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# Dietary shifts drive the slowdown of declining methylmercury related health risk in China

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## Abstract

Chinese population suffers severe health risk from dietary methylmercury (MeHg) exposure. However, the temporal change of such risk and socioeconomic driving factors remain unknown. This study investigates this issue by compiling time-series inventory of China's MeHg-related health risk at the provincial scale and revealing critical socioeconomic influencing factors through structural decomposition analysis. Results show that the per-fetus IQ decrements from dietary MeHg exposure have declined by 60% nationally during 2004-2019. Such decline results from the joint effects of dietary shifts (contributing 44%) and the decrease of MeHg concentrations in foods consumed (contributing 56%). However, the declining trend has slowed down since 2014 and even leveled off after 2016, which is mainly affected by dietary pattern changes. Especially, the increased intake level and proportion of fishes in underdeveloped provinces of China have dominated the slowdown of declining trend after 2016. Moreover, the affluence and education levels have significantly negative associations with per-fetus IQ decrements. Rich and well-educated people have higher ability of risk perception, which indicates the importance of rational consumption patterns. Our findings can help develop socioeconomic regulatory policies on reducing per-fetus IQ decrements from dietary MeHg exposure in China.

**Keywords:** Mercury pollution; Human health; Methylmercury exposure; Food system; Socioeconomic factors; Dietary patterns.

## Introduction

Mercury (Hg) is a global pollutant that can be transported globally and impose adverse impacts on human beings (Chen et al., 2019; Giang and Selin, 2016; Li et al., 2020a). One of its most toxic forms, methylmercury (MeHg), can bioaccumulate in food webs and pose serious health risk to human beings (Driscoll et al., 2013; Sundseth et al., 2017). Exposure to MeHg has been associated with neurodevelopmental delays in children and cardiovascular impairment in adults (Grandjean et al., 2012; Hu et al., 2017; Roman et al., 2011). In addition, it has adverse effects on renal, reproductive, and immune systems (Bose-O'Reilly et al., 2016; Henriques et al., 2019). The World Health Organization (WHO) has treated Hg as one of the top ten chemicals of major public health concern (World Health Organization, 2017). To protect people from Hg-related health risk, 128 nations (including China) have signed the Minamata Convention on Mercury. The Article 16 of the convention emphasizes “Health aspects” and Article 19 points out the requirements for assessing the health risk of Hg (United Nations Environment Programme, 2013).

China is particularly important in global Hg cycle. On one hand, China is the largest Hg emitter in the world, contributing about 25% (565 t) of global atmospheric Hg emissions in 2015 (United Nations Environment Programme, 2019). On the other hand, Chinese population has suffered from serious MeHg-related health risk. For example, MeHg intake in China resulted in 0.14 points of per-fetus IQ decrements and 7360 deaths from fatal heart attacks in 2010 (Chen et al., 2019). Moreover, China has been experiencing in recent years and will continue to experience tremendous socioeconomic transitions which leads to significant changes in people's dietary patterns (He et al., 2019). Understanding the historical temporal changes of health risk from dietary MeHg exposure and identifying socioeconomic driving factors can provide more explicit hotspots for socioeconomic policies to reduce health risk from dietary MeHg exposure in China. However, these points have not been well characterized.

Existing studies have investigated the food sources of the health risk of MeHg. Fish consumption is assumed to be the main dietary source of MeHg exposure for most populations worldwide (Liu et al., 2018b; Sunderland et al., 2018). However, for certain regions in China, especially in southern inland areas and Hg mining areas, rice consumption is the most important pathway of dietary MeHg exposure (Li et al., 2012; Zhang et al., 2010). In addition to quantifying health risks of dietary MeHg exposure, previous studies have also considered the interregional food trade among Chinese regions and estimated the health risks of MeHg intake from the viewpoint of whole food system (Liu et al., 2020). The interregional food trade has significant impacts on health risks of dietary MeHg intake in China. Taking the interregional trade into account, studies have quantified the health risk of dietary MeHg exposure based on particular time points in China (Chen et al., 2019; Li et al., 2020a; Li et al., 2020b). However, the temporal change of health risk from dietary MeHg exposure in China and the socioeconomic driving factors remain unknown.

The main objective of this study is to quantify the temporal changes of health risk from dietary MeHg exposure at the provincial level in China during 2004-2019 and identify critical socioeconomic factors influencing changes in health risk, including midpoint factors (i.e., dietary factors including dietary intake level, dietary structure, and food trade structure) and endpoint factors (i.e., underlying factors including affluence, education levels, and traffic accessibility). Previous studies find that major adverse effects of MeHg exposure are neurological, and the neurological effects are closely related to dietary intake (Gao et al., 2014). Thus, this study takes the per-fetus IQ decrements as the indicator for the health risk of dietary MeHg exposure. We first constructed the inventory of China's provincial MeHg-related health risk during 2004-2019, including compiling MeHg concentrations of foods, simulating the interregional food trade, evaluating the MeHg intake, and estimating per-fetus IQ decrements from dietary MeHg exposure. We then identified the midpoint and endpoint factors influencing changes in the health risk by using structural decomposition analysis (SDA) method and the panel regression model. Our findings can help develop socioeconomic regulatory policies on reducing per-fetus IQ decrements from dietary MeHg exposure in China. Moreover, these findings are enlightening to similar nations around the world and thus can help promote the progress of the Minamata Convention on Mercury globally.

## Methodology

The research framework of this study consists of three components: compiling time-series inventory of China's per-fetus IQ decrements from dietary MeHg exposure at the provincial scale, analyzing the sources and evolution of China's per-fetus IQ decrements from dietary MeHg exposure, and identifying critical socioeconomic factors influencing the health risk changes (Fig. S1). This study considers 30 provinces in mainland China and the coastal seas. Tibet, Hongkong, Macau, and Taiwan are not considered, due to data unavailability. The details on the methods can be found in the Supplementary Information.

**Compiling provincial inventories of per-fetus IQ decrements from dietary MeHg exposure.** This study constructs China's provincial inventories of dietary MeHg exposure during 2004-2019. This part includes four steps: compiling MeHg concentrations of foods, simulating the interregional trade of foods, evaluating the estimated daily intake (EDI) of MeHg, and estimating per-fetus IQ decrements from dietary MeHg exposure.

First, this study compiles MeHg concentrations of foods in China. The categories of foods in this study include marine fishes, freshwater fishes, and rice. We collected both total Hg (THg) and MeHg concentrations of these foods from existing studies. The list of literature for THg and MeHg concentrations of foods is provided in Supplementary Data 8. For the estimation of MeHg exposure, the data near contaminated sites are excluded to reduce the errors. For species with only THg concentrations, we converted the data into MeHg by linear relationships which were estimated from studies with both THg and MeHg observations (Fig. S2). We average the MeHg concentrations every four years during 2004-2019 to investigate the general trend of MeHg concentration changes, which can reduce the impact of MeHg concentration changes of particular time points on the general trend. The concentrations of marine fishes, freshwater fishes, and rice are shown in Fig. S3.

