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Embedded Health Risk from Arsenic in Globally Traded Rice

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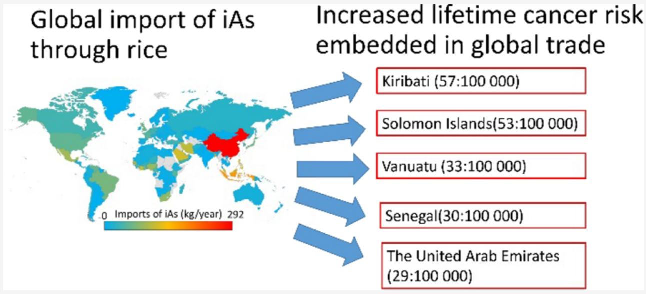
ABSTRACT: International food trade is fundamental to global food security but with often negative consequences in the producing country. We propose a method of quantifying flows of inorganic arsenic (iAs) and embedded increased lifetime cancer risks (EHR) at a global scale, where negative impacts are felt on the importing country. Computations were made for 153 countries. Vietnam exports the most iAs embedded in rice (796 kg/year) followed by India (788 kg/year), Thailand (485 kg/year), and the United States (323 kg/year). We show that continental China, Indonesia, and Malaysia have the highest imports of iAs (292, 174, and 123 kg/year, respectively). Bangladesh ranks highest in EHR followed by Vietnam and Cambodia (150, 141, and 111 per 100,000, respectively). Countries that depend exclusively on imported rice are importing a substantial amount of risk, as, e.g., Kiribati and Solomon Islands (57 and 53 per 100,000, respectively). We discuss the potential policy options for reducing population dietary health risks by well-balanced apportioning of rice sources. This study targets policy design solutions based on health gains, rather than on safe levels of the risk factor alone.



KEYWORDS: *rice, arsenic, embedded health risks, international trade*

INTRODUCTION

Global food security is underpinned by international food trade; however, global trade flows have been shown to result in flows of embedded resources with often negative consequences for the environment[1,2] and resource depletion.[3] The direct impacts of global trade on human nutrition are potentially positive;[4] however, changing global diets is strongly linked to global challenges for environmental sustainability and human health.[5] The redistribution of food through global trade results in global displacement of the embedded environmental and social impacts of food supply chains[6,7] with negative consequences primarily,[8] but not exclusively,[2] borne by exporting and spillover countries. Progress toward a number of the United Nations Sustainable Development Goals requires clear understanding and accounting for the full range of transboundary risks associated with interactions between systems connected through global trade.[9]

Embedded health risks (EHR) due to the transport and consumption of hazardous substances away from the point of production may be substantial.[10] They occur in the opposite direction to those usually examined in traditional trade-based embedded flow analysis and have not been well characterized. The balance of risks for importing and exporting countries can easily be unfavorable for importing countries and may be unequally distributed to developing countries with high levels of specific food imports.[9]

Rice is a staple for more than half of the world population, is widely traded on the global market, and can contain contaminants such as mercury[11] and arsenic,[12] which represent risks depending on population exposure in the country of consumption. Therefore, intake of inorganic arsenic through rice can be a big problem that can cause potential health problems globally.[12] For example, Liu et al.[9] observed that the international rice trade aggravated MeHg exposure in Africa, Central Asia, East Asia, and Europe and mitigated exposure in North America, South America, South Asia, South East Asia, and Oceania. The EHR from arsenic exposure in imported rice depends on cumulative exposures particular to the country of consumption, the concentration of arsenic, and amount of rice consumed. Globally, EHR depends on international supply chains as well as local consumption patterns.

This study estimates the flows of inorganic arsenic incorporated in the global rice trade and the associated EHR for importing countries. The health endpoint considered here is the increased lifetime cancer prevalence. The motivation for

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this analysis comes from the observation that none of the frameworks for identifying and ranking food-related domestic risks facilitate tracing the movement of contaminants in foodstuffs through international trade, and current frameworks fall short of supporting risk management and communication of risks from contaminants in global food supply chains (see the Supporting Information).

We build an embedded arsenic mass and global trade health risk modeling that details flows between countries. The database on the arsenic concentration in rice includes over 23,000 records. Diet and trade data were retrieved from the Food and Agriculture Organization of the United Nations (FAO). We then compute estimates of traded inorganic arsenic embedded in rice, population exposure due to imported and local rice, and the associated health risks for 153 countries. We discuss the potential implications of reducing population-level dietary health risks through policy approaches that favor reductions in health risks as a complement to the current use of safety levels.

MATERIALS AND METHODS

Model. The method in this study follows a stepped reasoning: (i) In a given country, the rice diet is a composite of imported and locally produced rice (if any); (ii) imported rice comes from multiple trade partner countries, in varied volumes; (iii) the concentration of inorganic arsenic in rice is variable according to the place of production; (iv) the presence of arsenic in rice is a health hazard; (v) the level of exposure to inorganic arsenic (iAs) varies with the amount of rice consumed in local diets; (vi) the expected lifetime risk from iAs exposure can be estimated per country; and (vii) unlike the hazard, the risk is specific for a country due to the influence of exposure (diet) on risk.

The flow of iAs, embedded in rice imported by a country, j, from a partner country, k (kg/year), is given by

$$\mathrm{IMPAs}_{jk} = \mathrm{IMP}_{jk}\mathrm{iAs}_{k}10^{-6} \quad (1)$$

with IMP_{jk} being the imports of country j from country k (kg/year) and iAs_k (mg/kg) being the concentration of the contaminant in the rice from country k. Note that the rice exported from country k may already be a mixture of rice from multiple origins.

The flow of iAs embedded in rice imported by country j from all partner countries (kg/year) is the sum of all contributions

$$\mathrm{IMPAs}_{j} = \sum_{k=1}^{n} \mathrm{ET}_{jk} \quad (2)$$

The excess lifetime health risk embedded in local rice is

$$\mathrm{EHR}_{jj} = \mathrm{IR}_{j}\mathrm{iAs}_{j}\mathrm{CSF}/\mathrm{BW} \quad (3)$$

with IR_j being the ingestion rate (kg/cap/day) for the population in country j; iAs_j (mg/kg) is the concentration of the contaminant in the rice from country j; CSF is the cancer slope factor for iAs; and BW is the body weight (kg), considered equal to 70 kg.

