Main Manuscript for

Potential Impacts of Fukushima Nuclear Wastewater Discharge on Nutrient Supply and Greenhouse Gas Emissions of Food Systems.

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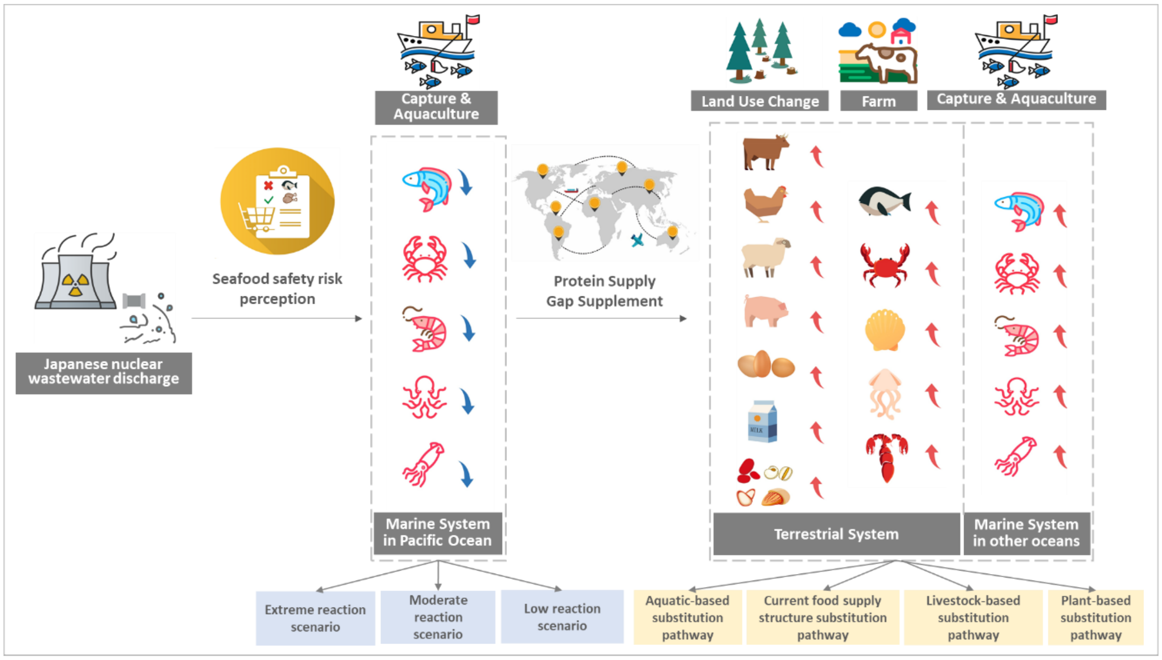
Abstract

Seafood plays a critical role in promoting a nutritious and climate-friendly food system but faces challenges from marine contamination that pose food safety risks. To address these challenges, we developed a Marine Pollution-induced Food System Risk Assessment and Response (MP-FSRAR) model to assess the impact of consumer perceptions of marine pollution risk events on nutrient supply and greenhouse gas (GHG) emissions. Applying this model to the proposed Fukushima Nuclear Wastewater Discharge (FNWD) into the Pacific Ocean, we identified the potential variation in nutrient supply and GHG emissions resulting from changes in Chinese consumers' willingness to consume seafood under 12 scenarios. Our analysis revealed nutrient supply gaps in daily protein, minerals, vitamins, and fatty acids, ranging from 1.5-2.7 g/person, 2.5-4.5 mg/person, 5.6-10.3 mcg/person, and 0.08-0.14 g/person, respectively. Closing the protein gap in China would require an additional 3.2-15.8 billion kg yr^{-1} protein-rich foods, including aquatic, livestock, dairy, and pulses. Additional food supply would increase extra GHG emissions by 1-79 billion kg CO_2e yr^{-1}, resulting in potential GHG emissions being transmitted to other countries through the trade chain. Furthermore, we found that the livestock-based food substitution pathway had 40 times higher GHG emissions than the plant-based one. Our MP-FSRAR model provides global stakeholders with new perspectives on the potential consequences of consumer perceptions of marine pollution risks and offers valuable insights for developing countermeasures to build a more resilient and low-carbon food system.

Graphical Abstract



Keywords: Marine pollution, consumer perceptions, food security, nutrition supply, GHG emissions.

1. Introduction

Global food demand is expected to rise to an unprecedented extent for the following decades, propelled by a projected one-third increase in total population and higher average individual incomes by 2050 (Godfray et al., 2010; Mueller et al., 2012; Tilman, Balzer, Hill, & Befort, 2011). Unfortunately, the current reality is that over one in four people suffer from hunger or lack regular access to nutritious and adequate food (Organization, 2020). To make matters worse, the prolonged COVID-19 pandemic, climate change, and regional conflicts pose additional stronger headwinds to global food security (Fujimori et al., 2019; Laborde, Martin, Swinnen, & Vos, 2020; Nature, 2022). Moreover, the current food system significantly contributes to global anthropogenic GHG emissions, with approximately one-third coming from meat consumption (Crippa et al., 2021; Foley et al., 2011; J Poore & T

Nemecek, 2018). Such food system emissions could preclude the attainment of 1.5℃-2℃ global climate change targets (Clark et al., 2020). The world is thus facing the formidable double challenge of ensuring the continued delivery of sufficient food while curbing overall GHG emissions.

Momentum is gathering to seek food from the ocean for a more nutritious and climate-friendly food system (Hicks et al., 2019; Walter Willett et al., 2019), leading to a significant increase in global capture fisheries and aquaculture production in recent decades (Fig. S1). Seafood consumption provides more than 15% of the average animal protein intake for 2.9 billion people (Smith Martin et al., 2010; Walter Willett et al., 2019), as well as being a vital source of essential micronutrients such as amino acids, omega-3 fatty acids, vitamins, and minerals, which are essential for human health (Hicks et al., 2019; Tacon & Metian, 2013). It is predicted that the marine food supply will increase by 21-44 million tonnes by 2050, representing a 36-74% increase compared to current yields (Costello et al., 2020) and accounting for one-eight to one-quarter of the anticipated meat consumption increase, primarily through marine aquaculture expansion (Gentry et al., 2017).

Efforts are underway to shift towards a more sustainable and nutritious food system by increasing seafood consumption, as it provides essential micronutrients and contributes to animal protein consumption for 2.9 billion people (W. Willett et al., 2019). Nonetheless, the potential benefits of such a shift could be overshadowed by the risk of seafood contamination resulting from marine pollution incidents, such as the Fukushima Daiichi Nuclear Disaster, the Gulf of Mexico Oil Spill, and the Dalian PetroChina marine pollution incident (K. O. Buesseler, 2012; Fisher et al., 2013; Onda et al., 2020). The impact of these pollution events on marine food availability can range from direct reduction in quantity to the potential for consumer panic due to microbial, chemical, and radioactive contamination (Aruga, 2017a, 2017b; Aruga & Wakamatsu, 2018; Kher et al., 2013). The decline in consumer confidence in food safety in recent years has been linked to food safety incidents (Jonge, Trijp, Renes, & Frewer, 2007; Lobb & Mazzocchi, 2007). Furthermore, consumers' perception of food safety risks will alter their purchase behaviour and ultimate food consumption structure (Grunert, 2005; Yeung & Morris, 2001). While some studies have examined the effects of pollution on food systems, less attention has been given to the changes in food consumption patterns and their nutritional and environmental impacts resulting from changes in consumer behaviour (Feng et al., 2022; Tai, Martin, & Heald, 2014; Yates et al., 2021). In developing risk mitigation strategies for food safety, the interests of stakeholders, including consumers, must be prioritized (Kher et al., 2013).

