



**Universidade
do Algarve**

**Faculdade de 2023
Ciências e
Tecnologia**



EMBEDDED HEALTH RISKS

SEMINÁRIO

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Sumário pormenorizado do seminário apresentado
no âmbito de Provas Públicas de Agregação
na Universidade do Algarve:

Embedded Health Risks

Luís Miguel Nunes

Faro, 4/7/2023

O presente documento constitui o sumário pormenorizado do seminário apresentado no âmbito de Provas Públicas de Agregação na Universidade do Algarve, de acordo com o estabelecido no artigo 5º, alínea b) do Decreto-Lei (DL) nº 239/2007, de 19 de junho.

O texto é apresentado em língua inglesa, por provir de um texto escrito nessa língua, e por aprovação Reitoral de 17 de novembro de 2022.

Luís Miguel Nunes

Faro, 04/07/2023

EMBEDDED HEALTH RISK FROM ARSENIC IN GLOBALLY TRADED RICE

SUMMARY

In this seminar I present a method for assessing the health risks associated with toxics present in globally traded food items which I developed in collaboration with colleagues from the Chinese Academy of Sciences (CAS), the North Ireland Institute for Global Food Security, and the Australian Centre for Global Food and Resources. The method was initially proposed by me as part of the sabbatical topic for my visit to CAS in Ningbo in 2017. Fruitful discussions with the other authors helped to build a more complete picture of the embedded health risks.

The text included here is an adapted version of the article “Embedded Health Risk from Arsenic in Globally Traded Rice”, written by me, Li Gang, Wei-Qiang Chen, Andrew Meharg, Patrick O'Connor, and Young-Guan Zhu, published in in 2022 in Environmental Science and Technology (<https://doi.org/10.1021/acs.est.1c08238>). The concept of embedded health risk in global trade, despite its novelty, has already called some attention (e.g., doi.org/10.1016/j.envpol.2022.120388).

International food trade is fundamental to global food security, but is often associated with negative environmental impacts in the producing country (spillovers). We proposed a method to quantify the negative spillover in the importing country due to the inflows of toxic substances and embedded increased lifetime cancer risks (HER) at a global scale.

We illustrated with inorganic arsenic in rice due to the importance of this cereal as staple food in many regions, and the well-known ability of rice to accumulate arsenic.

Estimates for the flows of embedded inorganic arsenic and health risks were made for a total of 153 countries.

Considering the results, we discussed the potential policy options for reducing population dietary health risks by well-balanced apportioning of rice sources, targeting policy design solutions based on health gains, rather than on safe levels of the risk factor alone, as set up in international regulations.

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 (Lin et al., 2014a)(Sun et al., 2018a), and resource depletion (Dalin et al., 2017). The direct impacts of global trade on human nutrition are potentially positive (Wood et al., 2018), however, changing global diets is strongly linked to global challenges for environmental sustainability and human health (Tilman and Clark, 2014). The redistribution of food through global trade is resulting in global displacement of the embedded environmental and social impacts of food supply chains (Tian et al., 2018; Wiedmann and Lenzen, 2018) with negative consequences primarily (Zhang et al., 2017), but not exclusively (Sun et al., 2018a), borne by exporting and spillover countries. Progress towards 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 (2013).

Embedded health risks (EHR) due to the transport and consumption of hazardous substances away from the point of production may be substantial (Ng and Goetz, 2017). 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 (2013).

This study estimated the flows of the toxic incorporated in the global foodstuff trade, and the associated EHR for importing countries. The health endpoint considered here is the increased lifetime cancer prevalence. The motivation for 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 appendix).

As for rice, it is staple for more than half of the world population, is widely traded on the global market, and can contain contaminants such as mercury (Liu et al., 2019) and arsenic (FAO/WHO, 2011) 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 (Lin et al., 2014b; Sun et al., 2018b). For example, Liu et al (2013) 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, Southeast Asia and Oceania.

We built an embedded arsenic mass and global trade health risk modeling detailing flows between countries. The database on arsenic concentration in rice includes over 23,000 records. Diet and trade data were retrieved from the Food and Agriculture Organization (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.

RICE IN THE GLOBAL TRADE MARKET

Rice Imports and Global Trade

The amount of rice being traded worldwide has been rising steadily over the last four decades (FAO, 2020), at an average rate of about 0.8 Mton year⁻¹. I.e., at a rate about ten-fold that of the growth of the human population in the same period (Figure S1 in appendix). Countries in North America, East Asia and the Pacific, Europe & Central Asia, the Middle East and North Africa, and Sub-Saharan Africa are the main regions responsible for this extraordinary increase. The observed growth has, however, different underlying origins: In North America, South & 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 ten-fold over a twenty-year period (Figures S2 – S5). This has led to a very unbalanced rice trade in the Middle East and North Africa, and Sub-Saharan Africa, which together spent over USD 96x10⁹ 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 (FAO, 2014). The largest producing countries are also the largest consumers.

Data on amounts of rice production and imports per country for each of that country's trade partners was compiled in February 2020 from data of the Food and Agriculture Organization of the United Nations' 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 Supplementary Material), means of the last five 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 (FAO, 2018).

In the period 2011-2015, the fifteen major importing countries were responsible for over 50% of the trade in rice (Figure 1 and Table S1). 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 of America (Figure 1a). This pattern closely follows rice dietary consumption in these countries (Figure 1b). Major rice exporters (Table S2) include India, Thailand, Vietnam, USA, Pakistan, Italy, Brazil, Uruguay, China, Argentina, Spain, Myanmar, Guyana, and Paraguay. The USA and China are both large importers and exporters and act as global rice distributors (Figure 2).

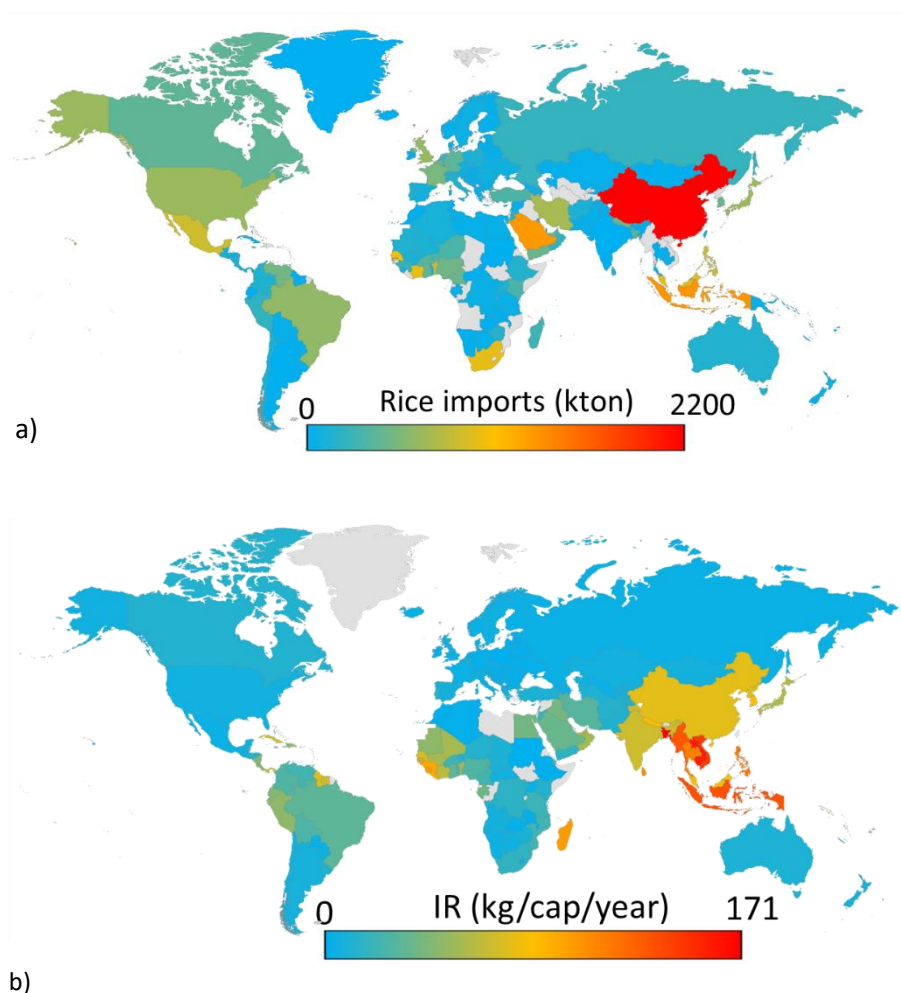


Figure 1. Global distribution of the rice trade: (a) imports of rice; (b) rice ingestion rates. All data are annual averages for the period 2011-2015.

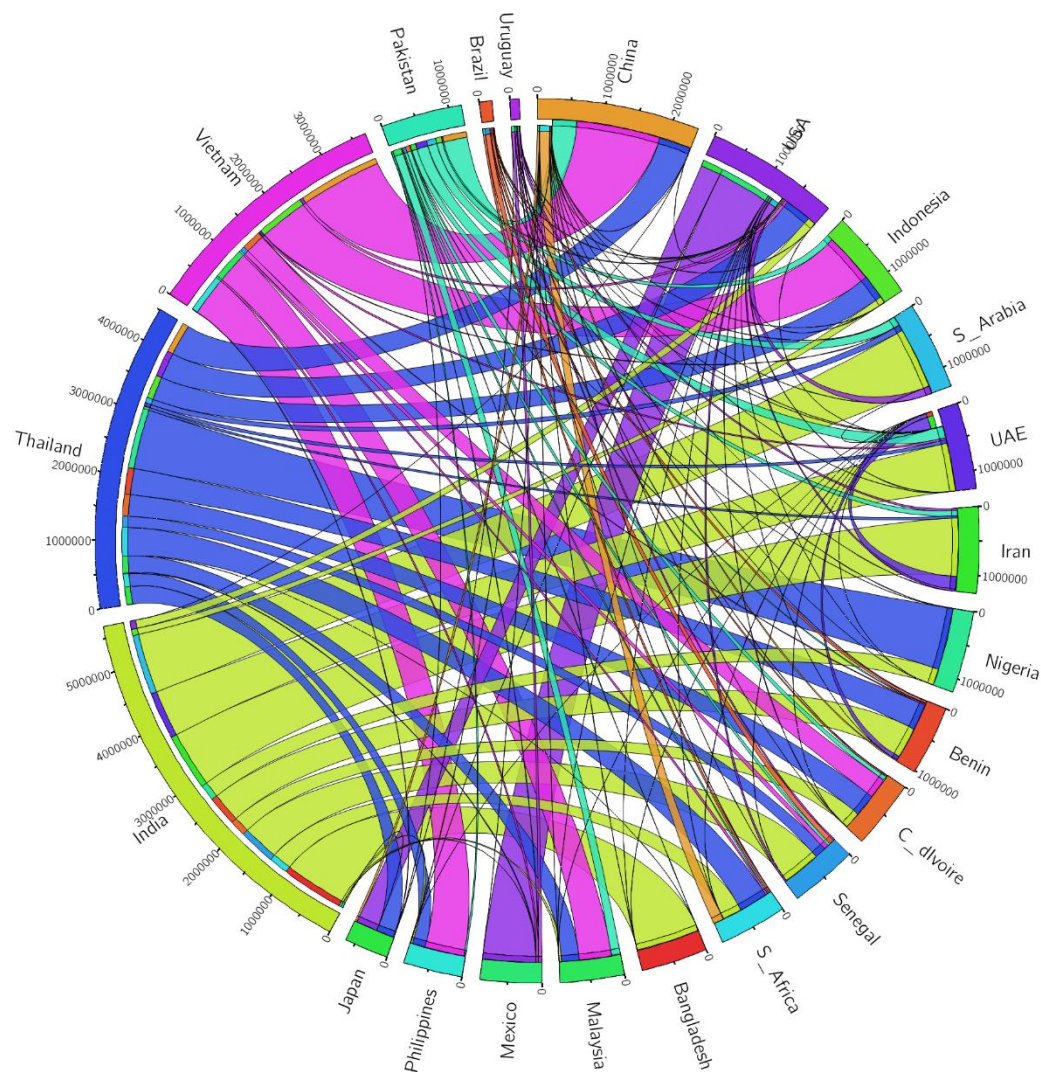


Figure 2. The fifteen largest rice importers and their trade partners. To read this figure, follow a colour ribbon from its origin to its destiny. Each ribbon has the color of the exporting country.