The excess lifetime health risk embedded in the rice imported by country j from a trading partner country k is

$$\mathrm{EHR}_{jk} = \mathrm{IR}_{j}i\mathrm{As}_{k}\mathrm{CSF}/\mathrm{BW} \quad (4)$$

The excess lifetime health risk embedded in the rice imported by country j from all its trade partners is

$$\mathrm{EHR}_{j}^{*} = \sum_{k=1}^{n} \beta_{jk}\mathrm{EHR}_{jk} \quad (5)$$

with β_{jk} being the fraction of the total rice imported by country j from partner country k.

Finally, the total excess lifetime health risk due to both locally produced and imported rice is

$$\mathrm{TEHR}_{j} = \alpha\mathrm{EHR}_{j} + \beta\mathrm{EHR}_{j}^{*} \quad (6)$$

with α being the fraction of rice consumed in country j, which is produced locally, and β being the fraction of rice that is imported ($\sum\beta_{jk}$).

Data. Data on iAs in raw white rice were compiled from (i) international journals (list provided in the Supporting Information), (ii) data published by the U.S. Food and Drug Administration,[13] and (iii) GEMS/food contaminants database maintained by the Word Health Organization (WHO).[14] Values when reported in dry weight were converted to wet weight by considering an average water content in the rice of 10%.[15] As only total arsenic concentrations were reported for some countries, values reported as total arsenic (tAs) were converted to iAs using the ratio of the means of iAs and tAs obtained from the data in the WHO GEMS/food contaminants database (N = 22,010), which is 0.627. This ratio is within the range reported in the literature.[16]

The exhaustive dataset is formed from a total of 23,022 records from 41 countries, including all the largest rice producers. For the remaining 112 countries, the arsenic concentrations were estimated from the mean iAs concentrations computed with the exhaustive dataset for the appropriate WHO regions, namely, Africa, 0.042 ± 0.035 mg/kg (N = 9); Eastern Mediterranean, 0.083 ± 0.023 mg/kg (N = 12); European region, 0.101 ± 0.167 mg/kg (N = 18,312); South East Asia, 0.069 ± 0.034 mg/kg (N = 833); Western Pacific, 0.099 ± 0.049 mg/kg (N = 1853); and Region of the Americas, 0.098 ± 0.053 mg/kg (N = 1953).

Data on amounts of rice production and imports per country for each of that country's trade partners was retrieved in February 2020 from FAOSTAT web page (http://www.fao.org/faostat) for the entire available period (1986–2015). Given that the amounts of rice traded globally have increased throughout the period (see details in the Supporting Information) means that the last 5 years were used to best reflect the contemporary situation. Rice production (paddy) was also retrieved from the same FAO's database and converted to milled equivalents by multiplying by a factor of 0.66.[17]

Food availability was sourced from the WHO FAOSTAT food balance sheets as food supply quantity (kg/capita/year), which represents the average supply available for each individual in the population as a whole and does not indicate what is actually consumed by individuals.[18] While FAO data have some limitations associated with necessary estimates made to compensate for limited data, it is generally accepted that they provide a useful indication of the food supply.[19] For the purposes of the global analysis made here, this definition is sufficient. The value of CSF was considered equal to 1.5 (mg/kd·day)$^{-1}$.[20]

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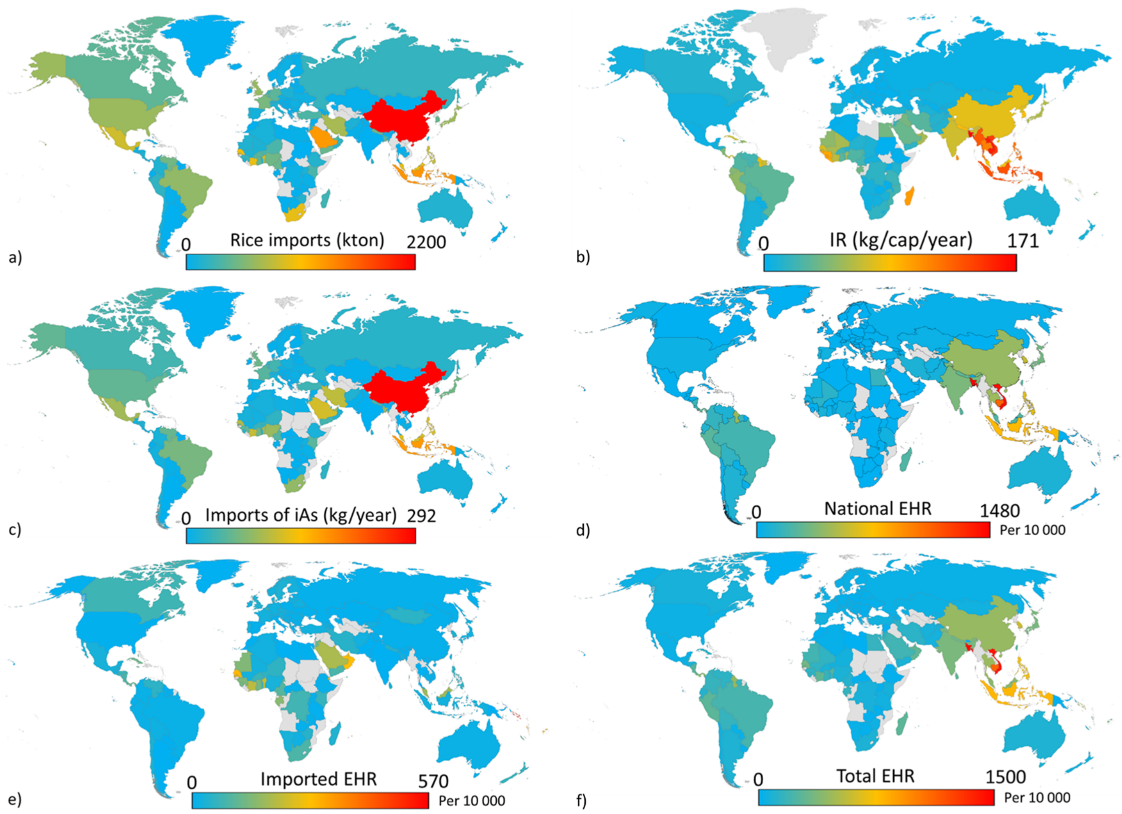

Figure 1. Global distribution of the rice trade, embedded iAs, and embedded health risk: (a) imports of rice; (b) rice ingestion rates; (c) embedded iAs in traded rice; (d) EHR due to the presence of iAs in rice in national markets; (e) imported EHR; (f) total EHR. All data are annual averages for the period 2011−2015.