On April 13, 2021, the Japanese government announced its decision to release millions of tonnes of filtered and diluted nuclear effluent from the Fukushima Daiichi nuclear power plant into the Pacific Ocean starting after 2023, with an expected 40-year timeline for the full discharge of wastewater (Normile, 2021a, 2021b). The news of Japan's plan to discharge nuclear wastewater into the Pacific Ocean immediately sparked intense discussion in China, mainly about the potential marine pollution and food safety caused by FNWD. China is the world's largest producer, exporter, and processor of aquatic products (FAO, 2022), accounting for 15% of the world's total seafood consumption (FAO, 2021). While some scientists have suggested that the risks are minimal (Nogrady, 2021), consumer perceptions of marine pollution risk could still alter the final food consumption structure. People may choose to abandon seafood or shift to protein-rich aquaculture products, terrestrial-based or aquatic foods from unaffected areas to make up for the loss of protein.

In most cases, the intensity of GHG emissions varies among different food products, and livestock products have different GHG emission intensity per unit of protein than marine foods (Clune, Crossin, & Verghese, 2017; Gephart et al., 2021; Nijdam, Rood, & Westhoek, 2012; Parker et al., 2018). Such a food system transition could lead to a change in the nutrition supply and GHG emissions. Given previous experiences with consumer perceptions of radiation-related food safety risks, it is likely that seafood consumption would be impacted if Japan proceeds with its plan to release nuclear wastewater. However, it remains unclear how and to what extent Chinese consumer perceptions of the Fukushima Daiichi nuclear wastewater discharge could affect the food system's nutrition supply and GHG emissions.

This study developed an MP-FSRAR model to assess a marine pollution event's potential impacts on food system nutrient supply and GHG emissions. Specifically, we applied the model to investigate how Chinese consumers' risk perceptions of the planned FNWD in 2023 could affect the food system's nutrition supply and GHG emissions. The Materials and Methods section describes the detailed analytical framework and data sources. In brief, the model consists of three components. First, we quantified the supply gaps of eight essential nutrients (protein, calcium, iron, zinc, vitamin A, vitamin B-12, vitamin D, and polyunsaturated fatty acids (PUFA)) under three scenarios of consumer perceptions of seafood safety risks. Next, we estimated the potential supply of protein-rich foods to close protein gaps under four substitution food pathways. We also built a global Protein-based GHG Emission Intensity Database for Terrestrial and Marine Food (PGHG-FOOD) to account for changes in GHG emissions resulting from changes in consumer consumption patterns. Finally, we simulate the potential GHG emissions that could be transferred through the trading chain to other countries under four different substitution food pathways. The model was applied to the planned FNWD, focusing on Chinese consumers as the research subject. We hope this analysis can stimulate a transdisciplinary debate about the impacts of consumer perceptions of marine pollution risks on food system nutrition supply and environmental consequences.

2 Materials and Methods

2.1 Summary.

The research developed an MP-FSRAR model to analyze the potential impacts of consumer risk perceptions on food system nutrient supply and GHG emissions. Three modules comprised the MP-FSRAR model: (1) Assessing nutrient supply gaps resulting from changes in consumption (without considering alternative food); (2) Estimating the supply of alternative high-protein foods needed to supplement the gaps under four food substitution pathways; (3) Evaluating changes in GHG emissions and the spillover effects on other countries through the food trade. To achieve this, we developed a global Protein-based GHG Emission Intensity Database for Terrestrial and Marine Food (PGHG-FOOD), which includes data for 217 countries (see Supplementary Table).

We investigated the potential impact of Japanese nuclear wastewater discharge into the Pacific Ocean on food system nutrient supply and GHG emissions, explicitly concerning Chinese consumers' risk perceptions. We used 2017 as the reference year because it was the most recent year for which data were available from all sources. Using a questionnaire, we examined extreme, middle, and low risk perception scenarios among Chinese consumers toward seafood from different regions worldwide. Based on the questionnaire results, we estimated the nutrient gaps for Chinese consumers and then accounted for alternative food supply and GHG emissions changes resulting from the food system transition to fill the nutrition gap. We also simulated the potential GHG emissions transferred through the trading chain to other countries under four different substitution food pathways. Details of each module and its application are described in the following sections.

2.2 Nutrient supplies gap resulting from changes in consumption.

Consumers' perception of seafood safety risks about exposure and bioaccumulation of radionuclides in marine organisms would change their willingness to consume seafood. This change in willingness would transmit to seafood production, trade, and consumption. We did not include the influence of price because previous research has shown that price is not one of the primary factors consumers consider when confronted with potential food risks. (Aruga, 2017b; Aruga & Wakamatsu, 2018). Consumers' perceived risk of marine pollution on food may be significant, and the willingness to consume would become the critical factor affecting consumption. To characterize consumers' unwillingness to purchase seafood from different regions, we introduced a decline parameter α.

To quantify the impact of changes in consumer willingness to consume seafood on regional aquatic production, trade, and consumption, it is necessary to first understand the material flow of seafood in the region and establish the protein supply baseline prior to any changes in consumer behaviour. We utilized the FAO Global Fishery and Aquaculture Production Statistics from FishstatJ and bilateral trade data from UN Comtrade to construct a Marine-based Food Supply Chain Network. We then calculated the nutrition gaps resulting from consumers' decreased willingness to consume seafood by linking the decline parameter, protein content, and seafood consumption. In this study, all aquatic animals, including finfish, crustaceans, and molluscs, harvested from marine (brackish) and freshwater environments through capture fisheries and aquaculture routes will be consumed by us, and they are commonly referred to as aquatic products. We excluded plants, shells, and corals, as well as non-nutritive commodities like ornamental fish, and estimated the proportion of each commodity that is edible by humans.

Aquatic animal food is an inexpensive and essential source of high-quality animal protein and essential amino acids, omega-3 fatty acids, vitamins, minerals, and trace elements. These nutrients are crucial for maintaining optimal health and preventing various diseases. This analysis focused on the eight prominent and specific nutrients in seafood, including protein, calcium, iron, zinc, vitamin A, vitamin B-12, vitamin D, and PUFA (Golden et al., 2021; Hicks et al., 2019). To estimate the nutritional value of each seafood item, we sourced data from the USDA Food Composition Database (https://www.ars.usda.gov/northeast-area/beltsville-md-bhnrc/beltsville-human-nutrition-research-center/food-surveys-research-group/docs/fndds-download-databases).