Second, this study simulates the interprovincial food trade by using the multi-regional input-output (MRIO) tables (Lenzen et al., 2012; Liang et al., 2014). It has been widely used to simulate the interprovincial trade of foods in previous studies (Deng et al., 2020; Liu et al., 2018b). Monetary data on the final demand (including urban household consumption, rural household consumption, and government consumption) of a given province in the MRIO tables are used to describe the sources of a specific food product consumed in the province. Different sectors in the MRIO tables are used to simulate the interprovincial trade of different food products. We introduce a ratio (i.e., the output value of a specific fish to gross agricultural output) to extract the final demand for the specific fish from the total final demand of the *Farming, Forestry, Animal Husbandry and Fishery* sector in the MRIO tables.

Third, based on the MeHg concentrations of foods, interprovincial food trade, food consumption, and the intake rate of each category of foods, this study calculates the EDI of MeHg by equation 1.

$$EDI_j = \sum_{ik} \frac{SC_{ijk} \times I_{ij} \times C_{ik}}{W} \tag{1}$$

The notation $EDI_j$ represents the EDI of MeHg by the population in province $j$; $SC_{ijk}$ indicates the source contribution of food $i$ in province $j$ driven by the supply of province $k$; $I_{ij}$ represents the per capita intake rate (g d$^{-1}$ capita$^{-1}$) of food $i$ consumed by the females in province $j$; $C_{ik}$ is the MeHg concentration (ng g$^{-1}$) of food $i$ harvested in province $k$; and $W$ represents the average body weights of Chinese females of childbearing age (15-50 years old). The data for female consumption of foods are obtained from the China Health and Nutrition Survey (CHNS) database.

Finally, this study estimates per-fetus IQ decrements due to MeHg intake in various provinces of China. MeHg can be transmitted to the fetus through prenatal exposure and damage the brain tissues of the fetus, resulting in neurodevelopmental disorders and IQ decrements for the fetus (Driscoll et al., 2013). The IQ decrements caused by MeHg exposure are calculated by the dose-response relationship, based on previous epidemiological studies (Axelrad et al., 2007; Giang and Selin, 2016; Rice et al., 2010). The assessment of the IQ effects is shown in equation 2.

$$\Delta IQ = \gamma\lambda\beta(\Delta EDI \times W) \quad (2)$$

The notation $\Delta IQ$ represents the change in IQ points and $\Delta EDI$ indicates the change in EDI of MeHg. The notation $W$ represents the average body weight of Chinese female adults. The blood-intake coefficient $\beta$ (μg Hg/L blood per μg Hg/day), hair-blood coefficient $\lambda$ (μg Hg/g hair per μg Hg/L blood), and IQ-hair mercury coefficient $\gamma$ (IQ points per μg Hg/g hair) represent the conversion factors of MeHg from intake to blood, blood to hair, and hair to IQ, respectively.

**Quantifying contributions of midpoint factors.** In this study, we use the SDA method to investigate the relative contributions of different factors to the changes of provincial per-fetus IQ decrements during 2004-2019 (Dietzenbacher and Los, 1998; Hoekstra and Bergh, 2002). We divide the $\Delta EDI$ of each province into the contributions of four independent variables including dietary intake level change, dietary structure change, food trade structure change, and MeHg concentration change. Therefore, for food category $i$ and the province $j$, the $\Delta EDI$ in each province can be written as equation 3.

$$\Delta EDI = LS(O \odot C)e \tag{3}$$

The notation $L$ represents the total food intake level per capita in this province; the $1 \times i$ row vector S represents the dietary structure, indicating the proportion of food $i$ intake to the total food intake in this province; the $\odot$ represents the element-wise matrix multiplication; the $i \times j$ matrix O indicates the food trade structure, indicating the proportion of food $i$ from province $j$ to the total consumption of the population in this province; the $i \times j$ matrix C indicates MeHg concentrations of foods, meaning the MeHg concentrations of food $i$ in province $j$; and the notation $e$ represents a $j \times 1$ unit vector.

Subsequently, the per-fetus IQ decrements can be described by equation 4 and the structural decomposition form is shown in equation 5.

$$\Delta IQ = \gamma\lambda\beta \cdot LS(O \odot C)e \tag{4}$$

$$\begin{gathered} \Delta IQ = \gamma\lambda\beta \cdot \Delta LS(O \odot C)e + \gamma\lambda\beta \cdot L\Delta S(O \odot C)e + \\ \gamma\lambda\beta \cdot LS(\Delta O \odot C)e + \gamma\lambda\beta \cdot LS(O \odot \Delta C)e \end{gathered} \tag{5}$$

The notation $\Delta IQ$ represents the change in per-fetus IQ decrements. Items on the right side of equation 5 indicate the per-fetus IQ decrement change $\Delta IQ$ caused by dietary intake level change $\Delta L$, dietary structure change $\Delta S$, food trade structure change $\Delta O$ and MeHg concentration change $\Delta C$. The SDA method has the problem of non-uniqueness (Rørmose and Olsen, 2005). There will be n! kinds of decomposition forms if the number of decomposed factors is $n$. We take the average of all first-order decomposition forms to address this problem (Dietzenbacher and Los, 1998; Guan et al., 2008; Liang et al., 2013).

**Endpoint factors influencing per-fetus IQ decrements from dietary MeHg exposure.** Socioeconomic factors outside the food system can be uncovered by the panel regression model (Cheng et al., 2021). The endpoint factors considered in this study include affluence level (represented by resident incomes), education level, and traffic accessibility (represented by road areas). Based on the results of the F-test and Hausman test, this study chooses an individual fixed effect model (Stuart et al., 2010) (equation 6).

$$LnIQ_{it} = \beta X_{it} + \mu_i + \varepsilon_{it} \qquad (6)$$

The notation $i$ indicates province $i$ and notation $t$ indicates year $t$; $LnIQ$ represents the natural logarithm of per-fetus IQ decrements; $\beta$ represents the regression coefficient of each independent variable; X represents each independent variables; $\mu_i$ represents the province-specific effect for province $i$; and $\varepsilon_{it}$ represents the stochastic disturbance term.

