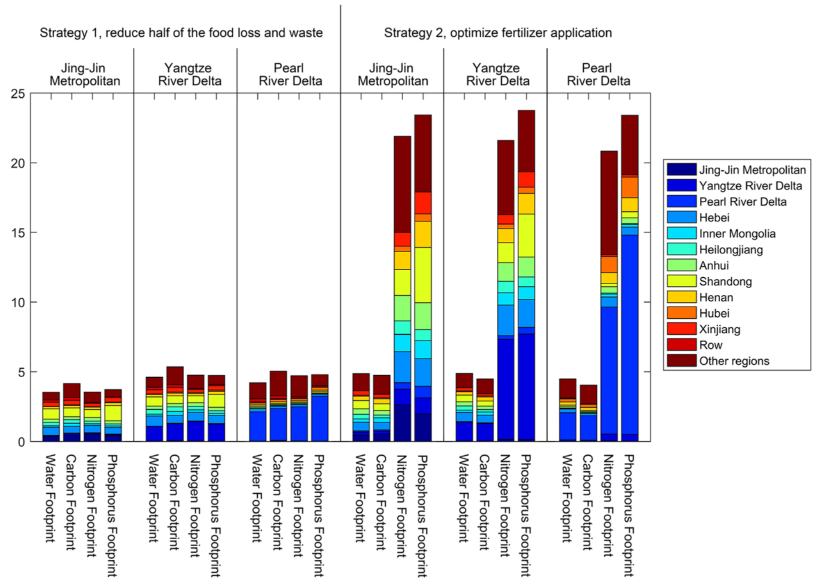

Figure 3. Mitigation effects contributed by the crucial regions and mitigation strategies in different stages of the supply chain. Unit is in percentage (%), denoting the reduction rate compared to the baseline situation, under different strategies.

mainly through the contribution by Hebei, Shandong, and the urban regions themselves (Figure 3 and Supporting Information, Table S5). Ideally, this will translate into a 2.9−8.6% reduction of emissions in food production in these supplying regions, if the saved food in urban regions results in a similar level reduction of food production. Optimizing fertilizer application across China will reduce more than 20% of nitrogen and phosphorus footprints (e.g., 23.8% of phosphorus footprint of the Yangtze River Delta) for the three urban regions. The reduction of reactive nitrogen impacts will also help to reduce the gray water footprint through nitrate and that of carbon footprint through nitrous oxide. Water and carbon footprints, therefore, also have an associated reduction rate of 4.1−5.1%. Cities can also mitigate food-related footprints through enhanced consumer awareness via various measures, such as labeling of environmental footprints or exerting taxation and subsidies to influence consumer choices. Other pathways through which cities can contribute include consolidating urban agriculture and reducing the meat consumption of citizens.[45]

There are also substantial differences amongst the mitigation effectiveness in the four environmental footprints and three urban regions. For example, while Shandong province has relatively larger shares in reducing phosphorus and water footprints, Hebei province contributes more in reducing nitrogen and carbon footprints (Figure 3). The local mitigation among the three urban regions differs greatly: Jing-Jin metropolitan takes around 10% of its total footprints reduction, while this ratio for Yangtze River Delta and Pearl River Delta is around 33 and 50%, respectively. Thus, cities can play stewardship but widely varying roles in environmental mitigation; it functions directly on the local stage (such as by avoiding food loss and waste or promoting urban agriculture) and communicates with the upstream stage indirectly through various local efforts. For example, cities can pair up with a specific region in which impacts are generated and collaborate to reduce these impacts. These results denote that, despite a few regions that can provide a universal reduction, the crucial supplying regions that can effectively reduce environmental footprints need to be specifically identified for different environmental footprints and urban regions.