■ RESULTS AND DISCUSSION

Rice Imports and Global Trade. Data from FAO[21] show that the amount of rice being traded worldwide has been rising steadily over the last four decades at an average rate of about 0.8 Mton year^{-1}, that is, at a rate about 10 times higher than the growth of the human population in the same period (Figure S1 in the Supporting Information). Countries in North America, East Asia and the Pacific, Europe and Central Asia, the Middle East and North Africa, and Sub-Saharan Africa are the main regions responsible for this extraordinary growth in trade. The observed growth has, however, different underlying origins: In North America, South and East Asia, and the Pacific, increased trade is due to a surplus of agricultural production, while in the remaining regions, increases in both production and trade have been necessary to meet the growing demand for rice. Africa is the continent where rice consumption has increased fastest; for instance, in Namibia, rice demand increased 10-fold over a 20 year period (Figures S2−S5 in the Supporting Information). This has led to a very unbalanced rice trade in the Middle East and North Africa and Sub-Saharan Africa, which together spent over \$96 × 10^9 importing rice from trade partners during the period 1986−2017. This financial effort has fostered the growth in average caloric supply, to which rice has contributed about 30%, only surpassed by wheat (ca. 50%) (FAOSTAT database). This increase in calories has contributed to the fight against famine and undernourishment in many developing countries. Despite the significant contribution of the rice trade, the total consumption of internationally traded rice remains a minor part of total consumption, being only about 7% of the rice consumed worldwide.[22] The largest producing countries are also the largest consumers.

In the period 2011−2015, the 15 major importing countries were responsible for over 50% of the trade in rice (Figure 2 and Table S1 in the Supporting Information). These countries are, in order of decreasing magnitude of rice imports, China, Indonesia, Saudi Arabia, Nigeria, Iran, Benin, the United Arab Emirates, Senegal, Côte d'Ivoire, South Africa, Malaysia, Bangladesh, Mexico, the Philippines, Japan, and the United States (Figure 1a). This pattern closely follows rice dietary consumption in these countries (Figure 1b). Major rice exporters (Table S2 in the Supporting Information) include India, Thailand, Vietnam, the United States, Pakistan, Italy, Brazil, Uruguay, China, Argentina, Spain, Myanmar, Guyana, and Paraguay. The United States and China are both large importers and exporters and act as global rice distributors (Figure 2).

The largest rice-importing region in the world is Africa (Sub-Saharan Africa), where the bulk of imports come from Asian countries (Figure 2 and Table S1 in the Supporting Information). The largest importers in the region are Nigeria (1251 kton/year), Benin (1080 kton/year), Senegal (1049 kton/year), Côte d'Ivoire (1018 kton/year), and South Africa (1000 kton/year). The Eastern Mediterranean region is the second largest global import market, led by Saudi Arabia (1330 kton/year), Iran (1215 kton/year), and the United Arab Emirates (1055 kton/year).

The total food imports of countries in Central America more than doubled over the last two decades, following a decrease in average tariffs in Central America from 45 to around 6% by 2000[23] (Figure S4 in the Supporting Information). Costa Rica

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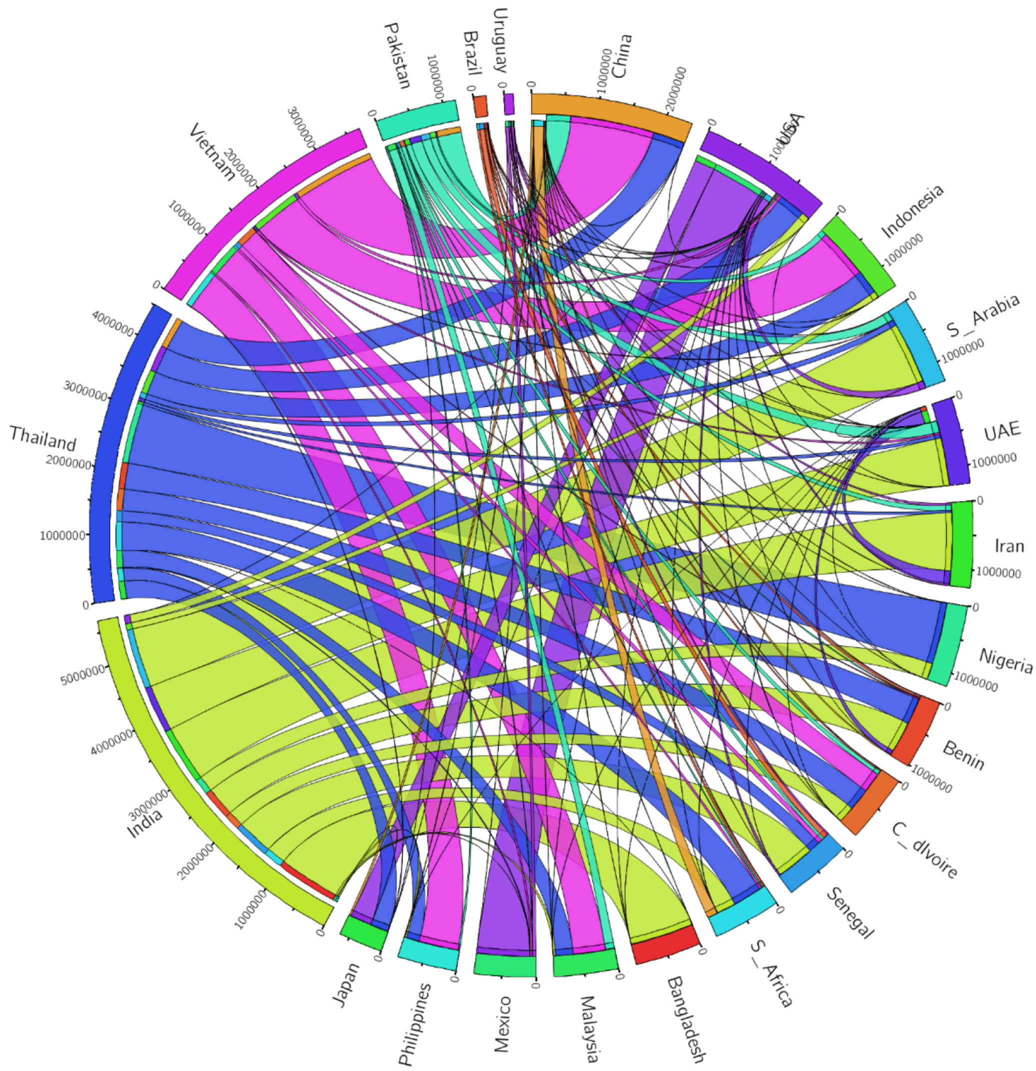