**Uncertainties.** The uncertainties of results in this study mainly come from the compilation of MeHg intake inventory and the evaluation of per-fetus IQ decrements. A Monte Carlo simulation with 10,000 samplings was conducted on variables in different stages. We set P10 and P90 values of the statistical distributions as lower and upper ranges of results, following previous studies (Chen et al., 2019). In 2010, the population-weighted mean per-fetus IQ decrements in this study were 0.052 (0.009-0.105) points. They are lower than that of Chen et al. (0.140 points) in 2010 (Chen et al., 2019). Compared to the previous study, this study has conducted more detailed calibrations for MeHg concentrations of foods by removing the sample data on MeHg concentrations of foods from heavily contaminated areas (because these foods are generally unavailable in the market). In addition, only rice, marine fishes, and freshwater fishes were considered in this study, rather than all foods in the previous study (Chen et al., 2019). This is because that fishes and rice are the most important pathway of dietary MeHg exposure, while MeHg in other foods is less detected (Li et al., 2012; Zhang et al., 2010). All the uncertainty results are presented in Supplementary Data 6.

**The verification of model estimates**. Previous studies have found that blood mercury concentrations can serve as an indicator of short-term exposure to organic mercury (Hong et al., 2016; Mahaffey et al., 2004). Therefore, we estimated the mercury levels in human blood based on the dose-response relationship between MeHg exposure and Hg biomarkers (equation 7) and then compared them with the measured data from existing studies of the corresponding years.

$$THg_{blood} = \beta \times \Delta\mathrm{EDI} \tag{7}$$

The notation $THg_{blood}$ represents the total Hg concentrations of blood; and $\beta$ is the blood-intake conversion coefficient between MeHg intake and MeHg in blood (μg Hg/L blood per μg Hg/ day).

Fig. S4 shows the relationship between measured data from existing studies and our model estimates. It shows that the model estimates for provinces with larger newborn populations are closer to the measured data. The national population-weighted mean of blood Hg concentration of the measured data is 1.60±0.57 μg/L. This is generally consistent with the national mean of model estimate (1.50±0.13 μg/L) in this study.

## Results

**Changing per-fetus IQ decrements from dietary MeHg exposure.** China's national per-fetus IQ decrements (national average using the neonatal population as the weight) from dietary MeHg exposure have continuously decreased by nearly 60% during 2004-2019, from 0.068 (0.011-0.132) points in 2004 to 0.028 (0.002-0.067) points in 2019. Per-fetus IQ decrements in China have experienced a rapid decline during 2004-2013, falling by 51% (Fig. 1A). The provinces with the greatest declines of per-fetus IQ decrements during this period include Hainan, Zhejiang, Guangdong, Shanghai, and Jiangsu. They are all located along the southern coast of China. However, during 2014-2019, China's national per-fetus IQ decrements has decreased by only 22% at a significantly slower rate. Moreover, the downward trend has flattened after 2016, with 3% increase in per-fetus IQ decrements during 2016-2019. This situation is mainly due to the increased per-fetus IQ decrements in Gansu, Shaanxi, and Shanxi. Gansu has the largest increase in per-fetus IQ decrements (by 14%) during 2016-2019. Given the generally declining trend of MeHg concentrations in foods consumed (Fig. S3), the slowdown and flattening of the declining trend is attributable to the changes in dietary patterns of the populations. It is worth noting that, the sudden increase of per-fetus IQ decrements during 2013-2014 is mainly due to the change in the scope of statistics between these two years.

The relationship between per-fetus IQ decrements and economic development (represented by per capita GDP in this study) has been further investigated (Fig. 1B). Some provinces with low per capita GDP have high per-fetus IQ decrements (e.g., Jiangxi, Hunan, and Anhui). These regions are mainly located in the middle reaches of the Yangtze River (Fig. S5). Provinces in coastal areas have high per capita GDP and high per-fetus IQ decrements (e.g., Shanghai and Guangdong). Provinces with high per capita GDP and relatively low per-fetus IQ decrements are mainly located in northern China, including Beijing, Shandong, and Inner Mongolia. In addition, provinces with low per capita GDP and low per-fetus IQ decrements are mainly located in the North and Southwest China (see Fig. S6 for regional grouping). Overall, the per-fetus IQ decrements of the North are generally lower than the South. Most of the southern provinces are high-risk areas, which may be related to their dietary patterns. Notably, provinces with relatively low per capita GDP are the main contributors to the flattening of risk declines after 2016, including Gansu, Shaanxi, and Shanxi (Fig. S7). Thus, for regions with relatively low per capita GDP, the changes in health risk caused by their rapid economic development deserve our attention.