The nutrition gaps in a given country resulting from decreased edible seafood consumption were quantified using equation (1):

$$P_x^n = \sum_{i=1,}^{i} \alpha^{n,w} * Q_i^n * p_{x,i} + \sum_{j=1}^{j} \sum_{m=1}^{m} \alpha^{n,w} * T_j^{n,m} * p_{x,j} \tag{1}$$

where P_x^n is the nutrition gap in nutrient *x* for country *n* (kg). $\alpha^{n,w}$ is the declining percentage of consumers' willingness in country *n* to purchase seafood sourced from country *w*. Q_i^n is fishing production of food *i* for domestic consumption of country *n* (kg). $p_{x,i}$ is the nutrient *x* content of the protein-rich food *i* (kg/kg). $T_j^{n,m}$ is seafood trade commodity *j* for domestic consumption from trading partner *m* (kg). $p_{x,j}$ is the nutrient *x* content of the protein-rich commodity *j* (kg/kg).

2.3 Alternative food supply.

After FNWD, consumers could have the option to supplement their nutrient gaps with aquatic or livestock and crop products. It is important to note that our research operates under the implicit assumption that the total protein requirement for consumers remains unchanged. Researchers often use linear programming models with optimized omnivore, vegan, or novel food diets to estimate the nutritional and environmental changes resulting from the substituted diet (Mazac et al., 2022). In this part, we set up four alternative food supply pathways: 1) the aquatic-based substitution pathway, 2) the current food supply structure substitution pathway, 3) the livestock-based substitution pathway, and 4) the plant-based substitution pathway.

In the aquatic-based substitution pathway, consumers who choose to stop eating seafood could be allowed to increase their intake of freshwater aquaculture to supplement their protein gap. Consumers who reduce and maintain their seafood consumption could supplement the protein gap by consuming freshwater aquaculture and imported seafood from the unaffected areas. The proportion of restricted imported seafood in each region depends on how much resistance consumers show towards seafood in that region. This food substitution pathway involves replacing reduced seafood with aquatic products from other sources. The proportion of each source should exclude seafood from areas where consumers are boycotting before replenishing seafood on a business-as-usual basis. In the current food supply structure substitution pathway, the protein gap is filled by eight types of protein-rich foods from terrestrial systems according to each country's current food supply structure, which is carried out on a business-as-usual basis. The aquatic food supplement part is handled in the same way as the aquatic-based substitution pathway. We also establish a livestock-based substitution pathway where livestock products such as beef, pork, chicken, and other meat replenish the protein supply gap. Finally, we provided a plant-based substitution pathway by using pulses (beans, soybeans, peas, nuts, and pulses nes) as the protein substitute which these typical plant-based high protein sources are usually treated as meat protein alternatives (Nijdam et al., 2012).

It is important to note that the four protein substitution pathways provide a framework for understanding possible food alternatives in extreme situations rather than an exhaustive list of all possible combinations. The actual food substitutions may vary depending on various factors, including the nutrient content of different foods, dietary culture, consumer income and so on. However, the fluctuations in these values may fall within the upper and lower boundaries of the extreme scenarios.

Subsequently, we created a network for a terrestrial-based food supply chain to monitor the regional origins of the substitute food supply. To accomplish this, we utilized the livestock and crops balance tables from FAO (https://www.fao.org/faostat/en/#data/FBS) and bilateral trade data from UN Comtrade (https://comtrade.un.org/data).

2.4 Impact of GHG emissions and their spillover effects on other countries through the food trade.

Establishing the PGHG-FOOD database. Under a uniform cradle-to-farm gate accounting boundary, we synthesized multiple data sources to quantify GHG emissions for crops, livestock products, inland aquaculture foods, and marine aquaculture/capture foods. Tab. S1 shows the system boundary definition for marine and terrestrial food GHG emissions. In this study, all food accounting boundaries are from cradle to farm gates.

However, seafood, crops, and livestock are subdivided into different accounting methods due to different farming or cultivation approaches. For instance, the farm gate for livestock is grown on the farm until it leaves the farm gate, while the farm gate for marine caught food is defined as when the product is caught ashore.

To calculate GHG emissions from crops and livestock products, we used the Comprehensive Accounting of Land-Use Emissions (CALUE) database (Hong et al., 2021), which derives agricultural and land-use change emissions from FAOSTAT (https://www.fao.org/faostat/en/#data) and the Bookkeeping of Land Use Emissions model (BLUE) (Hansis, Davis, & Pongratz, 2015). Notably, the CALUE database does not specify GHG emissions related to feed for livestock. We accounted for feed emissions in the GHG emissions of supplemental meat foods, assigning emissions from feed crops to livestock that consume them. We used the Food and Agriculture Biomass Input-Output model (FABIO), a multi-regional supply, use, and input−output table that documents the flows of agricultural and food products in the global economy (Bruckner et al., 2019), to determine the amount of each crop consumed by each livestock. We extracted the domestic and imported quantities of crop consumed by live animals in each country and converted the number of live animal heads into net livestock weight to build a connection between net livestock weight per unit and its crop consumption. We then multiplied the amount of each crop by its GHG emissions intensity to obtain the feed GHG emissions of each country. The FABIO model was up to date through 2014, and we used 2017 food production data to scale their original data equally. The equation (2) can be used to quantify GHG emissions from feed consumed by livestock.

$$G_{feed}^{n} = \sum_{l=1}^{l} \sum_{f=1}^{f} \left(\beta^{n} * {Q_{feed}}_{l,f}^{n} * E_{f}^{n}\right) \qquad (2)$$

Where G_{feed}^{n} is the GHG emissions of feed consumed by livestock for country *n* (kg). β^{n} is the ratio of food production in 2017 to 2013 of country *n* (kg). ${Q_{feed}}_{l,f}^{n}$ is the feed *f* consumption of livestock *l* in country *n*. E_{f}^{n} is GHG emissions intensity of feed *f* for country *n* (kg/kg).

Only GHG emissions related to freshwater aquaculture were considered for inland aquatic foods. The marine food category includes marine and brackish water capture or aquaculture products. The GHG emissions for global freshwater and marine aquaculture and marine capture fisheries were obtained from MacLeod et al. and Parker et al. research. GHG emissions intensities for some specific countries were estimated using continent-average or world-average parameters where data was missing. Finally, a protein-based GHG intensity inventory for 28 easily accessible protein-rich foods in 217 countries and regions was developed using food protein content data and mass-weighted GHG intensity. Please refer to the Supplementary Table for further information.