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). 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 decline in average tariffs in Central America from 45% to around 6% by 2000 (Thow and Hawkes, 2009)(Figure S4). Costa Rica registered the highest rate of import growth. Imports of rice into the country increased more than nine-fold in the period; four times more than the growth of wheat and thirteen times that of maize (USDA, 2020). 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).

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).

International trade can 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 (Wood et al., 2018).

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 (FAO, 1991). 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 (Kabat, 2020). For the purposes of the global analysis made here this definition is sufficient. The value of CSF was considered equal to $1.5 \text{ (mg/kd.day)}^{-1}$ (USEPA, 1995).

Concentrations of inorganic arsenic in rice

Concentrations of inorganic arsenic (iAs) in rice are highly variable across the producing regions of the globe, but also within these regions (Meharg et al., 2009). Results from analysis of the dataset compiled (Table S3) 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 to those in other regions ($F(5, 23016) = 8.01, p < 0.05$). 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.

Data on iAs in raw white rice shown here compiled from i) international journals (see appendix); ii) data published by the United States Food and Drug Administration (USFDA, 2013); iii) GEMS/Food contaminants database maintained by the World Health Organization (WHO, 2018). Values when reported in dry weight were converted to wet weight by considering an average water content in the rice of 10% (Williams et al., 2006). 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=22010), which is 0.627. This ratio is within the range reported in the literature (Meharg et al., 2007).

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, $0.042 \pm 0.035 \text{ mg/kg}$ (N= 9); Eastern Mediterranean, $0.083 \pm 0.023 \text{ mg/kg}$ (N= 12); European Region, $0.101 \pm 0.167 \text{ mg/kg}$ (N= 18312); South-East Asia,

0.069±0.034 mg/kg (N= 833); Western Pacific, 0.099±0.049 mg/kg (N= 1853); Region of the Americas, 0.098±0.053 mg/kg (N= 1953).

Table 1. Concentrations of inorganic arsenic per region and country. Calculated using data shown in Table S2.

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 EuropeanRegion (N= 18312)	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 of America	0.104	0.052
Uruguay	0.030	NA
Ecuador	0.040	0.028

MATERIALS AND METHODS

Model

The method in this study follows a stepped reasoning: 1) in a given country, the rice diet is a composite of imported and locally-produced rice (if any); 2) imported rice comes from multiple trade partner countries, in varied volumes; 3) the concentration of inorganic arsenic in rice is variable according to the place of production; 4) the presence of arsenic in rice is a health hazard; 5) the level of exposure to inorganic arsenic (iAs) varies with the amount of rice consumed in local diets; ; 6) the expected lifetime risk from iAs exposure can be estimated per country; 7) 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

$$IMPAs_{jk} = IMP_{jk} iAs_k 10^{-6} \quad (1)$$

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,

$$IMPAs_j = \sum_{k=1}^n ET_{jk} \quad (2)$$

The excess lifetime health risk embedded in local rice is

$$EHR_{jj} = IR_j iAs_j CSF / BW \quad (3)$$

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 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

$$EHR_{jk} = IR_j iAs_k CSF / BW \quad (4)$$

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

$$EHR_j^* = \sum_{k=1}^n \beta_{jk} EHR_{jk} \quad (5)$$

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

$$TEHR_j = \alpha EHR_j + \beta EHR_j^* \quad (6)$$

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 ($\sum \beta_{jk}$).

RESULTS AND DISCUSSION

iAs embedded in internationally traded rice

The total amount of iAs imported by a country from a specific trade partner is calculated using equation (1) and the amounts imported from all that country's trade partners is given by equation (2).

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 kg iAs/year and 174 kg iAs/year, respectively (

Figure 3a; see also Table S6). Malaysia and the Philippines, which rank 11th and 13th for rice imports, are ranked 3rd and 4th for imported embedded iAs, 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 amongst the largest rice producers (

Figure 4). Countries importing rice from Thailand, India, and Pakistan import, by comparison, less embedded iAs. Of the fifteen major rice importing countries, the USA imports the lowest embedded iAs, at 57 kg iAs/year (Figure S6), due most of its rice being imported from Thailand, where arsenic content is low. Values for all countries are included in the 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 22900 ton iAs/year of mineral arsenic traded globally (USGS, 2020). 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 (WHO, 2019). 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 1 b), 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 USA (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 (Liu et al., 2019): India (62 kg MeHg); USA (23 kgMeHg), Vietnam (18 kgMeHg), and Thailand (17 kgMeHg). In comparative terms, the mass of embedded arsenic is more than one order of magnitude higher than that of MeHg.

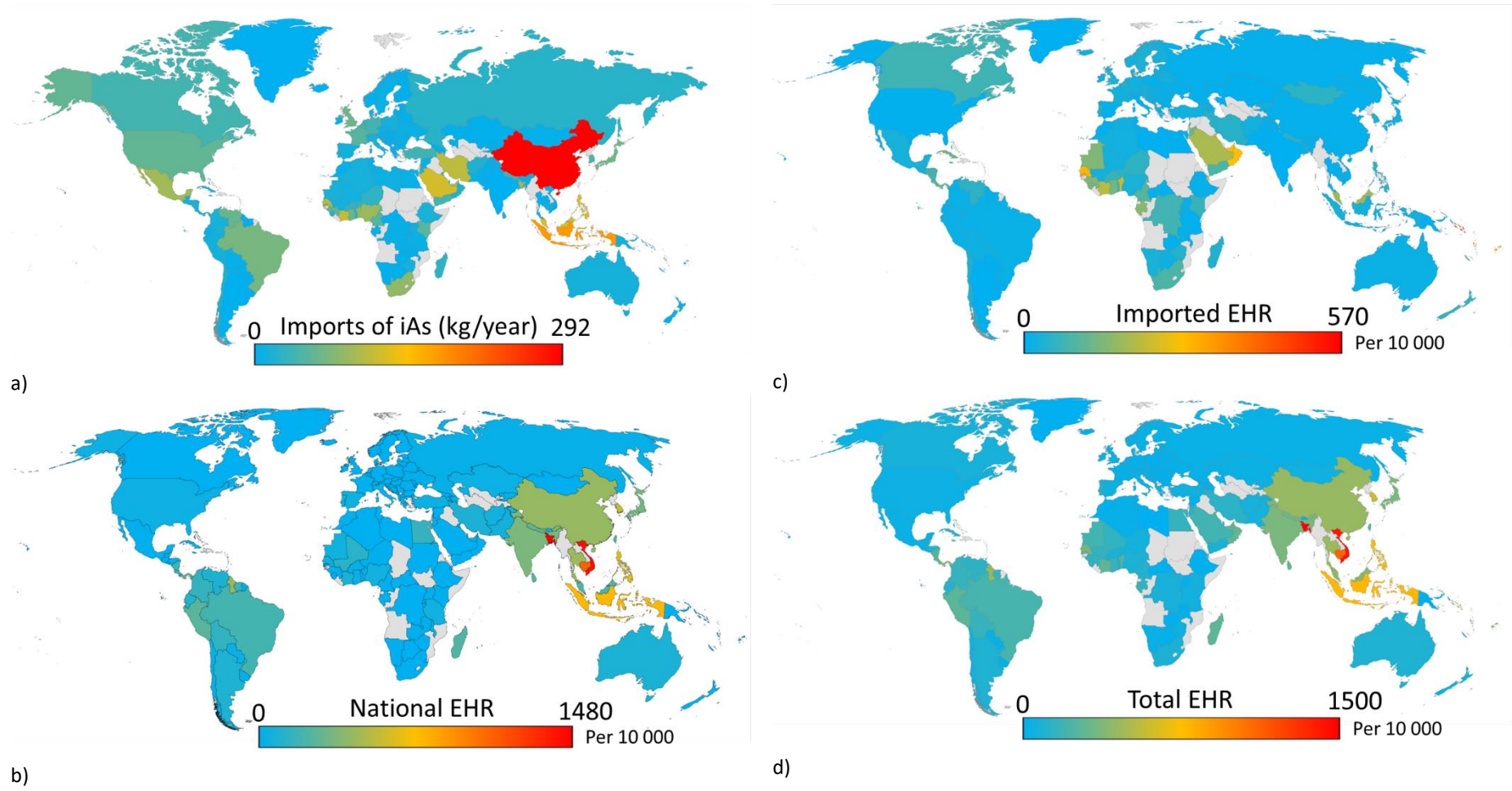


Figure 3. Global distribution of embedded iAs, and embedded health risk (a) embedded iAs in traded rice; (b) EHR due to the presence of iAs in rice in national markets; (c) imported EHR; (d) total EHR.

Table 2. Exported iAs embedded in internationally traded rice (average \pm st. deviation over the period 2011-2015)