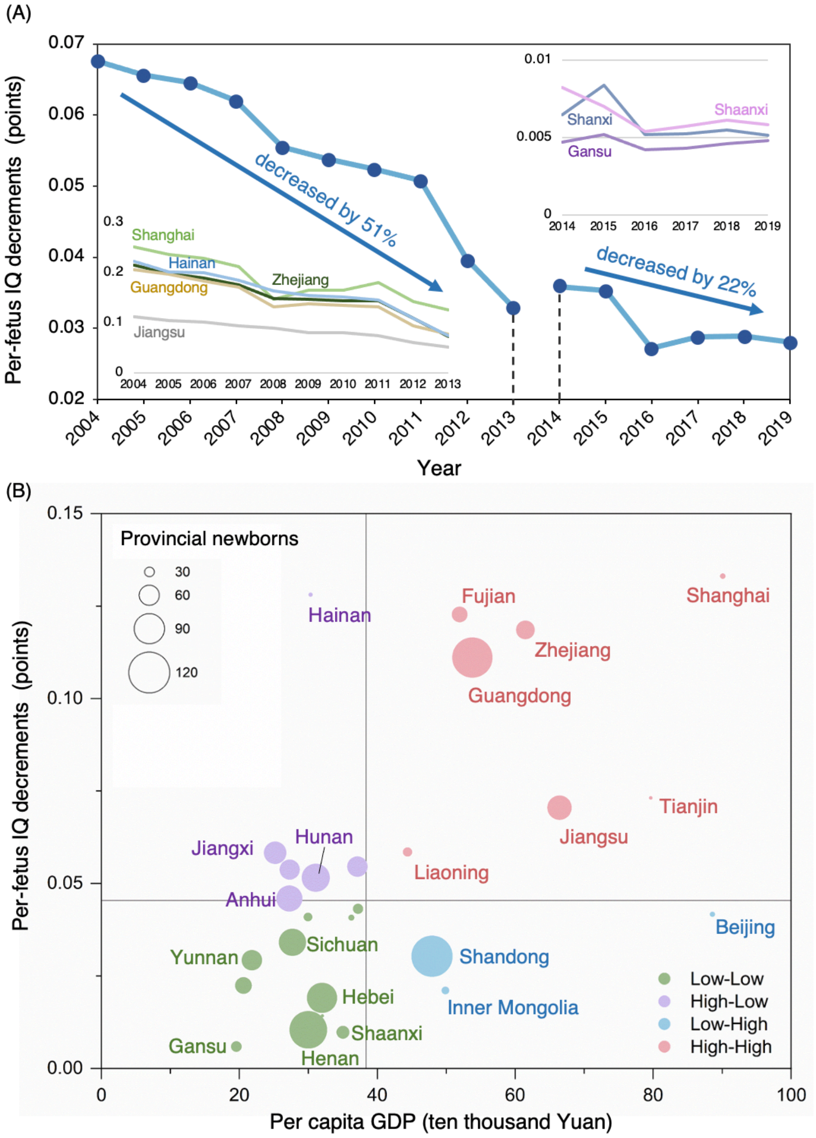

**Figure 1. National and provincial per-fetus IQ decrements in China due to dietary MeHg exposure during 2004-2019.** Graphs showing the temporal change of population-weighted mean per-fetus IQ decrements in China (**A**) and the relationship between average provincial per-fetus IQ decrements and per capita GDP (**B**). The bottom left corner of panel A represents the top five provinces with the largest declines of IQ loss during 2004-2013, and the upper right corner represents the provinces with relatively less decline in per-fetus IQ decrements during 2014-2019. Based on the relationship between per-fetus IQ decrements and per capita GDP during 2004-2019, we divided China's 30 provinces into four groups: High–High (i.e., High risk High per capita GDP), Low–High (i.e., Low risk–High per capita GDP), Low–Low (i.e., Low risk–Low per capita GDP), and High–Low (i.e., High risk–Low per capita GDP).

**Food sources of per-fetus IQ decrements from dietary MeHg exposure.** Food sources of per-fetus IQ decrements from dietary MeHg exposure in China during 2004-2019 are shown in Fig. 2. The consumption of fishes and rice is considered as the most significant source of dietary MeHg in existing studies (Giang and Selin, 2016; Qing et al., 2022; Selin et al., 2010; Zhang et al., 2010). Moreover, MeHg is mainly detected in aquatic products and rice, and the data on MeHg concentrations of other foods are usually unavailable (Li et al., 2010). Thus, this study only considers per-fetus IQ decrements caused by the consumption of marine fishes, freshwater fishes, and rice.

Fig. 2A shows **temporal changes of food sources** for the per-fetus IQ decrements during 2004-2019. The per-fetus IQ decrements caused by marine fishes have increased significantly, with the proportion rising by about 13 percentage points during this period. Six provinces including Heilongjiang, Tianjin, Shanghai, Guangxi, Beijing, and Hebei contributed about 50% of the increase in marine fish sources. In contrast, the per-fetus IQ decrements induced by MeHg exposure from rice intake decreased by 14 percentage points. This decline is mainly contributed by several western (e.g., Sichuan, Ningxia, Shaanxi, and Xinjiang) and central (e.g., Anhui and Jiangxi) provinces. The per-fetus IQ decrements caused by freshwater fish intake remain relatively stable during 2004-2019. These changes in food sources reflect the transition of people's dietary patterns due to rising living standards.

Fig. 2B shows **significant spatial heterogeneity of food sources** for the per-fetus IQ decrements during 2004-2019. The per-fetus IQ decrements generally decreased from the southeast coast to the northwest. Shanghai, Hainan, Fujian, Zhejiang, and

Guangdong have suffered fairly high per-fetus IQ decrements during 2004-2019, followed by Tianjin, and Jiangsu. These provinces are located in coastal areas and their per-fetus IQ decrements are mainly from the intake of **marine fishes** with high MeHg concentrations, except for Jiangsu. Nearly 70% of the per-fetus IQ decrements in Hainan and Fujian come from the intake of marine fishes. Other provinces with a high proportion of per-fetus IQ decrements caused by marine fishes include Shandong and Liaoning. These provinces are also located along the coast. Notably, about 78% of the per-fetus IQ decrements in Shandong come from the intake of marine fishes. However, the per-fetus IQ decrements in Shandong are much lower than those in southern coastal provinces. This may result from the differences in intake levels and differences in MeHg concentrations of marine fishes from different seas.

The provinces where per-fetus IQ decrements are dominated by **freshwater fish** intake are mainly located in the Northwest (e.g., Xinjiang and Qinghai), Southwest (e.g., Sichuan and Chongqing), and middle reaches of the Yangtze River (e.g., Anhui and Jiangxi). In particular, Hubei has the largest proportion of per-fetus IQ decrements from freshwater fish intake, accounting for 69% among all food sources.

In addition to aquatic products, **rice**, as a staple food in southern China, also poses significant health risk. For instance, per-fetus IQ decrements in Guizhou, Yunnan, and Hunan mainly result from the intake of rice. The per-fetus IQ decrements from rice account for 77%, 56%, and 52% of the total risk from all food sources in these three provinces, respectively, during 2004-2019. Although MeHg concentrations of rice are lower than those of fishes, high levels of rice intake have ultimately led to high per-fetus IQ decrements in these southern inland areas.

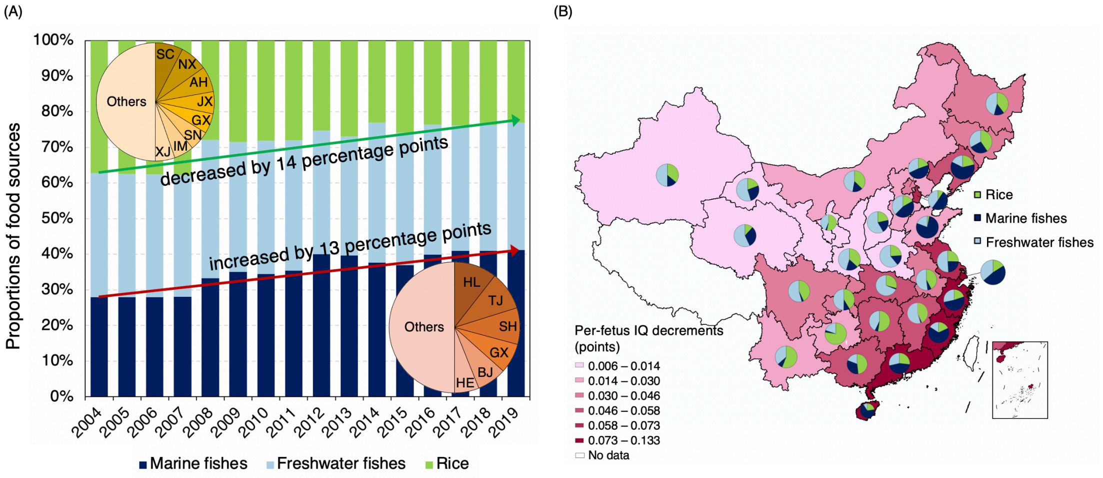

**Figure 2. Food sources of per-fetus IQ decrements during 2004-2019.** Graphs showing the temporal change in the proportion of food sources for per-fetus IQ decrements (**A**) and spatial distribution of dominating food sources for per-fetus IQ decrements (**B**). The pie charts in panel **A** show the major regions contributing to the change in proportions of food sources during 2004-2019. Full names of the region abbreviations are shown in Fig. S6. The colored background in panel **B** represents the provincial population-weighted mean per-fetus IQ decrements during 2004-2019, and pie charts represent the proportion of food sources for per-fetus IQ decrements in each province.