Figure 2. Fifteen largest rice importers and their trade partners. To read this figure, follow a color ribbon from its origin to its destiny. Each ribbon has the color of the exporting country.

registered the highest rate of import growth. Imports of rice into the country increased more than 9-fold in the period, 4 times more than the growth of wheat, and 13 times that of maize.[24] The largest importers in the American region are Mexico (892 kton/year), the United States (674 kton/year), Brazil (632 kton/year), and Venezuela (497 kton/year). Most of the rice imported by the South American region originates in the United States (Table S7 in the Supporting Information).

Asian countries (in South East Asia and the Western Pacific regions) are the largest global rice producers and also important trade markets. China is the largest Asian global importer (2215 kton/year) followed by Indonesia (1348 kton/year), Malaysia (984 kton/year), and Bangladesh (976 kton/year). The region is a net exporting region accounting for 70% of world rice exports (Table S1 in the Supporting Information).

International trade can not only increase the nutrient supply in a country but also make it vulnerable to sudden changes in global trade relations and conditions. Overall, the current global food system is associated with increasing equality of nutrient access.[4]

iAs in Rice. The arsenic concentration in rice is highly variable not only across the producing regions of the globe but also within these regions.[25] Results from analysis of the dataset compiled (Table S3 in the Supporting Information) show that it is admissible to assume differences in mean concentrations of iAs in rice entering the market in different WHO regions; specifically, SE Asia shows significantly different concentrations from those in other regions ($F(5, 23{,}016) = 8.01$, $p < 0.05$; details are provided in the Supporting Information). The intra-regional variability in iAs concentrations is also high (Table 1), justifying non-significant differences between the remaining regions. This result is expected as, in many of the countries studied, marketed rice is a composite of rice from different origins. The number of samples available for calculating statistics on iAs concentrations per WHO region is quite variable, with Africa and the Eastern Mediterranean regions represented by a total of only 21 rice samples. Under-sampling in many countries hinders the establishment of robust statistical analysis at the country scale. However, given that under-sampled countries are mostly rice importers, this under-representation does not affect the subsequent analysis.

iAs Embedded in Traded Rice. The total amount of iAs imported by a country from a specific trade partner is calculated using eq 1, and the amounts imported from all that country's trade partners are given in eq 2.

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Table 1. Concentrations of Inorganic Arsenic per Region and Country[a]

country/WHO region	mean iAs (mg/kg)	standard deviation (mg/kg)
WHO Africa region (*N* = 9)	0.042	0.035
Ghana	0.042	0.035
WHO Eastern Mediterranean region (*N* = 12)	0.083	0.023
Egypt	0.067	0.025
Pakistan	0.089	0.020
WHO European region (*N* = 18,312)	0.101	0.167
Austria	0.090	0.057
Belgium	0.097	0.054
Bulgaria	0.018	0.011
Cyprus	0.050	0.026
Czech Republic	0.086	0.052
Denmark	0.120	0.089
Finland	0.117	0.081
France	0.063	0.064
Germany	0.102	0.209
Greece	0.067	0.046
Hungary	0.071	0.021
Ireland	0.298	0.365
Italy	0.094	0.039
Luxembourg	0.183	0.088
Poland	0.049	0.034
Portugal	0.128	0.064
Slovakia	0.050	0.078
Slovenia	0.083	0.045
Spain	0.114	0.080
United Kingdom	0.101	0.118
WHO South East Asia region (*N* = 883)	0.069	0.034
Bangladesh	0.150	0.101
India	0.088	0.016
Nepal	0.060	NA
Sri Lanka	0.041	NA
Thailand	0.068	0.034
WHO Western Pacific region (*N* = 1853)	0.100	0.049
Australia	0.160	0.051
Cambodia	0.118	0.100
China	0.097	0.054
Japan	0.102	0.040
Singapore	0.053	0.049
South Korea	0.122	NA
Vietnam	0.155	0.090
WHO/PAHO Region of the Americas (*N* = 1953)	0.098	0.053
Argentina	0.180	NA
Brazil	0.111	0.052
Canada	0.076	0.047
United States	0.104	0.052
Uruguay	0.030	NA
Ecuador	0.040	0.028

[a]Calculated using data shown in Table S2.

China (continental) and Indonesia are the two countries where average imports of embedded arsenic from all trade partners were highest in the period 2011−2015, with 292 and 174 kg iAs/year, respectively (Figure 1c; see also Table S6 in the Supporting Information). Malaysia and the Philippines, which rank 11th and 13th for rice imports, are ranked third and fourth for imported embedded iAs, respectively, both with 123 kg iAs/year. Vietnam is the main rice trade partner of these four countries and has the highest inorganic arsenic concentration in rice among the largest rice producers (Figure 3). Countries importing rice from Thailand, India, and Pakistan import, by comparison, less embedded iAs. Of the 15 major rice importing countries, the United States imports the lowest embedded iAs, at 57 kg iAs/year (Figure S6 in the Supporting Information), due to most of its rice being imported from Thailand, where the arsenic content is low. Values for all countries are included in the Supporting Information (Table S6). We estimated that the total embedded iAs in the global rice trade is 3466 kg iAs/year. As a material flow, this quantity is very small (e.g., compared with the 22,900 ton iAs/year mineral arsenic traded globally[26]). However, unlike mineral arsenic, arsenic embedded in food has a direct route of exposure to consumers, and in areas where arsenic is not naturally present at high levels, food contributes most to the daily intake of arsenic.[27] The magnitude of the flows provides a gross indication of the hazard, but the health risk due to dietary exposure is additionally affected by local diets (Figure 1b), which means that we need to examine the risk in relation to rice ingestion rates.