The net food system's GHG emission changes and the food system's GHG emission absolute changes by the country could be obtained by equation (3):

$$G_{net}^{n} = G_{abs}^{n} - G_{d}^{n} + G_{feed}^{n} = \sum_{i=1}^{i}(A_{i}^{n} * E_{i}^{n}) - \sum_{i=1}^{i}(P_{x}^{n} * E_{i}^{n}) + G_{feed}^{n} \qquad (3)$$

where G_{net}^{n} is the net GHG emission changes of the food system in country *n* (kg). G_{abs}^{n} is the food system's GHG emission absolute changes in country *n* (kg). G_{d}^{n} is the reduced GHG emission due to a decrease in the willingness to consume seafood in country *n* (kg). A_{i}^{n} is the additional supply of protein of food i in country *n* (kg). $E_{i}^{n}$is GHG emission of per-gram protein of food i of country *n* (g/g). P_{x}^{n} is the nutrient gap of food *i* (kg). Here, *i* refers to seafood, and *x* refers to protein.

Processed products must be converted into primary livestock or crops to match the

PGHG-FOOD database. To achieve this, we used the technical conversion factor provided by the FAO to convert the first stage of processed products into primary crops and livestock products (Sukhatme, 1960).

2.5 Model application.

Previous studies have shown that a significant proportion of consumers in Japan and its surrounding regions (e.g., Korea), estimated to be around 50-80%, are reported to be unwilling to consume seafood from Fukushima or even from Japan altogether following the Fukushima Daiichi Nuclear Disaster, citing concerns about radiation-related risks (Aruga, 2017a; Kim et al., 2015), due to the potential radiation-related risk. Even when the radioactivity levels of the food are below the official criteria, a considerable proportion of consumers (i.e., 20–50%) still refuse food from Fukushima (Miyata & Wakamatsu, 2018; Ujiie, 2012). To quantify the degree of Chinese consumers' unwillingness to purchase seafood from different regions, we introduced a parameter denoted as $\alpha^{china,w}$. As the FNWD event has not yet occurred, we assessed Chinese consumers' response to seafood through surveys to provide a basis for determining the parameter $\alpha^{china,w}$.

2.5.1 Sampling and sample size.

The data for the sample used to analyze consumers' willingness to consume seafood in China were collected through an online questionnaire survey conducted between March 29 and April 5 2022, with participants from 30 provinces of China. A regional stratified sampling method was used to ensure comprehensive country coverage, with random sampling below the provincial level. This sampling method provided good geographic representation and ensured a reasonable proportion of coastal and inland consumers. After a quality check, 2260 valid questionnaires were obtained for the seafood consumption intention survey. The demographic variables related to consumers' age, gender, education, location, family members, number of children, number of elderly people, and income are described in Tab. S2.

2.5.2 Seafood consumption intention survey questionnaire.

(a) Presurvey. In the presurvey, Chinese consumers' reactions to Japan's plan to discharge nuclear wastewater into the Pacific Ocean were monitored by Zhejiang public opinion monitoring platform. We collected about 10,000 comments from microblogs, official media, newspapers, forums, news, WeChat, and other platforms on April 12 and its week, and the vast majority of Chinese consumers expressed their unwillingness to consume seafood from the affected waters.

(b) Pre-questionnaire. The pre-questionnaire was designed based on the presurvey, consumer concerns, and demonstrated tendencies. Some questions and terms in the questionnaire were modified according to respondents' feedback and expert opinions, and the final questionnaire was formalized.

(c) Final questionnaire. In the final questionnaire, respondents were asked to answer the basic information, daily seafood consumption behaviour, and three parallel sub-questionnaires (A, B, and C) representing low, middle, and extreme consumer reaction scenarios, respectively. In Questionnaire A, the consumers were informed that the discharge of nuclear effluent from the Fukushima Daiichi nuclear power plant into the sea would begin after 2023. In Questionnaire B, respondents were told that radionuclides contained in the nuclear wastewater would spread to the Pacific Ocean. In Questionnaire C, respondents were asked about their responses if radioactive material had been detected in the sea area of region *A* following the discharge of nuclear wastewater from Japan.

2.5.3 Data analysis.

The data collected from the survey were analyzed to assess consumers' willingness to consume seafood under different scenarios of nuclear wastewater discharge. In Questionnaire A, 34% of respondents said they would no longer consume seafood after the discharge of Japanese nuclear wastewater, 52% said they would reduce their consumption, and 14% said they would keep their consumption the same as usual. In questionnaires B and C, representing middle and extreme consumer reaction scenarios, the proportions of respondents who chose these three options were 46%/63%, 44%/30.0%, and 9%/6%, respectively.

To estimate the impact of these consumer responses on seafood consumption, we assumed that consumers who refuse to consume seafood would no longer consume seafood from any region, while those who chose to reduce their seafood consumption would cut half of their usual seafood consumption volume. Very few consumers chose to increase their consumption, so we ignored fluctuations that might arise due to a slight increase in serving size.

As a result, $\alpha^{China,w}$ can be calculated by equation (4).

$$\alpha^{China,w} = \alpha_1^{China,w} + \alpha_2^{China,w} * 50\% \tag{4}$$

$\alpha^{China,w}$ is the declining percentage of Chinses consumers' unwillingness to purchase seafood sourced from region *w*. $\alpha_1^{China,w}$ was the proportion of Chinses consumers who would refuse to continue consuming seafood from region *w*. $\alpha_2^{China,w}$ was the proportion of Chinses consumers who would reduce the amount of seafood consumed from region *w*. The resulting parameter $\alpha^{China,w}$ setting under different Chinese consumers' perceptions of FNWD-induced seafood safety risk is shown in Tab. S3.

3 Results

3.1 Nutrient supply gaps caused by consumer perceptions of seafood safety risks.

Fig. 1(a) depicts the FNWD-induced total supply gaps for eight typical nutrients (without considering alternative food). We created three scenarios based on Chinese consumers' changed consumption intentions in response to seafood's safety risks. The nutrient gaps from reduced seafood consumption without alternative food supplements are estimated. The results showed that under these scenarios, there would be a potential protein gap of 0.7-1.4 billion kg in China, equivalent to the total protein supply of protein-rich foods in the UK in 2017 (1.4 billion kg). The largest share of the protein deficit was caused by pelagic fish, accounting for 63% of the total protein gap, followed by demersal fish (22%) and molluscs (21%). Cephalopods and molluscs took a higher amount of losses due to their higher zinc and iron content, leading to a mineral gap. A reduction in pelagic fish consumption would result in a 2.9-5.3 k kg vitamin gap, including vitamin A, vitamin B-12, and vitamin D. FNWD was also found to contribute to a gap of 73 million kg PUFA.

Fig. 1(b) shows the daily per capita potential nutrient supply gaps under the extreme, middle, and low consumer reaction scenarios. It is estimated that Chinese consumers would suffer a per capita protein gap of 1.5-2.7 g/day. The highest daily per capita nutritional loss among the three minerals is calcium, while vitamin-A showed the largest daily per capita nutritional gap among the vitamins. It should be noted that the nutritional deficit of 80-140 mg/day of PUFA resulting from reduced seafood consumption would be difficult to replace with other foods and would lead to an irreparable nutritional loss, as PUFA, mainly n-3 PUFA intake, is dominated obtained from marine fish.