**Geographical sources of per-fetus IQ decrements from dietary MeHg exposure.** Fig. 3A-B show the geographical sources of per-fetus IQ decrements. Per-fetus IQ decrements in many southern provinces (e.g., Jiangxi, Hubei, Hunan, and Anhui) mainly result from the consumption of local foods, with local sources accounting for over 80% during 2004-2019. Per-fetus IQ decrements occurred in these provinces are dominated by the consumption of rice and freshwater fishes (Fig. 2A). In addition to local food consumption, the adjacent sea areas and foreign regions are also major sources of provincial per-fetus IQ decrements. For example, per-fetus IQ decrements in Hainan, Guangxi, and Guangdong mainly come from the consumption of aquatic products from the South China Sea. Per-fetus IQ decrements in Fujian and Zhejiang are closely related to aquatic products from the East China Sea.

It is worth noting that in 2004, Anhui in East China is an important supplier of food products (Fig. 3A). It poses per-fetus IQ decrements in most provinces of China, especially in North (e.g., Beijing, Shanxi, and Inner Mongolia) and Northwest China (e.g., Shaanxi, Gansu, Qinghai, Ningxia, and Xinjiang). In 2019, Heilongjiang in Northeast China replaced Anhui to be an important geographical source of per-fetus IQ decrements (Fig. 3B). The consumption of food products from Heilongjiang posed per-fetus IQ decrements in Northwest China and Southwest China. In addition, foreign sources have been becoming increasingly important in the contributions to China's per-fetus IQ decrements during 2004-2019. For example, 58%, 45%, and 44% of the per-fetus IQ decrements of Shanghai, Beijing, and Tianjin in 2019 are caused by the consumption of foods from foreign regions.

**Interregional flows of per-fetus IQ decrements induced by food trade.** We further identified major interregional flows of per-fetus IQ decrements caused by food trade in 2004 (Fig. 3C) and 2019 (Fig.3 D). During 2004-2019, the adjacent sea areas have been major sources of per-fetus IQ decrements. For example, the largest flow of per-fetus IQ decrements is the South China Sea–Hainan. The consumption of marine fishes from the South China Sea has led to 0.132 and 0.054 points of per-fetus IQ decrements in Hainan in 2004 and 2019, respectively.

The critical flows of per-fetus IQ decrements have been spatially shifting during 2004-2019. For example, Shanghai is a main receptor of per-fetus IQ decrements in 2004 (Fig. 3C). The IQ decrements occurred in Shanghai came not only from foreign regions and adjacent seas, but also from the consumption of foods in Anhui (0.019 points), Jiangxi (0.015 points), Jiangsu (0.011 points), and Hunan (0.008 points). However, in 2019, per-fetus IQ decrements in Shanghai are mainly from the consumption of foods from foreign regions. Foreign regions have been becoming a more and more important geographical source during 2004-2019. For instance, the consumption of imported foods from foreign regions became an important geographical source for per-fetus IQ decrements in Beijing, Fujian, and Guangdong in 2019. We observed similar situations for the Yellow Sea. For example, the intake of marine fishes from the Yellow Sea has been becoming an important source for per-fetus IQ decrements in more and more regions (e.g., Shandong and Jiangsu) during 2004-2019. This may be related to the increased MeHg levels in marine fishes from the Yellow Sea (Supplementary Data 9).