Vietnam exports the most iAs embedded in rice (796 ± 168 kg/year) followed by India (788 ± 11 kg/year), Thailand (485 ± 26 kg/year), and the United States (323 ± 18 kg/year) (Table 2). The same group of countries were found to be primarily responsible for the export of embedded MeHg in rice over the same period:[11] India (62 kg MeHg), the United States (23 kg MeHg), Vietnam (18 kg MeHg), and Thailand (17 kg MeHg). In comparative terms, the mass of embedded arsenic is more than 1 order of magnitude higher than that of MeHg.

Embedded Health Risk. The excess lifetime health risk embedded in the rice (EHR) found in local markets is calculated using eq 3, the EHR in imported rice from a specific country is given in eq 4, and the EHR in imported rice from all trade partners is calculated using eq 5. For a given country, the excess lifetime risk due to ingestion of iAs in rice is the weighted sum of eqs 4 and 5, with the weights determined by the fraction of rice that is imported (eq 6). The EHR of a foodstuff varies depending on the place where consumption occurs because risk is a function of the hazard (toxicity and concentration of the toxic substance) and the level of exposure of the population (local diet and anthropometric characteristics). We should make it very clear that the values shown here represent national estimates for the entire population using aggregate indicators of consumption and arsenic concentrations. They do not reflect population characteristics, age groups, and local geochemical conditions regulating the availability and uptake of arsenic species by rice. For the same reason, cooking methods and arsenic concentrations in cooking water are excluded. The aforementioned factors certainly contribute to regional variability in risk estimates that should be considered in more refined future studies. Unfortunately, at present, detailed regional data are scarce, hindering analysis at a global scale.

The values of total EHR from rice in given consumer countries ($TEHR_j$) are highest in the South East Asian and Western Pacific regions, excluding Australia. Bangladesh, with a $TEHR_j$ of 150:100,000, is ranked highest (Table 3). The subsequent rankings are Vietnam (141:100,000), Cambodia (111:100,000), Indonesia (78:100,000), the Philippines (70:100,000), the Republic of Korea (59:100,000), Thailand

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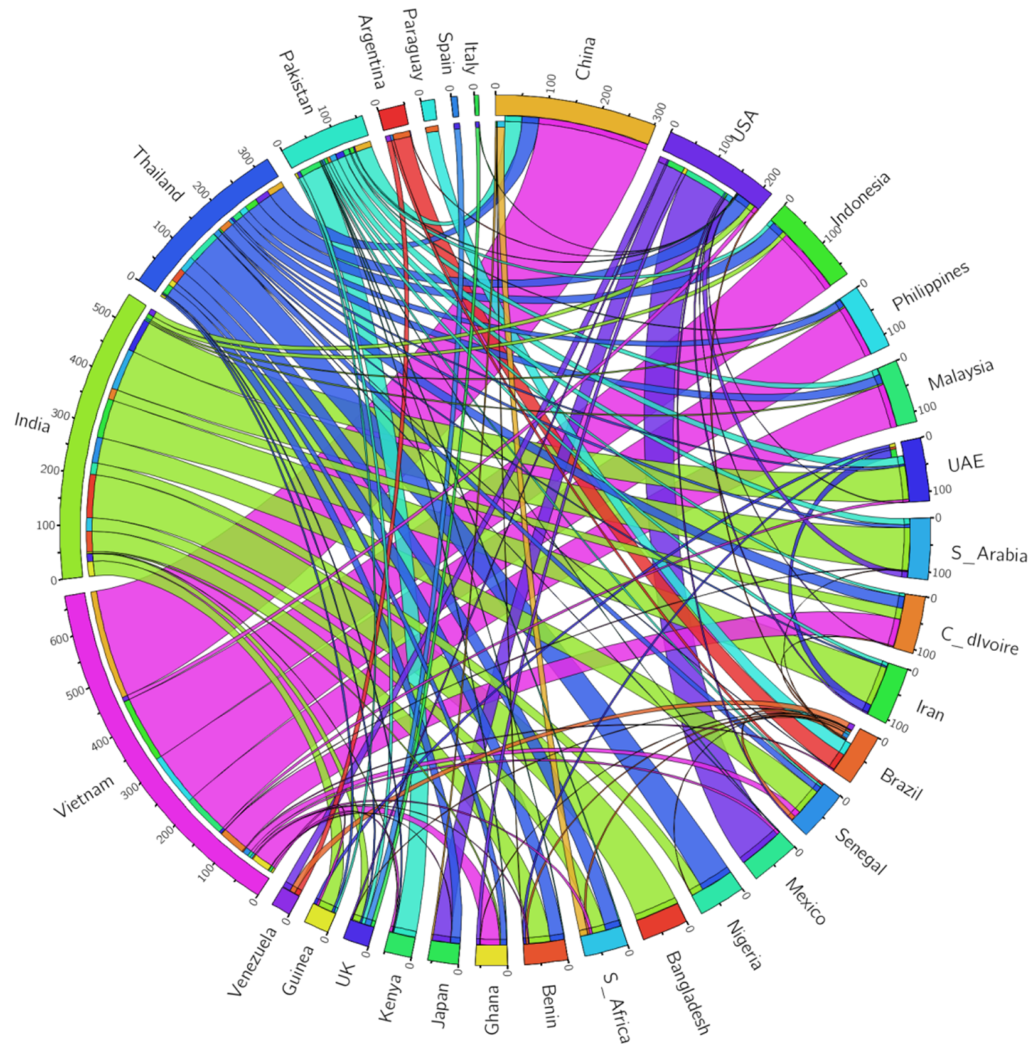

Figure 3. Amount of iAs embedded in internationally traded rice (mean 2011−2015), calculated using eq 1. To improve readability, only flows above 7 kg of embedded iAs are shown. To read this figure, follow a color ribbon from its origin to its destiny. Each ribbon has the color of the exporting country.