■ DISCUSSION

Similarities and Differences of Footprints. The footprints and mitigation effectiveness show both similar and varied patterns of distribution across the supplying regions and sectors, which could inform individualized and effective mitigation targets and strategies. The similarities are revealed mainly by the large proportion of transboundary footprints (44−93%) and by the significant footprints from regions (such as Hebei, Shandong, and Henan province) and sectors (such as agriculture and food processing) that supply food for urban regions. Actions in these regions and sectors can simultaneously reduce the four footprints in three urban regions. The varied patterns of footprints are jointly shaped by two detailed facts. First, the different supplying sources of food-related footprints in urban regions will determine different mitigation priorities, and almost all supplying sources (i.e., except for Hebei) only relate to the mitigation of a few aspects of footprints in a few urban regions. For instance, mitigating the phosphorus footprint in Jing-Jin metropolitan relies more on Shandong and Anhui, while mitigating the nitrogen footprint of Pearl River Delta relies more on Hubei and Henan provinces (Table 1 and Figure 3). Second, the mitigation effectiveness from upstream and local stages of urban food supply chain plays substantially varied roles in different urban regions, as the local stage in Pearl River Delta has much larger effects on mitigation compared to that in the other urban regions: although the efforts from both cities and upstream are important.

Reducing Footprints from the Pilots. Various environmental footprints in many regions in China are unsustainable.[18,19,76,77] To reduce the intensive footprints of the urban food consumption, there is an urgent need to develop strategies that incorporate transboundary and intersectoral footprints with cautious identification of the underlying similarities and differences. Mitigation strategies can only be effective and produce more co-benefits when the prioritized targets of environmental footprints and urban regions are carefully identified from the diverse patterns. Numerous agricultural policies and innovative programs have been formulated and implemented by Chinese governments or institutions over the recent two decades.[78−81] However, balanced strategies should include the unequal environment and economic status between western and eastern China and between urban regions and their hinterland. Specifically, Xinjiang and Inner Mongolia in western China provide raw agricultural products (rather than processed products, see Figure 2) for the eastern region and urban regions in China. Water and carbon footprints from Xinjiang, and carbon and nutrient footprints from Inner Mongolia in this food supply could aggregate the resource and environmental pressure in western China (Table 1). These stressed hotspots deserve special attention in policy making. Generally, the agriculture sector in Hebei and Shandong, and food-processing, hotel, and other services sectors in Anhui, Henan, rest of China, and most abroad regions have the greatest criticality in mitigating the environmental footprints of urban food consumption.

With the implementation of "Development of the Western Region of China" and other national strategies in the past decades, the infrastructure and ecological conditions in western China have been substantially upgraded, which facilitates the development of modern agriculture. However, national plans and policies could focus on integrating agriculture with food processing and manufacturing sectors that have higher margins and less environmental costs. Many beneficial actions, such as the promotion of agricultural equipment use and applying emerging technology in agriculture could be partially supported by the compensation from consumers and labor resources in eastern China. These analyses could provide additional implications for the specific implementation of the newly released guidance for development of the western China by the State Council.[82]

General Implication and Future Research. This research characterized the urban food-related footprints, identified the crucial regional and sectoral footprint network and determined the mitigation effectiveness of the regions with both stressed environmental situation and large footprint contribution. Other environmental impacts, such as land-use change and biodiversity loss, are not included in this research because of the lack of data and commonly used methods.[83] The regional water stress could be better measured with the method in recent FAO report which incorporated environmental flow at sub-basin and grid scales.[84] Besides, more up-to-date MRIO data[85] could better illustrate recent or current food supply chain and could be used in future studies. The significant next steps include addressing the effects of unequal price and timing constraints in the supply chain data, incorporating more diverse mitigation strategies[86] and emerging technology for sustainability assessment[87,88] and connecting the national or regional impacts with the Sustainable Development Goals or Planetary Boundaries.[89,90] We anticipate that our identification of significant similarities and differences of the footprint supply chain could underpin the promotion of a sustainable transition at cross-regional and sectoral levels from food production on farms to food consumption in cities worldwide.

■ ASSOCIATED CONTENT

Supporting Information

The Supporting Information is available free of charge at https://pubs.acs.org/doi/10.1021/acs.est.0c01294.

Environmental accounts of agriculture and other sectors, mapping the grid footprints of food consumption, measuring the environmental stress, strategy settings, uncertainty analysis, and supplementary results (PDF)

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Notes

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