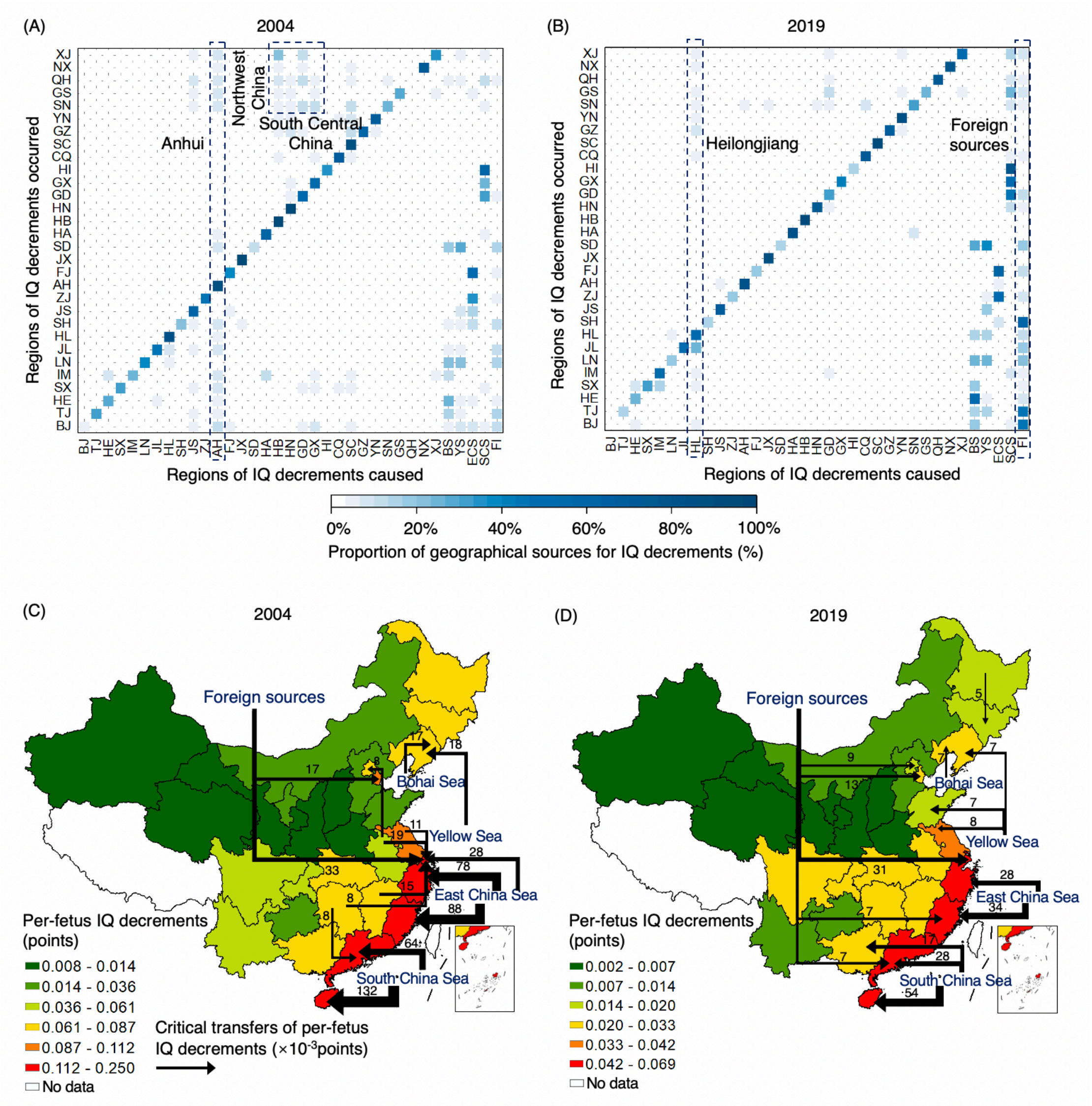

**Figure 3. Geographical flows of per-fetus IQ decrements during 2004-2019.** Graphs **A, B** showing the proportion of per-fetus IQ decrements from geographical sources to each province in 2004 (**A**) and 2019 (**B**). The vertical axis represents the provinces where IQ decrements occur, and the horizontal axis represents the geographical sources of IQ decrements. Each cell represents the proportion of per-fetus IQ decrements in the province from different regions. Graphs **C, D** showing critical interregional flows of per-fetus IQ decrements ($\times 10^{-3}$ points) in 2004 (**C**) and 2019 (**D**). Full names and geographical locations of the region abbreviations are in the Supplementary Information (Fig. S6).

**Midpoint factors affecting China's per-fetus IQ decrements.** The per-fetus IQ decrements of MeHg intake are closely associated with MeHg concentrations of foods and dietary factors including dietary intake levels, dietary structure, and geographical source structure (i.e., food trade structure). The per-fetus IQ decrements have generally shown a declining trend during 2004-2019 (Fig. 1). Such decline results from the joint effects of dietary shifts and the decrease of MeHg concentrations in foods. The dietary shifts have contributed 44% of the decreased per-fetus IQ decrements during 2004-2019, while the reductions in MeHg concentrations of foods contributed 56%. Moreover, the contributions of these factors are spatially heterogeneous. For example, for coastal regions, changes in dietary factors are the leading cause of the decline, contributing 61% of the decreased per-fetus IQ decrements. In contrast, for northern China, the reductions of MeHg concentrations take the leading role.

However, the declining trend has slowed down after 2014 and even leveled off after 2016. Per-fetus IQ decrements have decreased by 51% during 2004-2013, but only 22% during 2014-2019. The average annual contribution of dietary pattern changes to changes in per-fetus IQ decrements during 2014-2019 has decreased by 53% than that during 2004-2013. In contrast, that for the decline in MeHg concentrations of foods has decreased by only 12%. Thus, such slowdown and flattening are mainly caused by changes in dietary patterns. This indicates that dietary pattern changes play an important role in reducing per-fetus IQ decrements. Thus, optimizing dietary patterns is critical to further reduce the per-fetus IQ decrements from dietary MeHg exposure.

The following paragraphs specially focus on the time periods of 2004-2013 and 2014-2019 (Fig. 4).

During 2004-2013, the decrease of China's per-fetus IQ decrements are mainly dominated by coastal regions, especially Hainan, Zhejiang, Guangdong, and Shanghai (Fig. 4B). This decline is mainly due to dietary pattern changes, with dietary factors contributing 71% of the decreased risk in coastal regions. The northern regions, especially Northwest (e.g., Gansu, Xinjiang, Qinghai, and Ningxia) and North China (e.g., Shanxi, Tianjin, Inner Mongolia, Shandong, and Hebei), have relatively small reductions of per-fetus IQ decrements. In general, the reduction of per-fetus IQ decrements is mainly caused by changes in dietary intake levels and dietary structure. The proportion of MeHg intake through marine fishes has increased in most provinces due to relatively high MeHg concentrations in marine fishes (Fig. S8E). However, the increased per-fetus IQ decrements are offset by a reduction in the proportion of MeHg intake through rice and freshwater fishes. For example, Hainan has the largest decline of per-fetus IQ decrements during 2004-2013. It is mainly due to the decreased proportion of MeHg intake through rice and freshwater fishes.

During 2014-2019, China's per-fetus IQ decrements have decreased by 22% (Fig. 1). The per-fetus IQ decrements have declined in most provinces, especially the coastal regions such as Shanghai and Fujian (Fig. 4C). The decreased level and proportion of MeHg intake through fishes are important factors for such decline (Fig. S8). Notably, even though MeHg concentrations of rice are much lower than fishes, changes in the intake levels of rice can still pose large impacts on per-fetus IQ decrements. For example, changes in dietary intake levels of Hebei have contributed 74% of the reduction in per-fetus IQ decrements. This is mainly due to the reduced proportion of MeHg intake from rice (Fig. S8F).

Notably, changes in food trade structure of certain provinces have resulted in the increase of per-fetus IQ decrements during 2014-2019. This increase was offset by the decrease in per-fetus IQ decrements caused by changes in dietary intake levels and dietary structure. Especially, changes in food trade structure of Shanghai have induced the increase of per-fetus IQ decrements by 0.002 points. During 2014-2019, Shanghai has significantly increased the consumption of marine fishes from foreign regions, while reduced the consumption of marine fishes from South China Sea, Bohai Sea, and Yellow Sea (Fig. S9A). This may explain the increased per-fetus IQ decrements caused by the changes in food trade structure of Shanghai, because the MeHg concentrations of marine fishes from foreign regions are much higher than those in China (Supplementary Data 9). Moreover, changes in food trade structure of Chongqing have contributed to the increase of per-fetus IQ decrements. During 2014-2019, Chongqing has increased the consumption of marine fishes from foreign regions (Fig. S9B). In addition, Chongqing has reduced the consumption of rice from the local, while increased that from Heilongjiang. The rice from Heilongjiang has relatively higher MeHg concentrations than that of Chongqing during 2014-2019 (Supplementary Data 9).