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

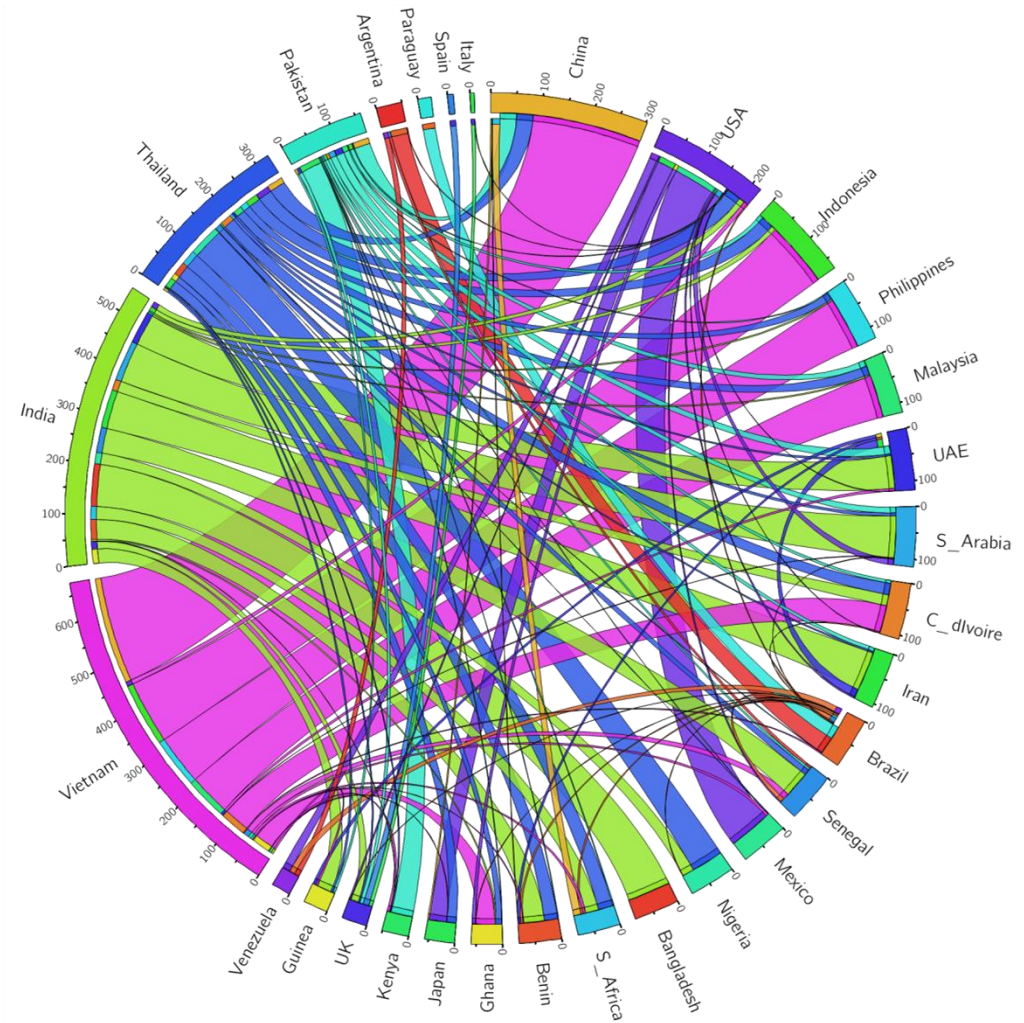


Figure 4. Amount of iAs embedded in internationally traded rice (mean 2011-2015), calculated using equation (1). To improve readability only flows above 7 kg of embedded iAs are shown. To read this figure, follow a color ribbon from its origin to its destiny. Each ribbon has the color of the exporting country.

Embedded health risk

The excess lifetime health risk embedded in the rice (EHR) found in local markets is calculated using equation (3); the EHR in imported rice from a specific country is given by equation (4); and the EHR in imported rice from all trade partners is calculated by equation (5). For a given country the excess lifetime risk due to ingestion of iAs in rice is the weighted sum of (4) and (5), with the weights determined by the fraction of rice that is imported (equation (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 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 ($TEHR_i$) are highest in the South-East Asian and Western Pacific regions, excluding Australia. Bangladesh, with a $TEHR_i$ of 150:100 000 is ranked highest (Table 3). The subsequent ranking is 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 (46:100 000), and China (45:100 000) (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 is due to 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 (Ahmed et al., 2016), Cambodia (Wang et al., 2013), Republic of Korea (Wang et al., 2013), Thailand (Hensawang and Chanpiwat, 2017), China (Li et al., 2011), Japan (Oguri and Yoshinaga, 2014), and Senegal (Ndong et al., 2018).

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 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 5). A complete matrix including all countries is included in Table S7. Sub-Saharan Africa is the region where imported EHR_j^* are the highest, following Senegal is 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 USA, where rice has lower arsenic content. These results point to the fact that the embedded risks are associated with the composition of the rice import bundle and not only import volumes. Consequently, the risk may be reduced by altering the source of the imported rice (Figure 6). Imports may also contribute to reducing risks when local rice is substituted by imported rice with lower arsenic content. This occurs in Bangladesh, for example, where rice imports account for about 2% ($\beta = 0.021$) 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 (Figure 6). 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. (2019), 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.

Low income countries where rice is a staple food (Group C in Figure 7) 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 $\log(\text{GDP})$) (see appendix). 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 $\log(\text{GDP})$ (Liu et al., 2019). In both our study and that of Liu et al. (2019), 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 Namibia, for example, per capita rice consumption grew ten-fold over the last thirty 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.

Table 3. Embedded health risk ($\text{EHR} \pm \text{st.dev}$) in rice (1: 100 000) for countries with the highest risks. Ranked by EHR_j .

Country	EHR for local rice, $A = (1-\beta) \text{EHR}_{ij}$	Imported rice, $B = \beta \text{EHR}_{ij}$	$A+B = \text{TEHR}_j^*$	Fraction of imported rice, β
Bangladesh	148±102	2±3	150±30	0.021±1×10 ⁻⁴
Vietnam	141±4	0±0	141±4	0.015±1×10 ⁻⁴
Cambodia	110±93	1±4	111±27	0.007±1×10 ⁻⁴
Indonesia	76±36	2±8	78±36	0.022±2×10 ⁻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±2×10 ⁻⁵
China, mainland	44±25	1±6	45±25	0.012±5×10 ⁻⁵
Guyana	44±24	0	44±24	0.001±1×10 ⁻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±5×10 ⁻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±4×10 ⁻⁴

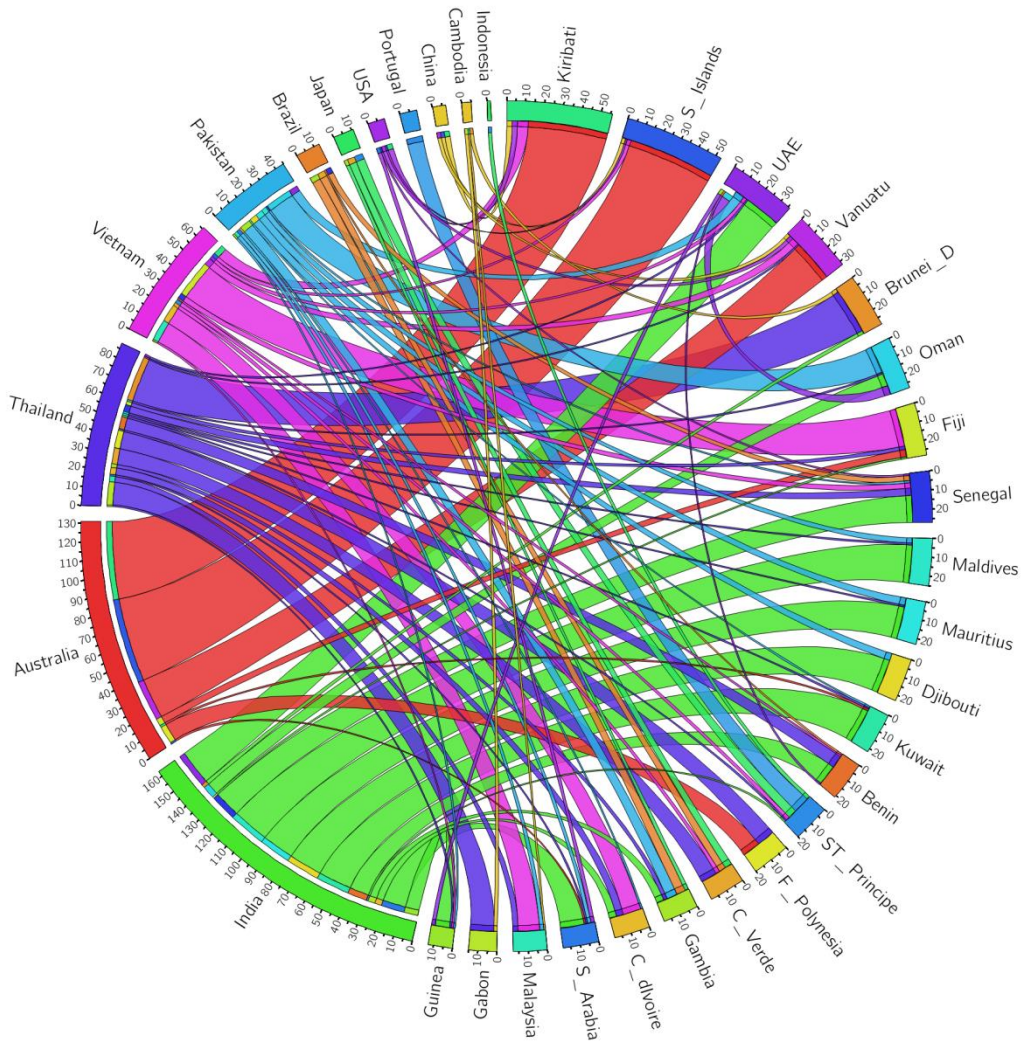


Figure 5. Amount of embedded health risk in internationally traded rice (mean 2011-2015). To read this figure, follow a color ribbon from its origin to its destiny. Each ribbon has the color of the exporting country.

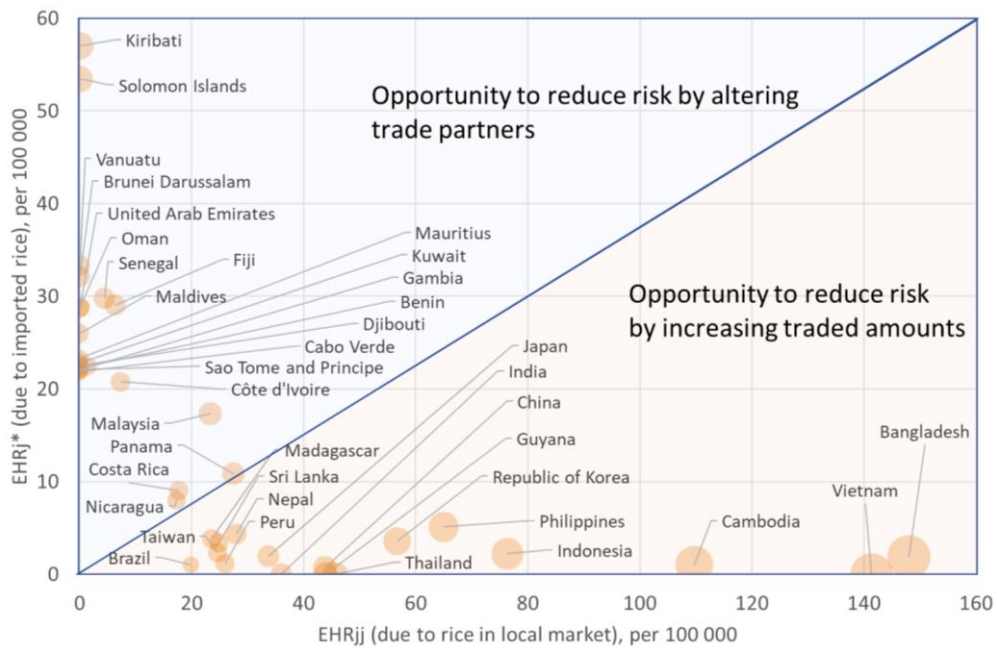


Figure 6. Comparison of embedded health risks due to imported rice and rice in the local market.

Climate change impacts are expected to reduce most crop yields by between 5-10% per °C of local warming, or 7-15% per °C of global warming (NRC, 2011). 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 to reduce the absorption of arsenic by rice, including agricultural production under aerobic (intermittent) conditions and the selection of arsenic-tolerant rice varieties with low uptake (FAO/WHO, 2017), 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. (2019) facilitate policy design based on health gains, rather than on safe levels of the risk factor alone.