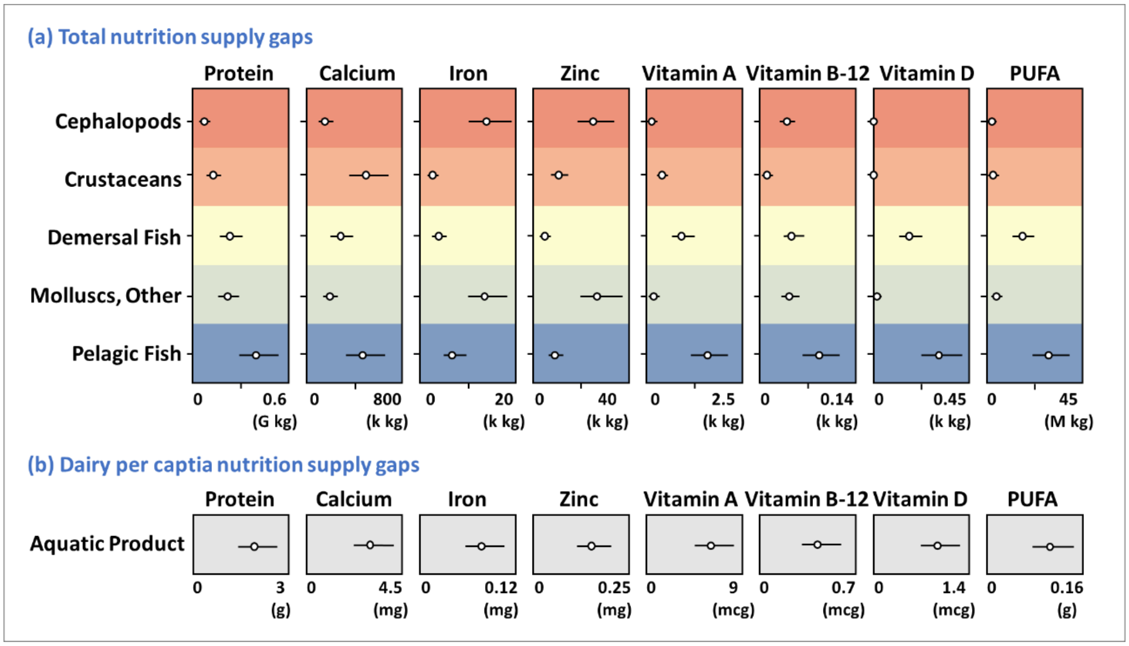
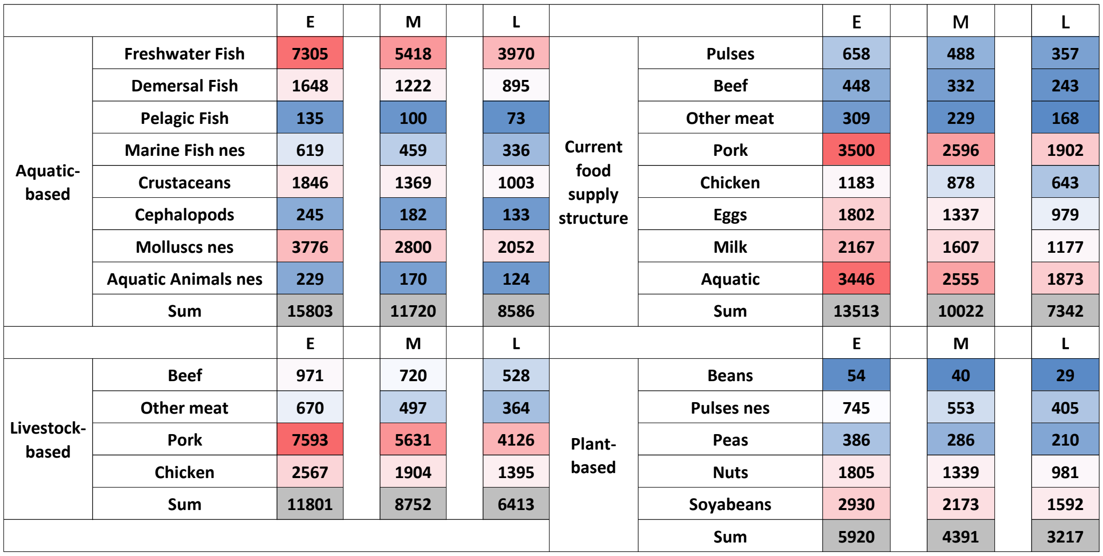


Fig. 1 Food system potential nutrition gaps in China caused by FNWD. (a) Total potential nutrition gaps for five types of seafood caused by FNWD under the low, middle, and extreme consumer reaction scenarios. The circles represent the middle consumer reaction scenario, while the left and right ends of the horizontal line represent low and extreme consumer reaction scenarios, respectively. The three scenarios simulate the consumers' reaction: after the FNWD, the Japanese nuclear wastewater spreads to the Pacific Ocean and the detection of nuclear radiation in sea A. (b) Daily per capita potential nutrient supply gaps for aquatic production under the extreme, middle, and low consumer reaction scenarios.

3.2 Growing food demand to close the protein gap.

Fig. 2 illustrates the additional quantity of food that would be required to bridge the protein gap in the aftermath of the FNWD. We devised four alternative food supply pathways, including 1) Aquatic-based substitution pathway; 2) Current food supply structure substitution pathway; 3) Livestock-based substitution pathway; 4) Plant-based substitution pathway. The details of these food substitution pathways can be found in the Materials and Methods section. We assumed that after FNWD, consumers might opt for protein-rich fish from other regions, livestock, or crop products to supplement the protein gaps. The results showed that the amount of food supplementation required in the extreme and low consumer reaction scenarios would be nearly twofold different. A total of 8.5-15.8 billion kg of aquatic products would be necessary for the aquatic-based substitution pathways. The demand for freshwater fish constitutes nearly half of the total aquatic food supply and the supply of molluscs, crustaceans, and demersal fish, each amounting to more than 1.5 billion kg. In the current food supply structure substitution pathway, the supply of eight types of protein-rich foods would increase by 7.3-13.5 billion kg. Three main types of alternatives would be dairy (including milk and eggs) (2.2-4.0 billion kg), pork (1.9-3.5 billion kg), and aquatic products (1.9-3.4 billion kg). In the livestock-based pathway, pork (4.1-7.6 billion kg) could be the most significant supplementation food, whereas the demand for chicken (1.4-2.6 billion kg) would also be relatively high. The least amount of food (3.2-5.9 billion kg) would be required if pulses were used as a protein alternative, with soybeans accounting for nearly half of the supplement.