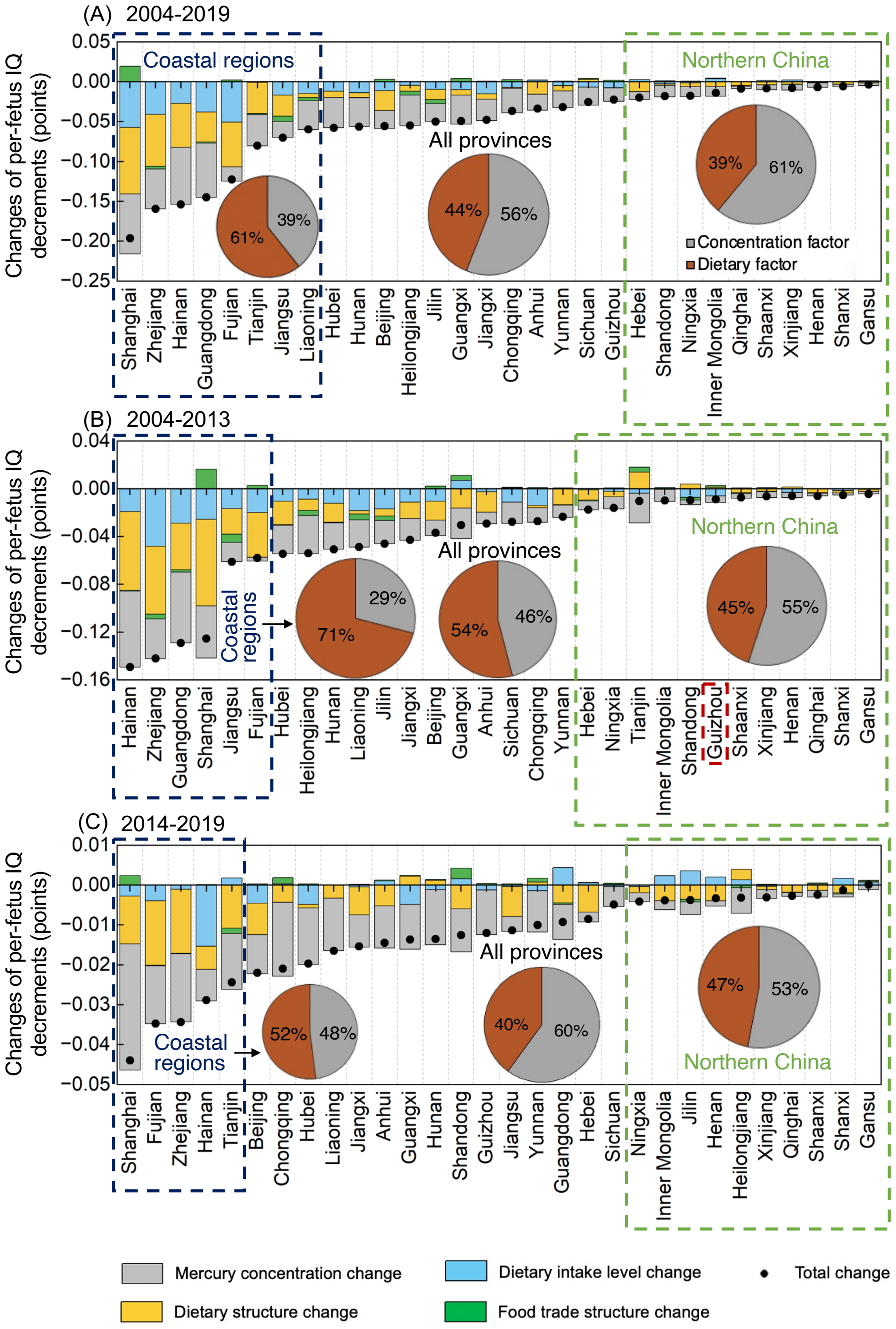

**Figure 4. Contributions of midpoint factors to changes in per-fetus IQ decrements in China.** Graphs **A, B, C** showing the relative contributions of MeHg concentrations and dietary factors to changes in per-fetus IQ decrements during 2004-2019 (**A**), 2004-2013 (**B**), and 2014-2019 (**C**). The pie charts in panels **A**, **B**, **C** represent the proportions for the contributions of MeHg concentrations and dietary factors to the reductions of per-fetus IQ decrements.

**Endpoint factors affecting China's per-fetus IQ decrements.** Dietary factors within the food system are termed as midpoint factors in this study. They are further affected by endpoint factors (i.e., affluence, education levels, and traffic accessibility in this study) (da Costa et al., 2022; Galvan-Portillo et al., 2018; Mullie et al., 2010). We further identified endpoint factors which are closely associated with China's per-fetus IQ decrements. This could help to formulate socioeconomic policies that complement diet-related control measures. We observe significant correlations between per-fetus IQ decrements and endpoint factors including affluence level, education level, and traffic accessibility (Table 1).

The affluence (represented by resident incomes) and education levels have significantly negative associations with per-fetus IQ decrements. This is because people with high levels of affluence and education have strong risk perception ability (Zobrist et al., 2009). These groups pay more attention to heavy metal contamination in diets. For example, they may be more likely to choose foods with low MeHg concentrations or foods from regions with less Hg pollution. Meanwhile, people with higher levels of affluence and education tend to consume healthier foods (e.g., vegetables, fruits, and other plant-based foods) that induce less MeHg-related health risk (Lenthe et al., 2015).

The traffic accessibility (represented by road areas) has significantly negative associations with per-fetus IQ decrements. It is probably because that good transport conditions are conducive to interregional food trade (Ge et al., 2021). Foods with relatively low MeHg concentrations can be more easily transported into regions with higher traffic accessibility. Thus, people in these regions have more opportunities to obtain foods with relatively low MeHg concentrations, and consequently suffer smaller per-fetus IQ decrements.

**Table 1. The empirical relationships between China's per-fetus IQ decrements and endpoint factors based on panel regression model**.

| **Variables** | **Coefficients** | **Standard Errors** | **Probability** |
|---|---|---|---|
| *LnIncome* | -1.369$^{***}$ | 0.304 | 0.000 |
| *LnEdu* | -0.319$^{**}$ | 0.126 | 0.017 |
| *LnRoad* | -0.547$^{***}$ | 0.142 | 0.001 |
| $R^2$ | 0.8 | | |
| Observations | 480 | | |
| Provincial level **fixed effects** | Yes | | |
| Hausman Test | 0.000 | | |

**Notes:** $^{**}$ indicates the 5% statistical significance level and $^{***}$ indicates the 1% statistical significance level. The *LnIncome* represents the natural logarithm of disposable income of residents; The *LnEdu* represents the natural logarithm of education levels (i.e., the share of the population with educated college degree or above in the total population above 6 years); and The *LnRoad* represents the natural logarithm of road areas. The Hausman test is used to determine whether to take a random effects regression or a fixed effects regression, with the original hypothesis that a random effects model is fully efficient.