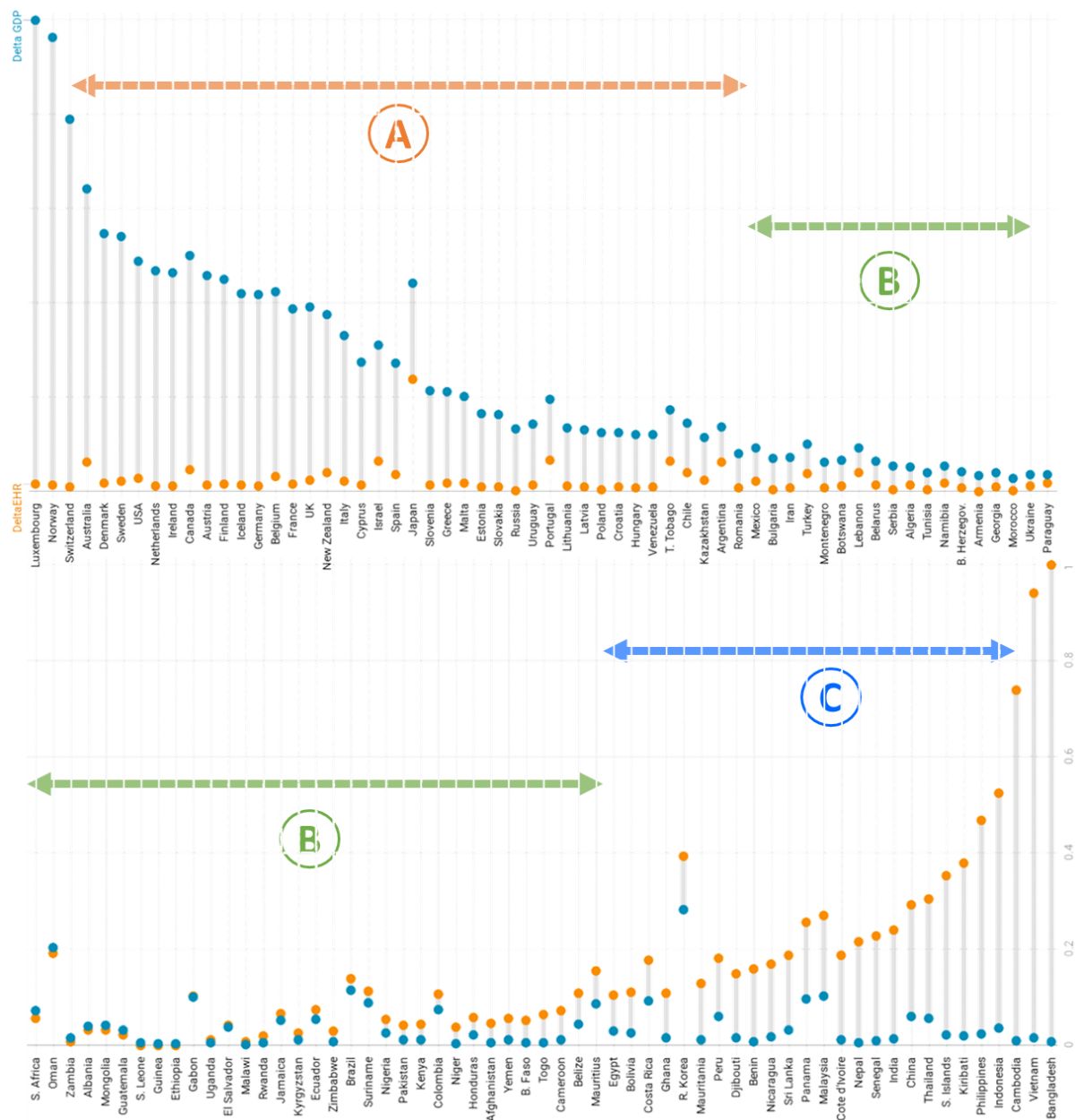


Figure 7. Relationship between GDP and EHRj*. Values were scaled by dividing by the maxima. The extremes for each variable show how a country stands in comparison to its peers. Three groups of countries are indicated: A) high income, low embedded risk; B) low to intermediate income and low embedded risk; C) low to intermediate income and high embedded risk.

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Appendix

Some remarks about uncertainty in our estimates

Uncertainty about food-associated risk estimates is high ¹ due to a lack of complete knowledge concerning the underlying mechanisms of action observed in experimental and epidemiological studies². For consumer groups (or general populations) with higher exposure levels, arsenic exposure represents a health risk³. The European Union EFSA Panel on Contaminants in the Food Chain ³ found that national inorganic arsenic exposures from food and water varied by a factor of 3 across 19 European countries. Uncertainties about the geography of exposure and mechanism of action make it difficult to set blanket threshold levels. In 2001, the FAO/WHO's Codex Committee on Contaminants in Food withdrew, without replacing, the previous provisional tolerable weekly intake (PTWI) for inorganic arsenic in (iAs) rice of 15 μ g/kg b.w.⁴. The maximum level of 0.2 mg/kg of iAs in polished rice established provisionally by the Committee in 2017 is scheduled to be reviewed in 2020.

Uncertainty is incorporated in assessments made by national and international food safety agencies and frameworks for identifying and ranking food-related domestic risks have been proposed. Newsome et al.⁵ introduced a bottom-up risk-ranking prototype for comparison of microbiological and chemical hazards, incorporating expert opinion/insight, resulting in a semi-quantitative measure. Hammerling et al.⁶ proposed the Guided Toxicology Health Impact scoring (GTHI), where the ranking problem was approached by introducing three impact attributes at the aggregation level, i.e. severity, duration, and proportion of population affected. This model has been little applied and more recently, the U.S. Food and Drug Administration launched a Web-based quantitative risk assessment system (the FDA-iRISK,)⁷. Users of the FDA-iRISK tool are able to assess, compare, and rank the risks posed by multiple food-hazard pairs at all stages of the food supply system, from primary production, through manufacturing and processing, to retail distribution and, ultimately, to the consumer. However, none of these frameworks facilitate tracing the movement of contaminants in foodstuffs through international trade and fall short of supporting risk management and communication of risks from contaminants in global food supply chains.

Details about the origin of the data

Data on iAs in raw white rice were compiled from i) international journals (list provided in Supplementary Material); ii) data published by the United States Food and Drug Administration⁸; iii) GEMS/Food contaminants database maintained by the World Health Organization⁹. Values when reported in dry weight were converted to wet weight by considering an average water content in the rice of 10%¹⁰. As only total arsenic (tAs) concentrations were reported for some of the countries, values reported as 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), equal to 0.627. This ratio is within the range reported in literature¹¹.

The exhaustive dataset is formed from a total of 23 022 records for 41 countries, including all the largest rice producers. For the remaining 112 countries the arsenic concentrations were estimated from the mean iAs computed from the exhaustive dataset for the appropriate WHO Regions, namely: the African Region, 0.042±0.035 mg/kg (N= 9); the Eastern Mediterranean Region, 0.083±0.023 mg/kg (N= 12); the European Region, 0.101±0.167 mg/kg (N= 18312);

South-East Asia, 0.069 ± 0.034 mg/kg (N= 833); the Western Pacific, 0.099 ± 0.049 mg/kg (N= 1853); the Americas, 0.098 ± 0.053 mg/kg (N= 1953).

Data on amounts of rice imported per country for each of its trade partners was retrieved in February 2020 from the Food and Agriculture Organization of the United Nations' FAOSTAT web page (<http://www.fao.org/faostat>) for the entire available period (1986-2013). Given that the amounts of rice traded globally have increased throughout the period (Figure S1), means of the last five years were used in this study to best reflect the contemporary situation. Rice production (paddy) data was also retrieved from the same FAO's database, and converted to milled equivalent by multiplying by a factor of 0.66¹².

The values of rice consumption were obtained from WHO FAOSTAT Food Balance Sheets, as food supply quantity (kg/capita/year). The value of CSF was considered equal to 1.5 (mg/kd.day)⁻¹¹³.

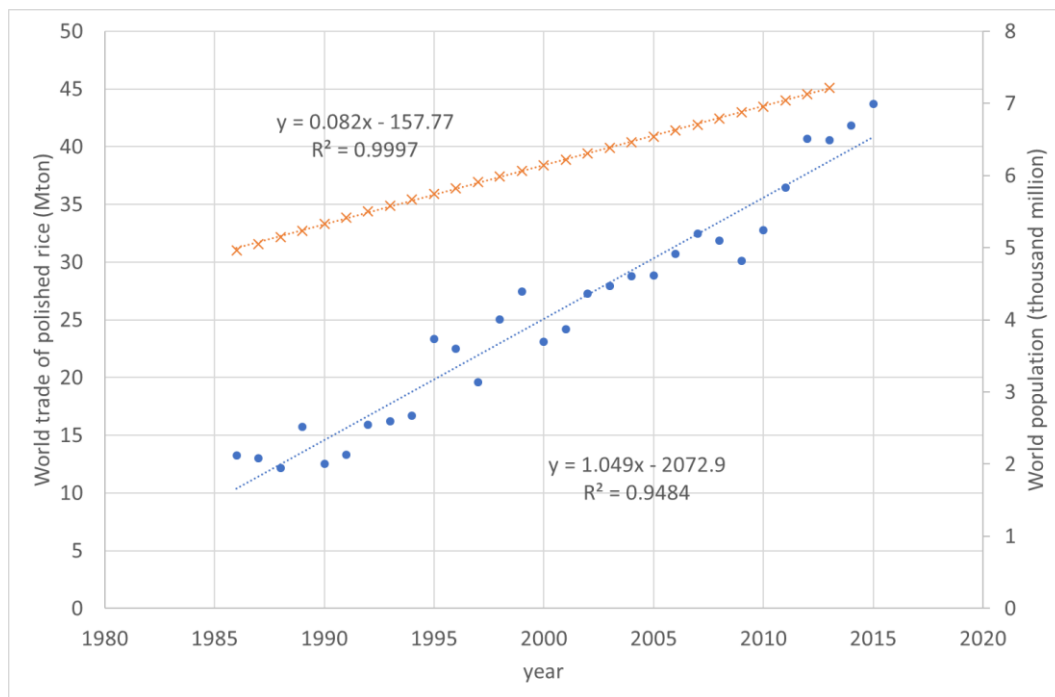


Figure S1. Traded amounts of white rice in the period 1986-2015. Dots show rice trade and crosses show population. (Data retrieved from WHO FAOSTAT database: <http://www.fao.org/faostat>)