		E	M	L			E	M	L
Aquatic-based	Freshwater Fish	7305	5418	3970	Current food supply structure	Pulses	658	488	357
	Demersal Fish	1648	1222	895		Beef	448	332	243
	Pelagic Fish	135	100	73		Other meat	309	229	168
	Marine Fish nes	619	459	336		Pork	3500	2596	1902
	Crustaceans	1846	1369	1003		Chicken	1183	878	643
	Cephalopods	245	182	133		Eggs	1802	1337	979
	Molluscs nes	3776	2800	2052		Milk	2167	1607	1177
	Aquatic Animals nes	229	170	124		Aquatic	3446	2555	1873
	Sum	15803	11720	8586		Sum	13513	10022	7342
		E	M	L			E	M	L
Livestock-based	Beef	971	720	528	Plant-based	Beans	54	40	29
	Other meat	670	497	364		Pulses nes	745	553	405
	Pork	7593	5631	4126		Peas	386	286	210
	Chicken	2567	1904	1395		Nuts	1805	1339	981
	Sum	11801	8752	6413		Soyabeans	2930	2173	1592
						Sum	5920	4391	3217

Fig. 2 Additional food supply to close the protein gap under three consumer reaction scenarios and four substitution pathways, million kg. The transition in a colour gradient from blue to red signifies the magnitude of food supplementation needed, with darker shades of blue indicating lower quantities and darker

shades of red indicating higher quantities. E, M, and L represent extreme, middle, and low consumer reaction scenarios.

3.3 Additional GHG emissions from the food system.

The additional food supplies required to close the protein gap could lead to additional net GHG emissions of 1-79 billion kg CO_2e yr^{-1} in the food system. Fig. 3 depicts the change in absolute and net GHG emissions in China depending on the consumer reaction scenarios and food substitution pathways selected. The livestock-based substitution pathway would inevitably result in a significant increase in terrestrial GHG emissions, which could reach up to 130 billion kg in the most extreme reaction scenario, equivalent to 5.4% of China's terrestrial food system (J. Poore & T. Nemecek, 2018). Pork and beef production are the largest sources of emissions, each contributing over 55 billion kg in the extreme scenario. Compared with the livestock-based substitution pathway (79 billion kg GHG emissions), the current food supply structure substitution pathway could potentially reduce net GHG emissions by almost half (42 billion kg GHG emissions).

In contrast, the aquatic-based and plant-based substitution pathways are more environmentally friendly options. The aquatic-based substitution pathway would lead to fewer potential net GHG emissions of 1-3 billion kg CO_2e yr^{-1}, accounting for only 3.8% of the emissions of the livestock-based substitution pathway. The plant-based substitution pathway would have the least GHG emissions mainly due to the lower GHG emission intensity and higher protein content of pulses. Nevertheless, China's total net GHG emissions under the four food substitution pathways would still be greater than zero, although the impact on GHG emissions resulting after FNWD may be partially mitigated by a shift towards a more plant-based protein diet.

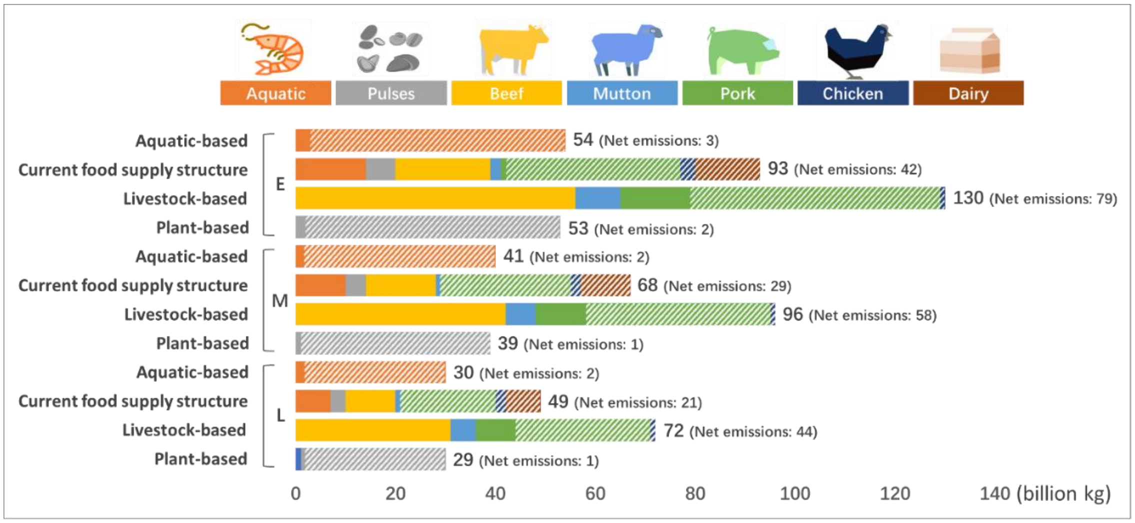
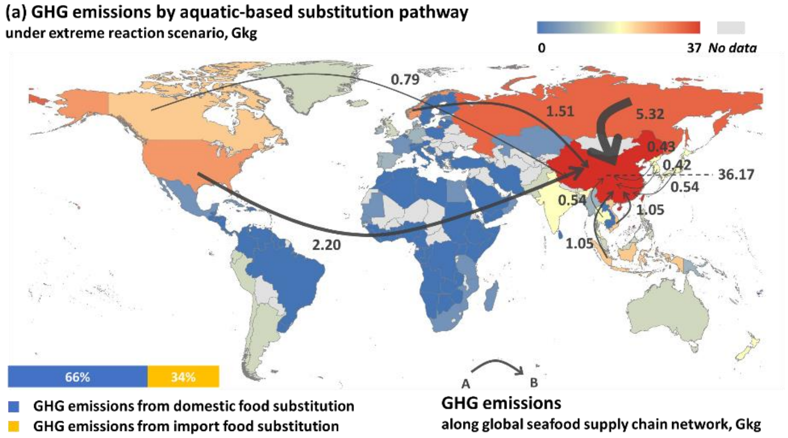


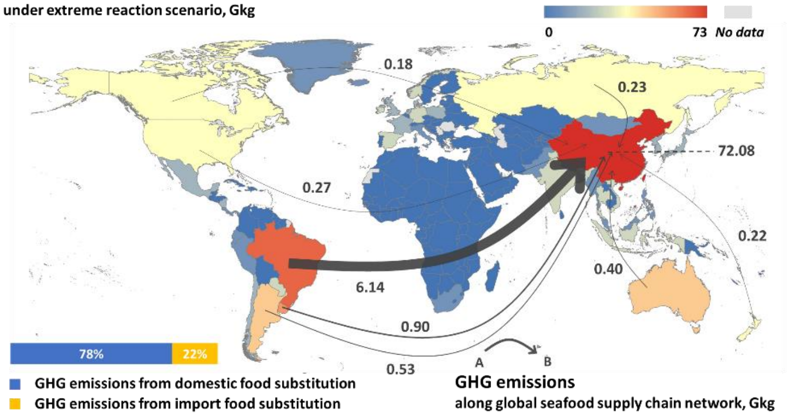
Fig. 3 The change in absolute and net GHG emissions in China under different protein supplement pathways, billion kg. E, M, and L indicate extreme, middle, and low consumer reaction scenarios. The white diagonal stripe in the figure represents the reduced GHG emissions from declining seafood production.