## DISCUSSION

This study investigates the temporal change of China’s per-fetus IQ decrements from dietary MeHg exposure during 2004-2019 and reveals socioeconomic driving factors. Our findings could provide the following implications for reducing MeHg-related health risk in China, as well as new inspirations for other nations and regions around the world.

**First, in addition to controlling Hg emissions, measures on health risk are essential for the successful implementation of the Minamata Convention on Mercury.** Many studies have analyzed Hg pollution control from the perspective of Hg emission reduction. However, the ultimate goal of the Minamata Convention on Mercury is to protect human beings from health threats caused by Hg pollution. Our results show that some regions have low levels of Hg emissions but high per-fetus IQ decrements. For example, the previous study shows that Hg emissions in Hainan are far lower than Beijing (Liu et al., 2018a). However, this study finds that Hainan has suffered per-fetus IQ decrements more than three times as much as Beijing during 2004-2019. That is, populations in low-emission regions may also suffer high health risk from dietary MeHg exposure. This may be related to the differences in dietary patterns between these two regions. According to the results of this study, the intake level and ratio of marine fishes (with higher MeHg concentrations) in Hainan is much higher than that in Beijing. Therefore, it is insufficient to implement Hg control measures simply from the emission side. Investigating MeHg-related health risk and underlying socioeconomic factors from the macro perspective is conducive to the better implementation of the Minamata Convention on Mercury.

**Second, the increasing health risk from dietary MeHg exposure in underdeveloped regions deserves more attention.** This study found that most provinces with increased per-fetus IQ decrements after 2016 had relatively low per capita GDP, including Gansu, Shaanxi, and Anhui. Gansu and Shaanxi have increased their intake of marine fishes, while Anhui has increased the intake of freshwater fishes., With the rapid economic development in the future, these regions will continue to face diet transitions. Relatively high MeHg concentrations of fishes may increase MeHg-related health risk. Minor changes in fish intake structures can lead to significant changes in health risk. It is important to establish strict food safety standards for fishes and incorporate them into dietary guidelines. Moreover, guiding consumers to choose marine fishes in areas with relatively low MeHg concentrations (e.g., Bohai Sea and Yellow Sea) can help control MeHg-related health risk.

**Third, the role of rice intake in reducing MeHg-related health risk must be concerned.** Existing studies find that the intake of rice and fishes is the primary pathway of dietary MeHg exposure (Sunderland et al., 2018; Zhang et al., 2010). Rice is a staple food in many regions of China and is consumed in large quantities. Therefore, although the MeHg concentrations of rice are much lower than fishes, rice intake plays an important role in the changes of health risk from dietary MeHg intake. For example, the large decline of per-fetus IQ decrements in Hainan, Guangdong, and Zhejiang during 2004-2013 was due to the reduction in the proportion of MeHg intake through rice consumption. Therefore, regions dominated by rice (e.g., Guizhou, Hunan, and Yunnan) can be encouraged to partly choose alternative staple foods with low MeHg concentrations (e.g., wheat, corn, and potatoes), which could also help reduce environmental impacts (Liu et al., 2021). Moreover, promoting the transformation of dietary patterns to plant-based diets (e.g., vegetables, fruits, and nuts) can help offset the increasing trend of MeHg-related health risk. This effort is also in line with the planetary health diet proposed by the ETA Lancet Commission (Willett et al., 2019).

**Fourth, strengthening the guidance on consumption patterns is an effective way to reduce health risk from dietary MeHg exposure.** The affluence and education levels have significantly negative correlation with per-fetus IQ decrements from dietary MeHg exposure. This is because that rich and well-educated people have higher ability of risk perception. They are more likely to choose foods with low MeHg concentrations. This further indicates the important role of consumption patterns. There is a need to strengthen the guidance of rational consumption patterns. For example, in rich and highly educated areas, foods could be labelled with MeHg concentrations. In this way, consumers are encouraged to choose foods with relatively low MeHg concentrations. Furthermore, guiding the advocacy for food safety in underdeveloped regions and regions with low educational levels is conductive to controlling national MeHg-related health risk.

**Finally, other nations around the world can refer to the findings of this study in developing socioeconomic regulation policies.** Developing nations with severe Hg pollution issues (e.g., India and Colombia) can refer to our findings. This study finds that the most important factor influencing per-fetus IQ decrements in coastal regions is the consumption of marine fishes. Thus, it is important for coastal regions of the world to monitor the MeHg concentrations of seafoods and choose reliable sources of marine fishes. Furthermore, international and intranational food trades can be strengthened.

This action could help reduce the dependence on foods from certain regions with relatively high MeHg concentrations.

## Conclusions

China plays an important and representative role in the implementation of the Minamata Convention on Mercury which aims to protect human beings from adverse impacts of mercury and its compounds. Chinese population has suffered severe health risk from dietary MeHg exposure. However, nothing is known about the historical trend of China's health risk from dietary MeHg exposure and relevant socioeconomic driving factors. This study fulfills these knowledge gaps and investigates the historical trends of China's MeHg-related health risk during 2004-2019. Moreover, this study identifies critical socioeconomic factors influencing changes in health risk.

We find that China’s per-fetus IQ decrements have decreased by 60% during this period. This decline results from the joint effects of dietary shifts and the decrease of MeHg concentrations in foods. However, the declining trend has slowed down after 2014 and even leveled off after 2016. Such slowdown and flattening are mainly caused by dietary pattern changes. For example, the increased intake level and proportion of fishes in underdeveloped provinces of China have dominated the slowdown of declining trend after 2016. Moreover, the affluence and education levels have significantly negative associations with per-fetus IQ decrements. Rich and well-educated people have higher ability of risk perception, which indicates the importance of rational consumption patterns.

The findings can help develop socioeconomic regulatory policies on reducing per-fetus IQ decrements from dietary MeHg exposure in China. Relevant policy implications include focusing on health risk alleviation in addition to Hg emission control, guiding consumers to choose marine fishes in areas with relatively low MeHg concentrations, establishing strict food safety standards for fishes, encouraging regions dominated by rice to partly choose alternative staple foods with low MeHg concentrations, as well as strengthening controls on international food trade.

## Author contributions

S.L. designed this study. Y.L., H.Z., and X.W. collected the data. Y.L. and Q.Z. conducted the calculations and interpretations of the results. S.L., Y.L., H.Z., X.W., P.H., Q.Z., and L.C. wrote and revised the paper. S.L. supervised this study.

## Declaration of interests

The authors declare no competing interests.

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