(46:100,000), and China (45:100,000) (an exhaustive list is included in the Supporting Information, Table S8). These highest ranked countries are rice producers and import only marginal amounts of rice (low β), and consequently, most of the EHR in these countries are due to the domestic consumption of locally produced rice. The calculated values for total EHR for the highest consumers are in agreement with those estimated in previous studies for Bangladesh,[28] Cambodia,[29] the Republic of Korea,[29] Thailand,[30] China,[31] Japan,[32] and Senegal.[33]

Countries that depend more on imported rice are importing a substantial fraction of their total risk. For instance, the EHR_j* for Kiribati (57:100,000), Solomon Islands (53:100,000), Vanuatu (33:100,000), Senegal (30:100,000), Oman (29:100,000), and the United Arab Emirates (29:100,000) indicate that these countries are the largest importers of embedded risk globally (Table 3). The flows of embedded risks to these countries are mainly from Australia and Vietnam for the first three countries, from Pakistan to Oman, and from India to Senegal (Figure 4). A complete matrix including all countries is included in the Supporting Information, Table S7. Sub-Saharan Africa is the region where imported EHR_j* is the highest, and following Senegal are Côte d'Ivoire (EHR_j* = 21:100,000), Benin (EHR_j* = 22:100,000), and Cabo Verde (22:100,000). The main exporters to Africa are Thailand, India, Pakistan, and Vietnam. Countries in Central and South America have relatively high rice imports but show low EHR_j* because rice imports are predominantly from the United States, where rice has a lower arsenic content. These results point to the fact that the embedded risks are associated with not only the composition of the rice import bundle but also import volumes. Consequently, the risk may be reduced by altering the source of the imported rice (Figure 5). Imports may also contribute to reducing risks when local rice is substituted by imported rice with a lower arsenic content. This occurs in Bangladesh, for example, where rice imports account for about 2% (β = 0.021) of the rice consumed but contribute only about 1% to the increase in risk (2/148) (Table 3). The same reasoning is valid for other rice producing countries where importing rice with low arsenic contents reduces the risk (see Figure 5). International trade can even out both rice and EHR surpluses and deficits between countries.

These results are in agreement with those of Liu et al.,[11] who showed that international rice trade aggravated MeHg exposure in Africa, Central Asia, East Asia, and Europe by 62, 98, 3.4, and 42%, respectively.

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Table 2. Exported iAs Embedded in Internationally Traded Rice (Average ± SD over the Period 2011−2015)

country	embedded iAs in traded rice (kg/year)
Vietnam	796 ± 168
India	788 ± 11
Thailand	485 ± 26
United States	323 ± 18
Pakistan	299 ± 6
Brazil	96 ± 6
Argentina	81 ± 6
Italy	67 ± 4
China, mainland	50 ± 21
Spain	44 ± 4
Australia	43 ± 4
Guyana	40 ± 4
Cambodia	37 ± 4
United Arab Emirates	34 ± 4
Paraguay	32 ± 4
Myanmar	31 ± 6
Uruguay	22 ± 44
Netherlands	20 ± 5
Belgium	16 ± 7
Russian Federation	13 ± 5
Germany	10 ± 6
Egypt	8 ± 3
Portugal	8 ± 1

Low income countries where rice is a staple food (group C in Figure 6; see the Supporting Information for detailed statistical data) have significantly higher TEHR ($F(2, 115) = 71.4$; $p < 0.05$) than the rest of the global population (groups A and B). However, GDP alone does not seem to be the most important factor affecting health risk globally, as indicated by non-significant correlations between the two variables (using log(GDP)) (see detailed analysis in the Supporting Information). This is contrary to what was found with respect to risks due to embedded MeHg in rice, where a significant negative correlation, though with a very small $R^2 = 0.11$, was found with log(GDP).[11] In both our study and that of Liu et al.,[11] local diet plays a major role in determining the amount of toxins ingested and the associated health risks.

It is known that local diets may be subject to slow changes due to increasing purchasing power. Countries where rice is a staple food have seen their per capita rice consumption decrease due to dietary substitution with meat. At the same time, rice has increased as a component of the diet in some countries (e.g., African countries), supplementing the basic nutrient supply (Figure S5 in the Supporting Information). In Namibia, for example, per capita rice consumption grew 10-fold over the last 30 years, and in Ethiopia, Kenya, Rwanda, Benin, and Zimbabwe, the consumption tripled in the same period. Given the demonstrated relationship between rice consumption and exposure to arsenic, the health risks in these countries have grown over the same period.

Climate change impacts are expected to reduce most crop yields between 5 and 10% per °C of local warming or 7 and 15% per °C of global warming.[34] Compared to maize and wheat, rice will be least affected if at all, putting more pressure on rice production and trade, increasing the flows of embedded iAs and of the traded embedded health risks for importing countries. Methods of reducing the absorption of arsenic by rice, including agricultural production under aerobic (intermittent) conditions and the selection of arsenic-tolerant rice varieties with low uptake,[35] may be complemented with well-balanced apportioning of rice sources in supply market composites. This would reduce population dietary health risks. Studies such as the present one and that of Liu et al.[11] facilitate policy design based on health gains, rather than on safe levels of the risk factor alone.

Table 3. Embedded Health Risk (EHR ± SD) in Rice (1:100,000) for Countries with the Highest Risks[a]