Fig. 4 (a-d) illustrates the changes in GHG emissions of the food system from the domestic and imported food supply by four substitution pathways under the extreme reaction scenario. Our results show that more than 60% of the total GHG emissions change resulting from the aquatic-based, current food supply structure, and livestock-based substitution pathway would occur domestically, while 86% of the GHG emissions change from the plant-based substitution pathway would take place abroad. The current food supply structure, livestock-based, and plant-based food substitution pathways exhibit similar patterns of GHG emission shifts. Brazil is responsible for the most significant GHG emissions change, followed by Argentina, Uruguay, and Australia. This is mainly due to China's large imports of soybeans from Brazil and imports of livestock from Uruguay and Australia. However, in the aquatic-based food substitution pathway, seafood imports from Russia would bear the most significant GHG emissions change abroad, generating GHG emissions of 5.32 billion kg.

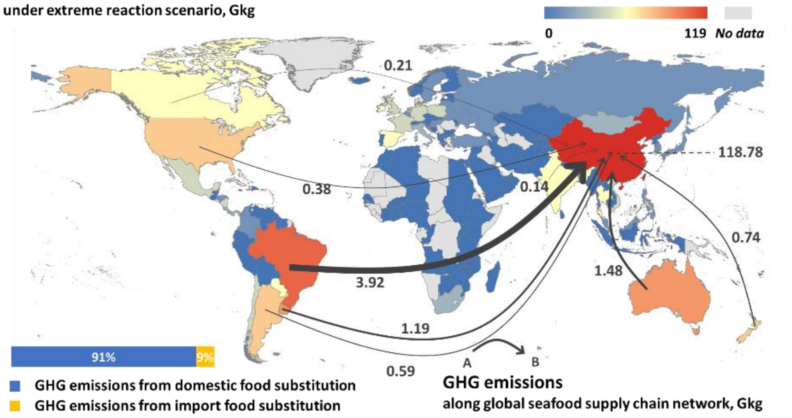
(a) GHG emissions by aquatic-based substitution pathway
under extreme reaction scenario, Gkg



(b) GHG emissions by current food supply structure substitution pathway
under extreme reaction scenario, Gkg



(c) GHG emissions by livestock-based substitution pathway
under extreme reaction scenario, Gkg



(d) GHG emissions by plant-based substitution pathway
under extreme reaction scenario, Gkg

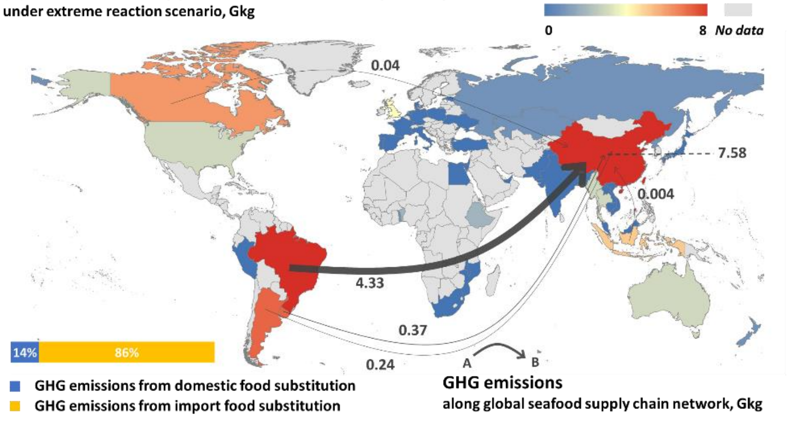


Fig. 4 GHG emissions from domestic and imported food substitution by four substitution pathways under the extreme reaction scenario.

4 Discussion

4.1 Potential nutrition supply challenges and resulting food security threats.

Current assessments of marine pollution risks mainly focus on studies on pollutant diffusion simulation, marine ecosystems, marine life, and human health (Behrens, Schwarzkopf, Lübbecke, & Böning, 2012; K. Buesseler, Aoyama, & Fukasawa, 2011; Fisher et al., 2013; Onda et al., 2020). However, the reassessment of marine pollution incidents on the influence of nutrition supply and GHG emissions along the food supply chain is less considered. Our findings suggest that FNWD would affect domestic food production and international trade as consumer behaviour shifts away from seafood consumption, resulting in multiple nutrient supply gaps. Fish protein is widely known to be rich in lysine, sulfur-containing amino acids, and threonine, making it a healthier source of protein than terrestrial animal proteins (McManus & Newton, 2011). In recent decades, China has made tremendous efforts to increase its protein and micronutrient availability, with per capita seafood consumption increasing sevenfold since 1978 (Bell, Lividini, & Masters, 2021; Fabinyi, 2016). Currently, China's fish protein supply accounts for 22.8% of the total animal protein supply, which exceeds the world average (Barange & Acuicultura, 2018).

However, in the extreme consumer reaction towards FNWD, Chinese consumers may experience a protein gap of 2.7 g/day due to decreased seafood consumption, equivalent to a 5% loss of daily protein recommendation per person. While some of these nutrients, such as protein, can be partly replenished by terrestrial- and freshwater-based food, others, such as PUFA, are challenging to replenish because the primary dietary source of long-chain omega-3 fatty acids (EPA/DHA) is fisheries (Hamilton, Newton, Auchterlonie, & Müller, 2020). The top categories of EPA/DHA -rich animal-source foods are all seafood, including pelagic fish and salmonids (Golden et al., 2021). Our results show that the extreme consumer reaction scenario would result in a 24.7% deficit in daily EPA/DHA recommendation intake for the Chinese consumer. Given the nutritional gaps that may result from changes in consumer behaviour, policies need to ensure adequate nutritional availability to address potential seafood boycotts by Chinese consumers after FNWD.

While food substitution can mitigate some of the nutrient gaps, FNWD still reduces food choices for consumers. The diversity of dietary choices is a crucial aspect of food security (Kennedy, Ballard, & Dop, 2011), and decreased seafood selectivity due to FNWD will lead to a rigid and homogeneous food system, which may reduce the safety and flexibility of the food system. Price is an essential factor in food choice (Steenhuis, Waterlander, & de Mul, 2011). However, the price mechanism fails in cases where consumers perceive a food risk, i.e., consumption still decreases when people feel that seafood is contaminated, even if the price is lower. This is similar to the results obtained from previous studies, where consumers are no longer willing to purchase risky foods after perceiving food safety risks, even if the food prices are lower (Aruga, 2017b; Aruga & Wakamatsu, 2018). In addition, this nutritional gap will be more challenging to replenish for consumers in poorer areas, where people have few other options to compensate for these impending micronutrient supply deficiencies (Golden et al., 2016). Communities are often forced to rely on locally harvestable food or less healthy processed foods, compromising micronutrient security in some poor areas, and would pose a whole new challenge to food security in rural China.