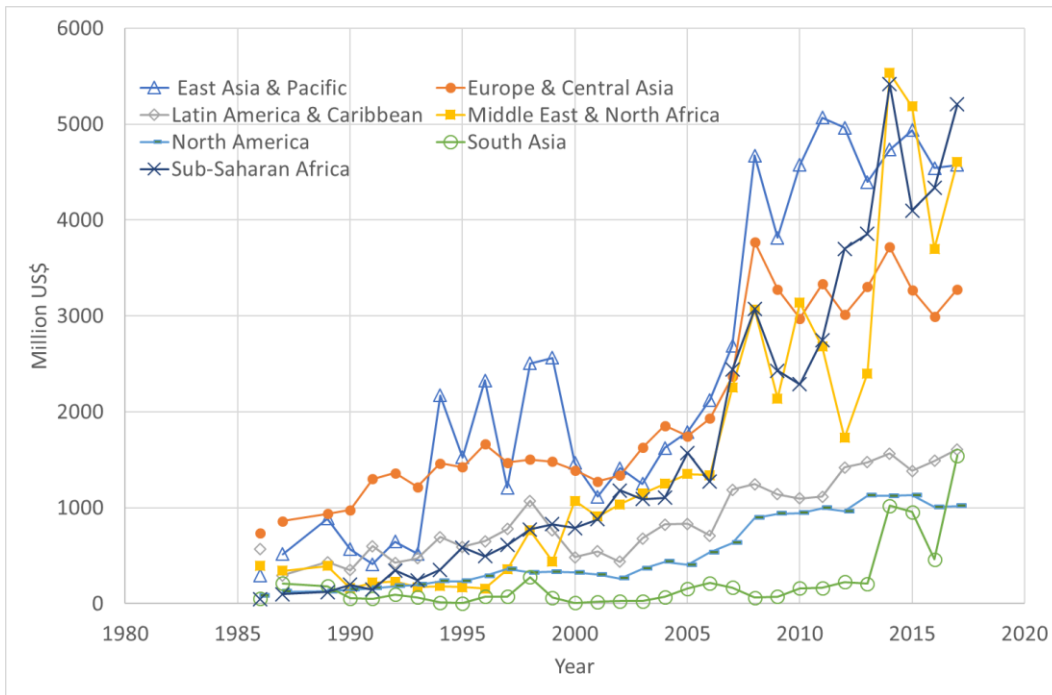
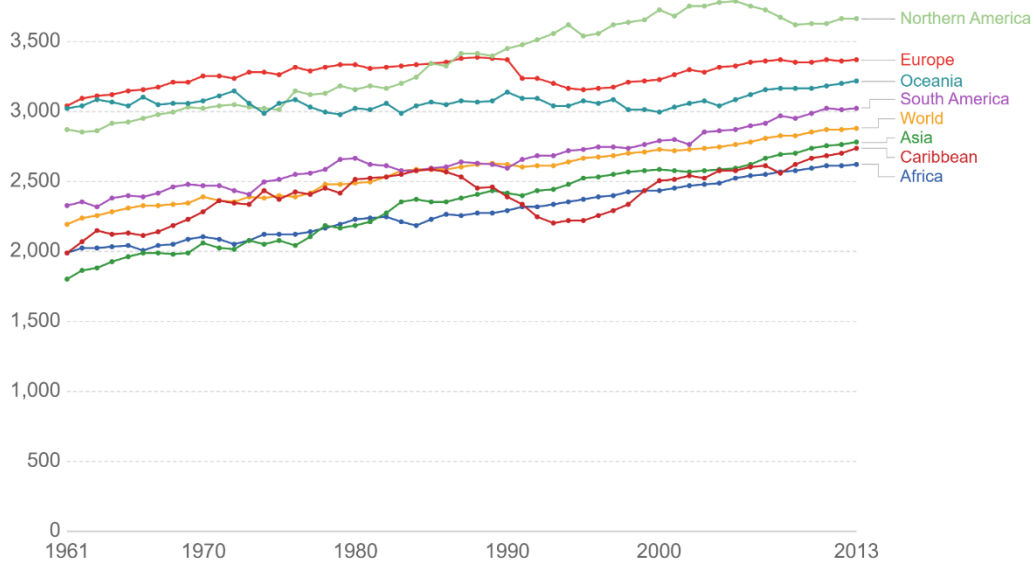


Figure S2. Rice imported per region over recent decades (Data retrieved from WHO FAOSTAT database: <http://www.fao.org/faostat>)

Food energy supply by region

Daily per capita food supply by world region, measured on the basis of average caloric supply (kilocalories per person per day). Note that this measures the food available for consumption at the household level but does not account for any food wasted or not eaten at the consumption level.



Source: UN Food and Agriculture Organization (FAO)

OurWorldInData.org/food-per-person/ • CC BY

Figure S3. Food supply by region (University of Oxford, 2020, *Our World in Data*: <https://ourworldindata.org/grapher/food-supply-by-region-kilocalories>)

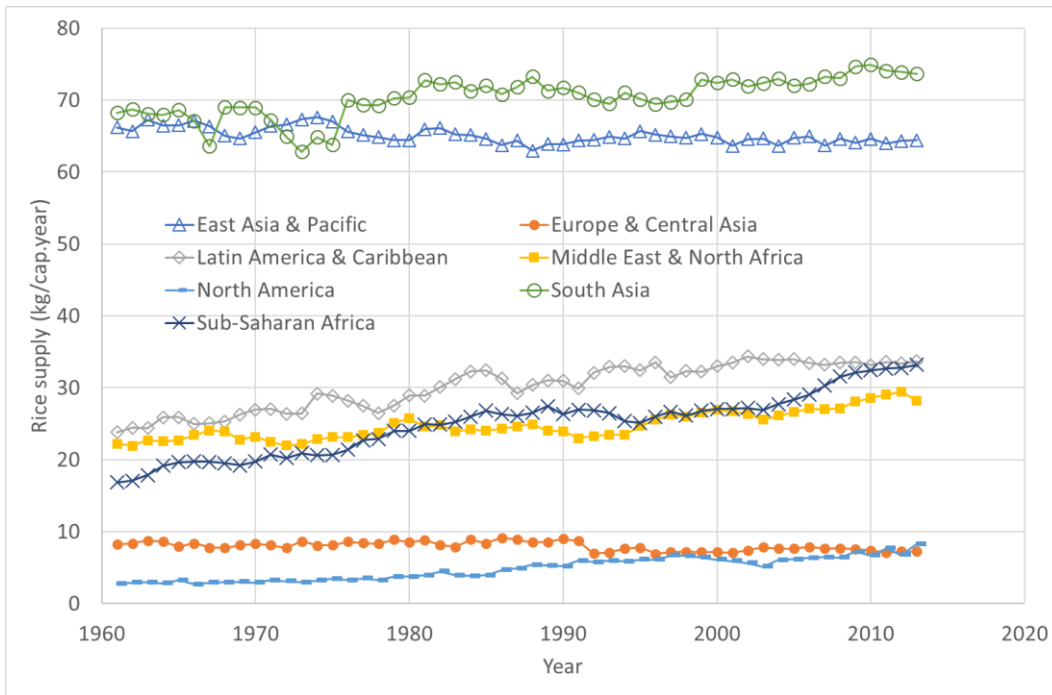


Figure S4. Rice supply per capita per region over recent decades (Data retrieved from WHO FAOSTAT database: <http://www.fao.org/faostat>)

Ingestion rates (ratios of kg/cap/year)

Ratio: IR in period 2000-2013 / IR in period 1986-1999



Figure S5. Change in rice per capita supply.

Amount of iAs embedded in imported rice (kg)

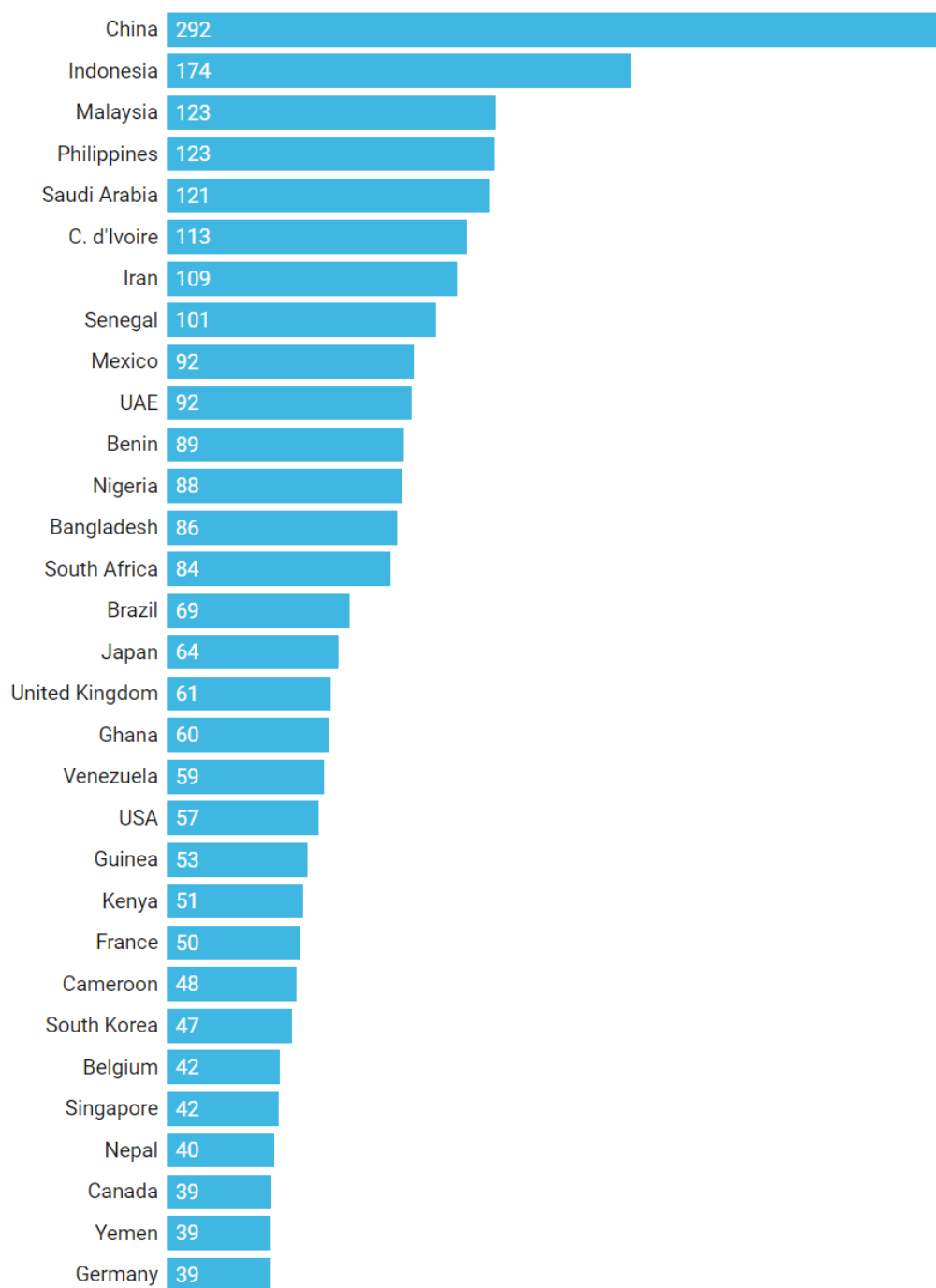


Figure S6. Major iAs importers (together responsible for 80% of the embedded iAs trade). Average imports per year in the period 2011-2015.