country	EHR for local rice, $A = (1 - \beta)$ EHR_{jj}	imported rice, $B = \beta EHR_{ij}$	$A + B = TEHR_j$*	fraction of imported rice, β
Bangladesh	148 ± 102	2 ± 3	150 ± 30	$0.021 \pm 1 \times 10^{-4}$
Vietnam	141 ± 4	0 ± 0	141 ± 4	$0.015 \pm 1 \times 10^{-4}$
Cambodia	110 ± 93	1 ± 4	111 ± 27	$0.007 \pm 1 \times 10^{-4}$
Indonesia	76 ± 36	2 ± 8	78 ± 36	$0.022 \pm 2 \times 10^{-4}$
Philippines	65 ± 37	5 ± 6	70 ± 37	0.052 ± 0.001
Republic of Korea	57 ± 36	4 ± 0	59 ± 36	0.070 ± 0.001
Kiribati	0	57 ± 14	57 ± 14	1.000
Solomon Islands	0	53 ± 16	53 ± 16	1.000
Thailand	46 ± 23	0	46 ± 23	$0.001 \pm 2 \times 10^{-5}$
China, mainland	44 ± 25	1 ± 6	45 ± 25	$0.012 \pm 5 \times 10^{-5}$
Guyana	44 ± 24	0	44 ± 24	$0.001 \pm 1 \times 10^{-4}$
Malaysia	23 ± 16	17 ± 4	41 ± 16	0.290 ± 0.004
Panama	27 ± 20	11 ± 2	38 ± 20	0.280 ± 0.004
India	36 ± 7	0	36 ± 7	$0.001 \pm 5 \times 10^{-5}$
Japan	34 ± 14	2 ± 4	36 ± 14	0.060 ± 0.001
Fiji	6 ± 14	29 ± 2	35 ± 14	0.760 ± 0.031
Senegal	4 ± 15	30 ± 4	34 ± 15	0.751 ± 0.003
Vanuatu	0	33 ± 4	33 ± 4	1.000
Nepal	28 ± 0	4 ± 16	32 ± 0	0.095 ± 0.001
Oman	0	29 ± 2	29 ± 2	1.000
United Arab Emirates	0	29 ± 2	29 ± 2	1.000
Sri Lanka	25 ± 0	3 ± 4	28 ± 0	$0.058 \pm 4 \times 10^{-4}$

[a]Ranked by EHR_j.

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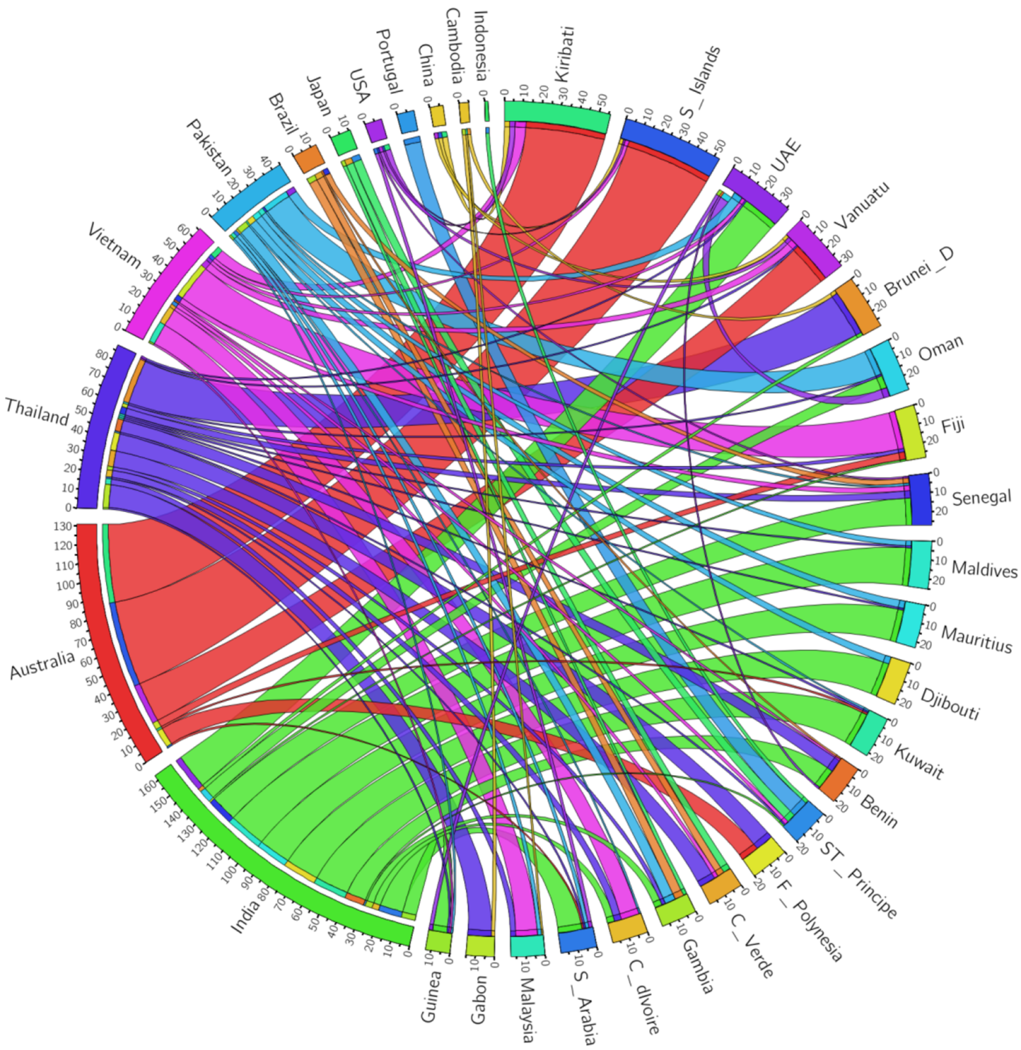

Figure 4. Amount of embedded health risk in internationally traded rice (mean 2011−2015). To read this figure, follow a color ribbon from its origin to its destiny. Each ribbon has the color of the exporting country.

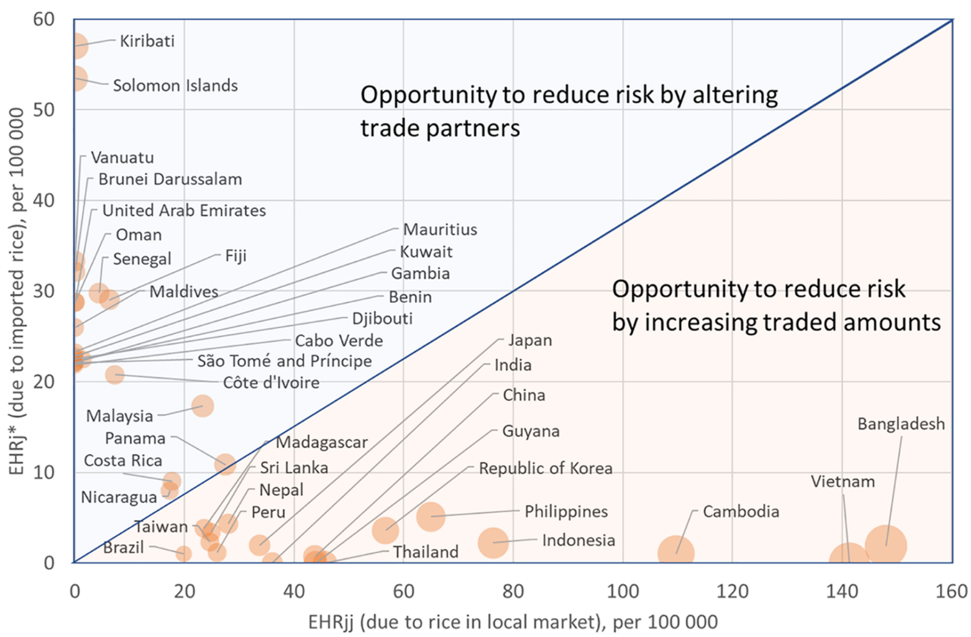

Figure 5. Comparison of embedded health risks due to imported rice and rice in the local market.