Compared to aquatic production, terrestrial animal protein production systems are less efficient because they produce food in a two-dimensional space, aggravating land use tension (Napier, Haslam, Olsen, Tocher, & Betancor, 2020). With far less arable land per capita than the world average, China is already facing the enormous challenge of land scarcity (Chen, 2007). In an extreme food substitution pathway, nearly 12 billion kg of livestock products would be needed to replace the protein reduction. Consideration needs to be given to whether there is enough additional arable land, livestock space, and resources in these areas to support additional terrestrial food demand growth. In addition to land use, water, feed, fertilizer, and biodiversity would all be affected by the production of alternative foods (Davis et al., 2016).

4.2 Challenges and potential for GHG mitigation after FNWD.

Different protein supplement pathways after FNWD would result in global GHG emission change patterns. For China, the livestock-based food substitution pathway could increase 44-79 billion kg of potential net GHG emissions, corresponding to 9.7%-17.5% of GHG emissions from the Chinese food system. GHG emissions caused by pork supplementation account for half of the total GHG emissions of all supplemental foods. Red meat, which Chinese consumers prefer, may shift the pressure on terrestrial food systems. China's agricultural production accounts for 13% of global GHG emissions (Zhao et al., 2021). Meeting the consumers’ food substitution needs without harming the environment would be a tremendous sustainability challenge for China (Zhao et al., 2021). Our results also found that, in addition to livestock, aquaculture is another crucial source of food nutrient supplementation. Despite differences in the environmental impacts of animal-derived food production sectors, aquaculture almost always produces fewer GHG emissions and uses less land than red meat farming. The large-scale and high-density freshwater and marine aquaculture in China may be a viable way to mitigate the consequences of FNWD through horizontal expansion, intensification, and more efficient resource use (Zhang et al., 2022).

Although international food trade could supplement seafood deficits to some extent, it shifts the GHG emissions pressure caused by the agricultural system to other countries and therefore does not reduce net GHG emissions from the global food system. China would import more seafood from Russia, Norway, etc., after FNWD to close the protein gap, which will also bring additional GHG emissions from these countries. Brazil, Argentina, and Uruguay in South America bear most of the GHG emissions increase from livestock and plant-based food substitution in China. Using comparative environmental advantages, potential ways to mitigate FNWD could be found through international trade. For example, China imports fewer emissions-intensive soybeans from the United States than Brazil and Argentina, suggesting that global emissions might be avoided if the United States could produce more soybeans and export them to China (Hong et al., 2022).

However, consumers' concerns about seafood safety may further emphasize the necessity of domestically produced land-based food and uncontaminated seafood products after Japan's nuclear wastewater discharge. The increased demand for these products may pressure those producing countries to restrict exports to ensure domestic supply as evidenced by many previous cases (Falkendal et al., 2021; Reinhart, 2020). While export restrictions may be understandable from the perspective of domestic supply, they could have severe implications for global food security. Such food export restrictions could push up food prices and exacerbate hunger and poverty (Carriquiry, Dumortier, & Elobeid, 2022;

Chung & Liu, 2022). It could also intensify competition between China and other countries between land-based and uncontaminated seafood products.

4.3 Uncertainty analysis

Our study provides valuable insights into the potential effects of FNWD on both domestic and international food systems, but it is essential to recognize the inherent uncertainties associated with the model used. The focus of this study is to evaluate the consumers' perceived changes after the discharge of Japanese nuclear wastewater and its possible nutrition and climate consequences, but our method may not capture all types of impacts. Our analysis assumes a static relationship between nutrient supply and consumer behaviour, whereas, in reality, this relationship may be dynamic and influenced by various social and economic factors. Given the complexity and variability of consumer behaviour, the boycott's scale, duration, and extent of consumer substitution are challenging to predict accurately. Hence, our estimates based on intentions may overestimate actual consumption levels. However, if real-world data on production or consumption reductions become available, our model can be updated accordingly for more precise results. In addition, the impacts of food substitution on nutrient availability may vary depending on the specific foods substituted and the geographic region in question, and the actual substitution pathways may be more complex and diverse than our model.

We must acknowledge that the issue of nuclear wastewater is highly controversial and sensitive, and it may attract widespread attention and public concern. Due to consumers' cognitive biases, when hazards are perceived as unknown, people tend to evaluate hazards as more threatening. People prefer reducing current risks and stricter regulatory measures for uncontrollable, global catastrophic, and difficult-to-reduce risk factors, such as nuclear technology and radioactive waste. Thus, caution is needed when interpreting our study's findings, and further research is necessary to understand better the intricate and dynamic interactions between consumer behaviour, nutrient supply, and GHG emissions.

5 Conclusions

The announcement of the FNWD news has led to widespread discussion among Chinese consumers. To investigate the potential impact of FNWD caused by the change in Chinese consumers' willingness to protein supply and GHG emissions, we developed an MP-FSRAR model. We found out that when a marine environmental risk incident occurs, the changes in food production due to changes in people's consumption preferences will result in a wide-ranging impact on nutrition security and GHG emissions mitigation efforts, which are much broader than previously assumed. Recognizing the possible larger scale and profound indirect impact of FNWD can give timely warnings to reduce risks and allow for better coordinated regional responses to the incident.

Considering the multi-risks that FNWD action may bring, we call on all parties concerned to review the FNWD action carefully and jointly formulate acceptable nuclear wastewater treatment schemes. First, countries should guide the public's food consumption choices, promote the diversification of protein food sources, and ensure a stable supply of high-quality protein sources to secure a food supply based on balanced nutrition. Second, keeping abreast of changes in consumers' dietary structure to monitor the pressure on the terrestrial food system and the transition to a diet with less climate impact can increase production efficiency to keep up with the change in human demand. Finally, we should strengthen the ecological environment monitoring of relevant sea areas, carry out simulation studies on the impact of nuclear wastewater pollution, assess potential risks, and formulate relevant countermeasures.

Data availability

The population is available from the World Bank database (https://databank.worldbank.org/indicator/SP.POP.TOTL/1ff4a498/Popular-Indicators). FAO data on protein supply and agricultural GHG emissions for crop and livestock production in 2017 (http://www.fao.org/faostat/en/#data). CALUE data on GHG emissions for crops and livestock are referred from Hong et al. (Hong et al., 2021). The GHG emissions for global freshwater and marine aquaculture and marine capture fisheries were sourced from MacLeod et al.(MacLeod, Hasan, Robb, & Mamun-Ur-Rashid, 2020) and Parker et al. (Parker et al., 2018). FABIO data on livestock's feed of multi-regional physical supply-use and input-output tables covering global agriculture and forestry (https://github.com/martinbruckner/fabio_v1). The nutrition value of each seafood was obtained from USDA Food Composition Database (https://www.ars.usda.gov/northeast-area/beltsville-md-bhnrc/beltsville-human-nutrition-research-center/food-surveys-research-group/docs/fndds-download-databases/). FishStatJ data on inland and marine aquaculture and capture foods production in 2017 (https://www.fao.org/fishery/en/statistics/software/fishstatj). UN Comtrade data on fishery products trade data (https://comtrade.un.org/data). The R original code used in data processing is available from the author on request.

Competing Interest Statement

All other authors declare they have no competing interests.

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Author Contributions:

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