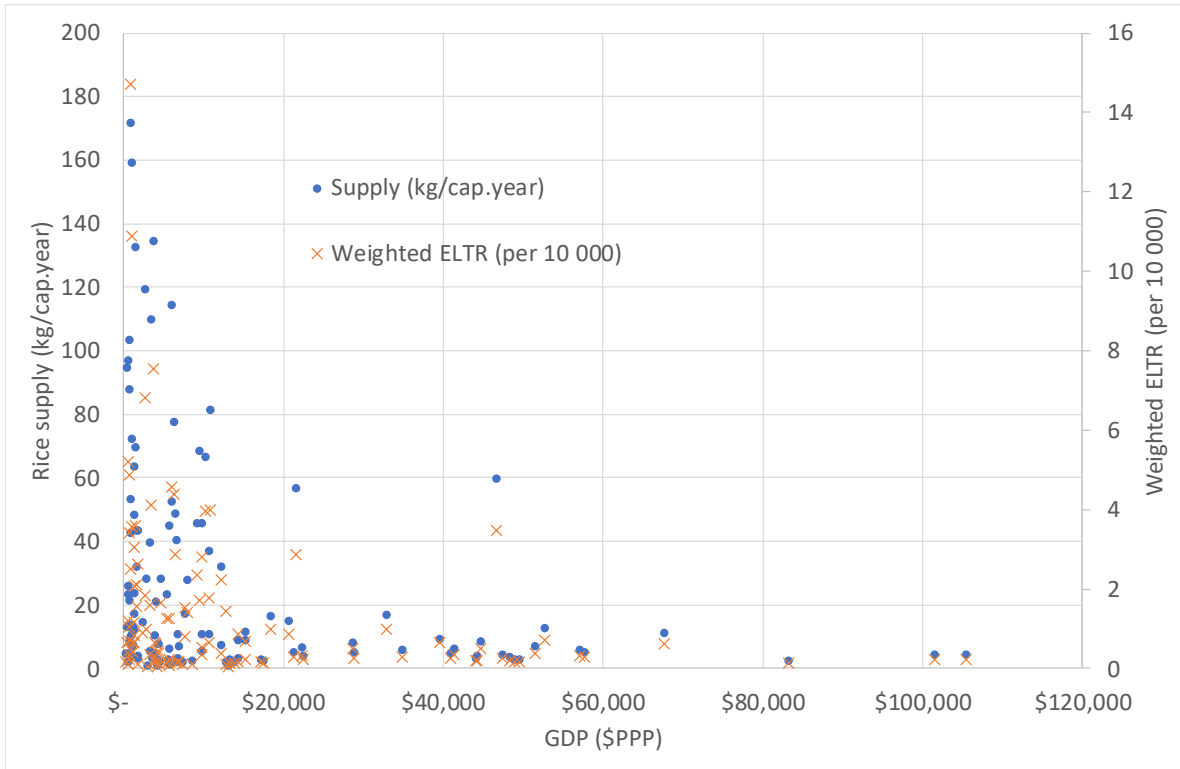


Figure S7. Relationship between national GDP (\$ corrected for purchasing power), amount of rice in the diet, and EHR.

Table S1. Rice imports averaged for the period 2011-2015 (retrieved in February 2020 from Food and Agriculture Organization of the United Nations' FAOSTAT web page (<http://www.fao.org/faostat>))

Country	Imported rice (average for the period 2011-2015), kton
China	2215
Indonesia	1348
Saudi Arabia	1330
Nigeria	1215
Iran (Islamic Republic of)	1210
Benin	1080
United Arab Emirates	1055
Senegal	1049
Côte d'Ivoire	1018
South Africa	1000
Malaysia	984
Bangladesh	976
Mexico	892
Philippines	859
Japan	684
United States of America	674
United Kingdom	661
Brazil	631
Guinea	584
Cameroon	573
Kenya	541
France	525
Venezuela (Bolivarian Republic of)	497
Belgium	453
Republic of Korea	451
Nepal	449
Yemen	449
Singapore	414
Canada	410
Ghana	404
Germany	403
Burkina Faso	380
Turkey	341
China, Hong Kong SAR	338
Niger	328
Sierra Leone	310
Madagascar	278
Netherlands	248
Russian Federation	232
Oman	218
Peru	216
Mali	212
Afghanistan	207
Kuwait	204

Country	Imported rice (average for the period 2011-2015), kton
Sri Lanka	195
Qatar	183
Jordan	175
Cuba	175
Zimbabwe	164
Ethiopia	160
Australia	151
Honduras	151
Djibouti	146
Mauritania	142
Italy	141
Colombia	141
Israel	128
Uganda	128
Poland	126
Togo	126
Nicaragua	125
Switzerland	123
Portugal	122
China, Taiwan Province of	120
Chile	119
Algeria	109
Costa Rica	104
Papua New Guinea	99
Gambia	98
Spain	95
Guatemala	95
Panama	92
El Salvador	90
Jamaica	88
Libya	83
Bahrain	83
Czechia	73
Ukraine	68
Romania	63
Lebanon	63
Sweden	61
Congo	61
Gabon	60
Mauritius	58
Syrian Arab Republic	57
Democratic Republic of the Congo	54
Cambodia	52
Comoros	48
United Republic of Tanzania	46
Egypt	46
Rwanda	43

Country	Imported rice (average for the period 2011-2015), kton
New Zealand	42
Austria	41
Denmark	39
Trinidad and Tobago	35
Fiji	34
Cabo Verde	33
Bolivia (Plurinational State of)	33
Pakistan	32
Eswatini	32
Brunei Darussalam	32
Azerbaijan	32
Bulgaria	32
Bhutan	31
Belarus	29
China, Macao SAR	28
Slovakia	28
Botswana	28
Hungary	28
Mongolia	26
Finland	25
Maldives	24
Norway	24
Solomon Islands	24
Ireland	22
Greece	21
Kazakhstan	21
Kyrgyzstan	19
Thailand	18
Albania	18
Tunisia	16
Burundi	16
Namibia	16
Zambia	14
Lithuania	13
Serbia	12
Georgia	11
Croatia	11
Slovenia	11
Armenia	10
French Polynesia	10
Morocco	10
Republic of Moldova	10
Kiribati	10
New Caledonia	10
Ecuador	9
Sao Tome and Principe	8
Bosnia and Herzegovina	7

Country	Imported rice (average for the period 2011-2015), kton
Latvia	7
Argentina	7
Cyprus	6
Seychelles	6
Barbados	5
Saint Vincent and the Grenadines	5
Bahamas	5
Vanuatu	5
Saint Lucia	4
Estonia	4
Aruba	3
Central African Republic	3
Luxembourg	3
Grenada	2
Malta	2
Uruguay	2
Antigua and Barbuda	2
Montenegro	1
Iceland	1
Paraguay	1
India	1
Suriname	1
Saint Kitts and Nevis	1
Dominica	1
Belize	1
Malawi	1
Bermuda	1
Remaining countries import < 1 kton/year	

Table S2. Rice exports averaged for the period 2011-2015 (retrieved in February 2020 from Food and Agriculture Organization of the United Nations' FAOSTAT web page (<http://www.fao.org/faostat>))

Country	Exported rice (average for the period 2011-2015), kton
India	6588
Thailand	6202
Viet Nam	4493
United States of America	2918
Pakistan	2765
Italy	703
Brazil	672
Uruguay	608
China, mainland	497
Argentina	392
Spain	372
Myanmar	357

Country	Exported rice (average for the period 2011-2015), kton
Guyana	323
Paraguay	316
Cambodia	304
Unspecified Area	272
Australia	242
United Arab Emirates	228
Netherlands	193
Belgium	169
Russian Federation	121
Egypt	105
Germany	97
Greece	85
South Africa	82
Senegal	81
France	79
Côte d'Ivoire	69
Singapore	50
Suriname	50
Bulgaria	44
United Republic of Tanzania	42
Japan	40
United Kingdom	36
Portugal	36
Lao People's Democratic Republic	29
Kazakhstan	23
Ecuador	23
Antigua and Barbuda	21
China, Taiwan Province of	21
Romania	20
China, Hong Kong SAR	18
Peru	18
Poland	18
Turkey	17
Switzerland	17
Uganda	15
Nicaragua	14
Czechia	13
Lebanon	12
Mozambique	11
Denmark	9
Bangladesh	9
El Salvador	9
Indonesia	8
Ukraine	7
Sri Lanka	7
Benin	6
Togo	6

Country	Exported rice (average for the period 2011-2015), kton
Costa Rica	5
Hungary	5
Oman	5
Kenya	5
Saudi Arabia	5
Lithuania	5
North Macedonia	5
Tajikistan	5
Canada	5
Turks and Caicos Islands	4
Tunisia	4
Malaysia	4
Rwanda	4
Honduras	3
Burkina Faso	3
Republic of Korea	3
Dominican Republic	3
Austria	3
Slovakia	3
Cameroon	3
Slovenia	2
Iceland	2
Ghana	2
Chile	2
Latvia	2
Iran (Islamic Republic of)	2
Ireland	2
Morocco	2
Cyprus	2
Belize	2
Bolivia (Plurinational State of)	1
Sweden	1
Mauritius	1
Liberia	1
Mexico	1
Guatemala	1
Finland	1
Cabo Verde	1
Malawi	1
Brunei Darussalam	1
Saint Vincent and the Grenadines	1
Zimbabwe	1
British Virgin Islands	1
New Zealand	1
Bahamas	1
Remaining countries export < 1 kton/year	

Table S3. Concentration of inorganic arsenic in white rice reported for different countries and regions (raw, wet weight)

Country	Mean (mg/kg)	Standard deviation (mg/kg)	N	Reference
Austria	0.090	0.057	34	14*
Belgium	0.097	0.054	200	
Brazil	0.114	0.053	305	
Bulgaria	0.018	0.011	14	
Canada	0.076	0.047	550	
Cyprus	0.050	0.026	20	
Czech Republic	0.086	0.052	512	
Denmark	0.120	0.089	1094	
Finland	0.117	0.081	100	
France	0.062	0.063	176	
Germany	0.102	0.209	4302	
Greece	0.067	0.046	60	
Hungary	0.071	0.021	30	
Ireland	0.298	0.365	234	
Italy	0.094	0.038	954	
Japan	0.102	0.040	1240	
Luxembourg	0.183	0.088	140	
Poland	0.049	0.034	340	
Portugal	0.128	0.064	78	
Singapore	0.053	0.049	81	
Slovakia	0.050	0.078	368	
Slovenia	0.083	0.045	78	
Spain	0.114	0.080	1960	
Thailand	0.067	0.034	833	
United Kingdom	0.101	0.118	514	
WHO European Region	0.094	0.183	7100	
United States of America	0.111	0.058	692	8,14
Ecuador	0.064	0.045	47	15
India	0.050	0.019	17	16*
Japan	0.107	0.025	17	
Egypt	0.031	0.038	108	
Egypt	0.031	0.038	110	11*
Nepal	0.038	0.019	12	
India	0.050	0.025	68	
Pakistan	0.056	0.063	16	
Ghana	0.063	0.050	34	
Bangladesh	0.082	0.038	100	
Australia	0.088	0.063	11	
Thailand	0.088	0.025	48	
China	0.094	0.038	92	
Italy	0.100	0.044	28	

Country	Mean (mg/kg)	Standard deviation (mg/kg)	N	Reference
France	0.119	0.025	21	
Japan	0.119	0.050	26	
Spain	0.119	0.088	51	
USA	0.157	0.056	174	
Bangladesh	0.080	0.060	14	11
India	0.030	0.010	10	
Japan	0.160	0.030	6	
Bangladesh	0.07	0.06	15	17
China	0.12	0.11	21	
Ghana	0.02	0.03	7	
India	0.03	0.03	13	
Italy	0.13	0.01	6	
Thailand	0.13	0.01	6	
Pakistan	0.09	0.0068	8	18
Uruguay	0.03	0.01	49	19
Brazil	0.121	0.037	38	20
Brazil	0.069	0.025	30	21
Pakistan	0.051	0.034	250	22*
Argentina	0.113	0.050	27	23*
Cambodia	0.161	0.088	10	24*
Cambodia	0.047	0.031	10	
Cambodia	0.015	0.008	10	
China	0.096	0.054	448	25
Bangladesh	0.320	0.160	30	26*
Ghana	0.037	0.031	7	27
Thailand	0.082	0.010	7	
USA	0.077	0.009	7	
India	0.094	0.003	29	28
Australia	0.075	0.019	12	29*
Australia	0.056	0.013	12	
Australia	0.138	0.013	12	
Australia	0.138	0.013	12	
Sri Lanka	0.026	0.006	4	30*
India	0.040	0.013	21	
Pakistan	0.056	0.025	6	
Egypt	0.064	0.006	2	
Australia	0.077	0.006	2	
Thailand	0.080	0.031	6	
Vietnam	0.106	-	1	
South Korea	0.076	0.019	63	31*
Vietnam	0.155	0.090	67	32

*: original values given as total arsenic were transformed into iAs by multiplying by 0.627, as determined for the average ratio iAs/tAs from the FAO's GEMS database data.