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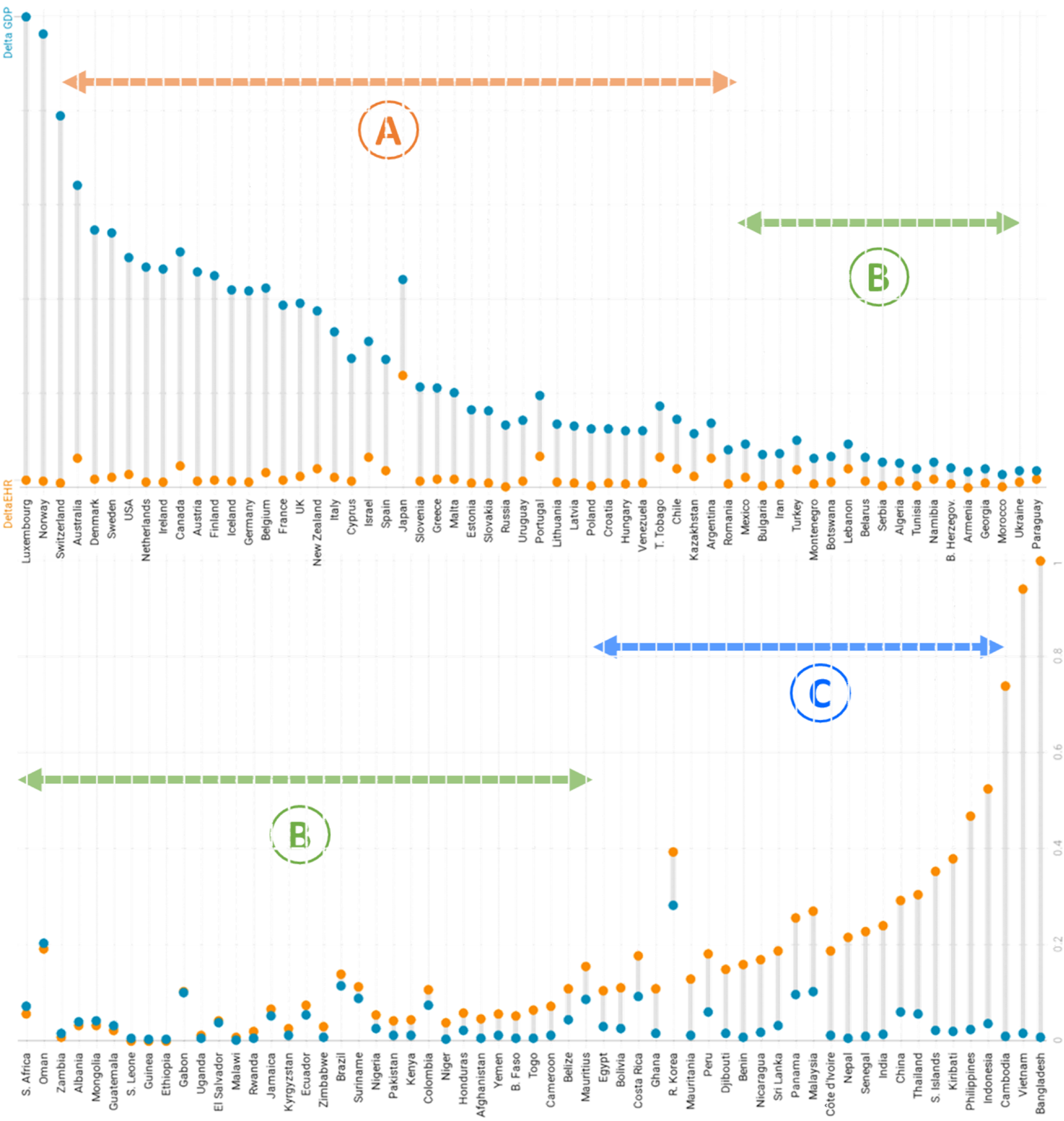

Figure 6. Relationship between GDP and EHR_j*. Values were scaled by dividing the maxima. The extremes for each variable show how a country stands in comparison to its peers. Three groups of countries are indicated: (A) high income and low embedded risk; (B) low to intermediate income and low embedded risk; (C) low to intermediate income and high embedded risk.

■ ASSOCIATED CONTENT

Supporting Information

The Supporting Information is available free of charge at https://pubs.acs.org/doi/10.1021/acs.est.1c08238.

Traded amounts of white rice in the period 1986−2015; rice imported per region over recent decades; food supply by region; rice supply per capita per region over recent decades; change in rice per capita supply; major iAs importers (together responsible for 80% of the embedded iAs trade); relationship between national GDP ($ corrected for purchasing power), amount of rice in the diet, and EHR; rice imports averaged for the period 2011−2015; rice exports averaged for the period 2011−2015; concentration of inorganic arsenic in white rice reported for different countries and regions (raw and wet weight); concentrations of inorganic arsenic per region and country; amount of embedded iAs in rice traded in the period 2003−2013 (mean values); per capita rice supply; exported iAs embedded in internationally traded rice (mean in the period 2011−2015);

embedded health risk (EHR) in rice imports by country, for all its trade partners; embedded health risk (EHR) in rice (1:100,000); comparison of mean iAs in different world regions; and relationship between GDP and TEHR (PDF)

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Notes

The authors declare no competing financial interest.

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