Table S4. Concentrations of inorganic arsenic per region and country. Calculated using data shown in Table S2.

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= 18312)	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

Country/WHO Region	Mean iAs mg/kg	Standard deviation mg/kg
Brazil	0.111	0.052
Canada	0.076	0.047
United States of America	0.104	0.052
Uruguay	0.030	NA
Ecuador	0.040	0.028

Table S6. Amount of embedded iAs in rice traded in the period 2003-2013 (mean values)

Country	iAs embedded in imported rice (kg/year), IMPAs _{ij}
China, mainland	291.63
Indonesia	173.78
Malaysia	123.17
Philippines	122.76
Saudi Arabia	120.57
Côte d'Ivoire	112.45
Iran (Islamic Republic of)	108.71
Senegal	100.70
Mexico	92.43
United Arab Emirates	91.85
Benin	88.81
Nigeria	88.02
Bangladesh	86.20
South Africa	83.73
Brazil	68.52
Japan	64.09
United Kingdom	61.21
Ghana	60.39
Venezuela (Bolivarian Republic of)	58.88
United States of America	56.70
Guinea	52.77
Kenya	51.20
France	49.60
Cameroon	48.40
Republic of Korea	46.91
Belgium	42.42
Singapore	42.10
Nepal	40.07
Canada	38.97
Yemen	38.71
Germany	38.67
Turkey	36.45
China, Hong Kong SAR	36.28
Burkina Faso	30.76

Country	iAs embedded in imported rice (kg/year), $IMPAs_{ij}$
Niger	27.36
Madagascar	26.17
Sierra Leone	25.06
Netherlands	24.17
Russian Federation	23.48
Cuba	21.17
Sri Lanka	20.17
Jordan	18.89
Oman	18.89
Afghanistan	18.66
Kuwait	18.08
Qatar	16.48
Chile	16.35
Honduras	15.90
Nicaragua	15.38
Italy	14.81
Ethiopia	14.64
Colombia	14.52
China, Taiwan Province of	14.33
Mauritania	13.44
Algeria	13.03
Israel	12.93
Djibouti	12.86
Australia	12.71
Zimbabwe	12.42
Switzerland	12.32
Poland	12.29
Portugal	12.07
Peru	11.54
Panama	11.52
Papua New Guinea	11.04
Togo	11.03
Costa Rica	10.92
Uganda	10.77
Mali	10.54
Guatemala	10.40
Spain	10.31
El Salvador	9.43
Gambia	9.37
Libya	8.57
Cambodia	8.05
Bahrain	7.32
Ukraine	6.96
Czechia	6.72

Country	iAs embedded in imported rice (kg/year), IMPAs _{ij}
Jamaica	6.32
Romania	6.16
Lebanon	6.11
Solomon Islands	5.89
Sweden	5.85
Egypt	5.46
United Republic of Tanzania	5.35
Syrian Arab Republic	5.22
Mauritius	5.10
Fiji	5.05
Congo	4.88
Bolivia (Plurinational State of)	4.83
New Zealand	4.70
Ecuador	4.42
Comoros	4.29
Gabon	4.28
Rwanda	4.15
Austria	3.88
Belarus	3.83
Denmark	3.78
Pakistan	3.60
Trinidad and Tobago	3.48
Bulgaria	3.17
Mongolia	3.13
Azerbaijan	3.02
Democratic Republic of the Congo	3.01
Cabo Verde	2.91
Bhutan	2.78
China, Macao SAR	2.72
Brunei Darussalam	2.51
Slovakia	2.47
Hungary	2.38
Finland	2.27
Albania	2.21
Greece	2.17
Norway	2.14
Maldives	2.12
Kazakhstan	2.12
Ireland	2.12
Kyrgyzstan	1.85
Thailand	1.81
Tunisia	1.66
Kiribati	1.53
Lithuania	1.42

Country	iAs embedded in imported rice (kg/year), IMPAs_{ij}
Vanuatu	1.37
Eswatini	1.37
Zambia	1.36
Botswana	1.22
Namibia	1.19
Burundi	1.17
Croatia	1.16
New Caledonia	1.16
Slovenia	1.09
Georgia	1.08
Morocco	1.06
Serbia	1.04
Sao Tome and Principe	1.01
Republic of Moldova	1.01
French Polynesia	0.98
Armenia	0.90
Bosnia and Herzegovina	0.78
Latvia	0.73
Central African Republic	0.72
Barbados	0.56
Seychelles	0.53
Argentina	0.51
Cyprus	0.46
Bahamas	0.43
Saint Lucia	0.40
Estonia	0.38
Saint Vincent and the Grenadines	0.37
Aruba	0.32
Uruguay	0.30
Luxembourg	0.27
Malta	0.22
Grenada	0.22
Antigua and Barbuda	0.19
Paraguay	0.17
India	0.16
Montenegro	0.15
Iceland	0.12
Belize	0.11
Suriname	0.10
Saint Kitts and Nevis	0.09
Dominica	0.08
Tonga	0.07
Bermuda	0.06
Malawi	0.04

Country	iAs embedded in imported rice (kg/year), IMPAs _{ij}
Tuvalu	0.04
Greenland	0.03
North Macedonia	0.02
Faroe Islands	0.02
Montserrat	0.01
Guyana	0.01
Cook Islands	0.00
TOTAL	3465.93

Table S5. Per capita rice supply ³³

Country	Supply (kg/cap.year)
Bangladesh	171.7
Lao People's Democratic Republic	159.1
Cambodia	159.1
Viet Nam	144.6
Indonesia	134.6
Myanmar	132.8
Philippines	119.4
Thailand	114.6
Sri Lanka	109.7
Sierra Leone	103.3
Madagascar	102.5
Guinea-Bissau	98.1
Guinea	97.1
Liberia	94.8
Nepal	87.8
Republic of Korea	85.2
Malaysia	81.3
China, mainland	78.2
China	77.5
Brunei Darussalam	76.7
Guyana	76.6
Democratic People's Republic of Korea	74.2
Senegal	72.3
India	69.5
Suriname	68.7
Cuba	67.7
Panama	66.4
Kiribati	65.8
Timor-Leste	64.2
Solomon Islands	63.8
Côte d'Ivoire	63.6

Country	Supply (kg/cap.year)
Gambia	61.8
Japan	59.9
Mali	57.0
Oman	56.6
United Arab Emirates	56.3
Benin	53.4
Dominican Republic	52.5
Maldives	50.7
Peru	48.9
Cabo Verde	48.8
Mauritania	48.4
China, Taiwan Province of	45.9
Costa Rica	45.7
Fiji	45.6
Mauritius	45.6
Ecuador	45.1
Kuwait	43.8
China, Hong Kong SAR	43.5
Djibouti	43.5
Nicaragua	43.3
Haiti	42.8
Vanuatu	41.2
Iraq	40.5
Egypt	39.8
Gabon	37.1
China, Macao SAR	36.5
Saudi Arabia	36.0
French Polynesia	35.6
Sao Tome and Principe	35.1
Saint Vincent and the Grenadines	33.7
Brazil	32.1
Ghana	32.0
Iran (Islamic Republic of)	30.0
Belize	28.4
Nigeria	28.2
Colombia	28.0
Bolivia (Plurinational State of)	27.0
Togo	26.0
Bahamas	24.0
Cameroon	23.9
Jamaica	23.5
Mozambique	23.4
Venezuela (Bolivarian Republic of)	23.4
Burkina Faso	21.4
Swaziland	21.2
United Republic of Tanzania	21.0

Country	Supply (kg/cap.year)
Saint Kitts and Nevis	19.9
Jordan	19.7
New Caledonia	17.5
South Africa	17.4
Yemen	17.4
Israel	16.8
Congo	16.5
Trinidad and Tobago	16.4
Barbados	15.7
Portugal	14.9
Honduras	14.4
Afghanistan	13.8
Niger	13.2
Kenya	12.9
Canada	12.7
Pakistan	12.3
Uruguay	11.5
Australia	11.0
Turkmenistan	10.9
Lebanon	10.8
Chad	10.8
Turkey	10.7
El Salvador	10.5
Saint Lucia	10.4
Zimbabwe	10.1
Grenada	9.6
Antigua and Barbuda	9.5
New Zealand	9.2
Chile	8.9
Argentina	8.8
Rwanda	8.7
Belgium	8.6
Dominica	8.4
Spain	8.3
Angola	8.1
Albania	7.8
Mongolia	7.7
Central African Republic	7.4
Kazakhstan	7.3
Kyrgyzstan	7.3
Botswana	7.1
Tajikistan	7.0
United States of America	6.9
Greece	6.6
United Kingdom	6.4
Namibia	6.3

Country	Supply (kg/cap.year)
Samoa	6.0
Sweden	6.0
Italy	5.7
Guatemala	5.7
Mexico	5.6
Bermuda	5.4
Denmark	5.0
Malta	5.0
Cyprus	4.9
Paraguay	4.9
France	4.9
Czechia	4.8
Malawi	4.8
Russian Federation	4.7
Uganda	4.6
Finland	4.4
Norway	4.4
Luxembourg	4.2
Slovenia	4.0
Iceland	3.9
Uzbekistan	3.9
Lesotho	3.7
Austria	3.7
Germany	3.3
Armenia	3.2
Belarus	3.2
Lithuania	3.1
Zambia	3.1
Ireland	3.0
Ukraine	3.0
Algeria	3.0
Republic of Moldova	3.0
Netherlands	2.9
Slovakia	2.9
The former Yugoslav Republic of Macedonia	2.8
Croatia	2.6
Georgia	2.6
Romania	2.6
Estonia	2.6
Switzerland	2.4
Ethiopia	2.3
Bulgaria	2.2
Montenegro	2.2
Latvia	2.2
Hungary	2.2
Azerbaijan	2.0

Country	Supply (kg/cap.year)
Bosnia and Herzegovina	1.9
Sudan	1.3
Serbia	1.2
Morocco	1.1
Tunisia	1.1
Poland	1.0

Table S7. Exported iAs embedded in internationally traded rice (mean in the period 2011-2015)

Country	Embedded iAs in traded rice (kg/year)
Vietnam	796
India	788
Thailand	485
United States of America	323
Pakistan	299
Brazil	95.9
Argentina	81.1
Italy	67.2
China, mainland	50.2
Spain	43.6
Australia	43.4
Guyana	40.3
Cambodia	37.0
United Arab Emirates	34.2
Paraguay	32.8
Myanmar	30.9
Uruguay	21.5
Netherlands	19.7
Belgium	16.4
Russian Federation	13.3
Germany	10.2
Egypt	8.37
Portugal	7.83
Japan	6.48
Greece	5.93
Peru	5.86
Senegal	5.77
France	5.17
South Africa	4.39
Côte d'Ivoire	4.36
Lao People's Democratic Republic	4.35
Singapore	3.81
United Kingdom	3.72
Nicaragua	2.92
Switzerland	2.80

Country	Embedded iAs in traded rice (kg/year)
Suriname	2.74
Antigua and Barbuda	2.57
Kazakhstan	2.55
Bangladesh	2.49
Ecuador	2.39
Indonesia	2.34
Turkey	2.27
China, Hong Kong SAR	2.26
United Republic of Tanzania	2.25
El Salvador	2.24
Romania	2.23
Lebanon	2.13
Oman	2.09
Tunisia	1.78
Dominican Republic	1.58
Ukraine	1.44
Uganda	1.41
Denmark	1.20
Czechia	1.12
Lithuania	1.03
Benin	0.890
Poland	0.873
Bulgaria	0.800
Belize	0.753
Rwanda	0.734
Republic of Korea	0.704
Ireland	0.603
Costa Rica	0.578
Iceland	0.547
Saudi Arabia	0.538
Sri Lanka	0.501
Mozambique	0.487
Turks and Caicos Islands	0.472
Chile	0.434
Togo	0.432
Burkina Faso	0.424
Malaysia	0.400
Honduras	0.397
Tajikistan	0.395
Hungary	0.388
Canada	0.386
Cyprus	0.335
Bahamas	0.294
Austria	0.285
Liberia	0.269

Country	Embedded iAs in traded rice (kg/year)
Cameroon	0.258
British Virgin Islands	0.229
Guatemala	0.226
Kenya	0.223
Saint Vincent and the Grenadines	0.217
Panama	0.201
Colombia	0.192
Bolivia (Plurinational State of)	0.191
Iran (Islamic Republic of)	0.183
Latvia	0.177
Slovenia	0.176
Sweden	0.160
Mexico	0.149
Finland	0.144
New Zealand	0.143
Slovakia	0.142
Ghana	0.136
Belarus	0.129
Morocco	0.117
Cabo Verde	0.112
American Samoa	0.099
Serbia	0.095
Philippines	0.085
Fiji	0.082
Venezuela (Bolivarian Republic of)	0.081
Mauritius	0.081
Luxembourg	0.057
Papua New Guinea	0.055
Libya	0.055
Estonia	0.052
Mongolia	0.049
Nigeria	0.049
Croatia	0.046
Bermuda	0.044
Malawi	0.043
Israel	0.043
Jordan	0.039
Trinidad and Tobago	0.039
Mali	0.037
Georgia	0.037
Namibia	0.035
Niger	0.034
Zambia	0.032
Vanuatu	0.031
Zimbabwe	0.030

Country	Embedded iAs in traded rice (kg/year)
Jamaica	0.030
Norway	0.028
Nepal	0.027
Malta	0.025
Kuwait	0.025
Bhutan	0.024
Syrian Arab Republic	0.023
China, Macao SAR	0.022
Democratic People's Republic of Korea	0.022
Botswana	0.021
New Caledonia	0.021
Qatar	0.016
Kyrgyzstan	0.012
Bahrain	0.012
Haiti	0.011
Mauritania	0.010
Saint Kitts and Nevis	0.010
Afghanistan	0.008
Democratic Republic of the Congo	0.008
Micronesia (Federated States of)	0.006
Republic of Moldova	0.006
Algeria	0.006
Madagascar	0.005
Azerbaijan	0.005
Gabon	0.004
Montenegro	0.003
Comoros	0.003
Iraq	0.003
Bosnia and Herzegovina	0.003
Samoa	0.003
Lesotho	0.002
Burundi	0.002
Dominica	0.001
Angola	0.001
Albania	0.000
Greenland	0.000
Equatorial Guinea	0.000
Guinea-Bissau	0.000
Unspecified Area	0.000
Yemen	0.000

Table S8. Embedded Health Risk (EHR) in rice imports by country, for all its trade partners. Ranked for countries with $EHR_{ij} \geq 1$. Means in the period (2011-2015).

Importing Country	Partner Country	Imports (ton)	iAs flow (kg/year)	EHR_{jk} (/100 000)
Afghanistan	Pakistan	203380	18.1	19
Albania	Egypt	1856	0.1	3
Albania	Italy	3077	0.3	6
Albania	Pakistan	1865	0.2	4
Albania	Romania	2507	0.3	5
Albania	Russian Federation	1550	0.2	3
Albania	Spain	1859	0.2	4
Albania	United States of America	1754	0.2	4
Albania	Viet Nam	3223	0.5	12
Algeria	India	35072	3.1	5
Algeria	Viet Nam	41661	7.0	11
Antigua and Barbuda	Brazil	284	0.0	9
Antigua and Barbuda	Guyana	1180	0.1	33
Antigua and Barbuda	United States of America	295	0.0	9
Armenia	Pakistan	3143	0.3	5
Armenia	Thailand	5013	0.3	6
Armenia	Viet Nam	794	0.1	2
Australia	India	26579	2.3	2
Australia	Thailand	78054	5.3	5
Austria	Germany	7676	0.8	4
Austria	Italy	19779	1.9	10
Azerbaijan	Pakistan	15686	1.4	4
Bahamas	Brazil	91	0.0	3
Bahamas	United States of America	3926	0.4	105
Bangladesh	India	969954	85.6	19
Barbados	Brazil	1269	0.1	24
Barbados	Guyana	2272	0.2	37
Barbados	United States of America	1695	0.2	30
Belarus	Lithuania	5942	0.6	3
Belarus	Pakistan	9509	0.8	4
Belarus	Russian Federation	6206	0.6	3
Belarus	Viet Nam	5633	1.0	5
Belgium	Egypt	39809	2.7	3
Belgium	India	25133	2.2	2
Belgium	Italy	50217	4.7	5
Belgium	Myanmar	36759	2.5	3
Belgium	Netherlands	44974	4.5	5
Belgium	Pakistan	24873	2.2	2
Belgium	Spain	90666	10.3	11
Belgium	Thailand	36494	2.5	3
Belgium	Viet Nam	17847	3.0	3
Belize	Guyana	820	0.1	8

Importing Country	Partner Country	Imports (ton)	iAs flow (kg/year)	EHR _{jk} (/100 000)
Belize	United States of America	297	0.0	3
Benin	Brazil	33115	3.7	9
Benin	China, Hong Kong SAR	10778	1.1	3
Benin	India	469515	41.5	105
Benin	Pakistan	15512	1.4	3
Benin	Singapore	22233	1.2	3
Benin	Switzerland	22363	2.3	6
Benin	Thailand	405199	27.5	69
Benin	United Arab Emirates	61467	5.1	13
Benin	Viet Nam	12424	2.1	5
Bermuda	United States of America	555	0.1	33
Bolivia (Plurinational State of)	Argentina	17356	3.1	11
Bolivia (Plurinational State of)	Brazil	13278	1.5	5
Bosnia and Herzegovina	Italy	4492	0.4	6
Bosnia and Herzegovina	Viet Nam	1271	0.2	3
Botswana	South Africa	26838	1.1	17
Brazil	Argentina	191176	34.4	5
Brazil	Paraguay	258993	25.3	4
Brunei Darussalam	Australia	160	0.0	3
Brunei Darussalam	Cambodia	1262	0.1	19
Brunei Darussalam	Germany	2289	0.2	30
Brunei Darussalam	India	1336	0.1	15
Brunei Darussalam	Thailand	28667	1.9	249
Brunei Darussalam	Viet Nam	102	0.0	2
Burkina Faso	India	76446	6.7	14
Burkina Faso	Myanmar	63677	4.4	9
Burkina Faso	Pakistan	35224	3.1	6
Burkina Faso	Thailand	128309	8.7	18
Burkina Faso	United States of America	10241	1.1	2
Burkina Faso	Viet Nam	26109	4.4	9
Côte d'Ivoire	Brazil	18328	2.0	4
Côte d'Ivoire	India	251089	22.2	41
Côte d'Ivoire	Myanmar	74014	5.1	9
Côte d'Ivoire	Pakistan	64286	5.7	11
Côte d'Ivoire	Thailand	338748	23.0	42
Côte d'Ivoire	Viet Nam	312319	52.8	97
Cabo Verde	Brazil	4580	0.5	38
Cabo Verde	Côte d'Ivoire	1285	0.1	4
Cabo Verde	Ghana	1492	0.1	5
Cabo Verde	Japan	5129	0.5	39
Cabo Verde	Portugal	272	0.0	3
Cabo Verde	Serbia	563	0.1	4
Cabo Verde	Spain	271	0.0	2

Importing Country	Partner Country	Imports (ton)	iAs flow (kg/year)	EHR _{jk} (/100 000)
Cabo Verde	Thailand	17471	1.2	89
Cabo Verde	Uruguay	4597	0.1	10
Cabo Verde	Viet Nam	1322	0.2	17
Cambodia	Viet Nam	42996	7.3	9
Cameroon	India	79958	7.1	14
Cameroon	Myanmar	18586	1.3	3
Cameroon	Pakistan	34526	3.1	6
Cameroon	Thailand	373092	25.3	51
Cameroon	Viet Nam	59863	10.1	21
Canada	India	36546	3.2	6
Canada	Thailand	96756	6.6	12
Canada	United States of America	244972	25.6	46
Central African Republic	United States of America	2120	0.2	2
Chile	Argentina	47383	8.5	18
Chile	Paraguay	35582	3.5	7
Chile	Viet Nam	14025	2.4	5
China, Hong Kong SAR	Australia	6275	1.0	8
China, Hong Kong SAR	China, mainland	25396	2.5	18
China, Hong Kong SAR	Pakistan	4957	0.4	3
China, Hong Kong SAR	Thailand	176541	12.0	90
China, Hong Kong SAR	United States of America	3638	0.4	3
China, Hong Kong SAR	Viet Nam	114050	19.3	145
China, Macao SAR	Cambodia	393	0.0	3
China, Macao SAR	China, Hong Kong SAR	7028	0.7	52
China, Macao SAR	China, mainland	675	0.1	5
China, Macao SAR	Myanmar	452	0.0	2
China, Macao SAR	Thailand	14745	1.0	75
China, Macao SAR	Viet Nam	4987	0.8	63
China, Taiwan Province of	Australia	12777	2.0	3
China, Taiwan Province of	Thailand	20201	1.4	2
China, Taiwan Province of	United States of America	54033	5.6	9
China, Taiwan Province of	Viet Nam	28370	4.8	8
Colombia	United States of America	115472	12.1	8
Congo	Brazil	2083	0.2	3
Congo	India	3877	0.3	5
Congo	Thailand	51348	3.5	52
Congo	Viet Nam	2576	0.4	6
Costa Rica	Argentina	5842	1.1	9
Costa Rica	Brazil	13585	1.5	12
Costa Rica	El Salvador	2540	0.2	2
Costa Rica	Nicaragua	3563	0.3	3
Costa Rica	United States of America	69796	7.3	60
Croatia	Italy	3858	0.4	5
Croatia	Viet Nam	1388	0.2	3
Cuba	Argentina	28898	5.2	29

Importing Country	Partner Country	Imports (ton)	iAs flow (kg/year)	EHR _{jk} (/100 000)
Cuba	Brazil	137658	15.3	86
Cuba	Ecuador	15768	0.6	4
Cyprus	Greece	1696	0.1	5
Cyprus	India	765	0.1	3
Czechia	Cambodia	7334	0.9	3
Czechia	Italy	34824	3.3	12
Denmark	Germany	11184	1.1	8
Denmark	Italy	8481	0.8	6
Denmark	Netherlands	4342	0.4	3
Djibouti	India	119669	10.6	185
Djibouti	Pakistan	25131	2.2	39
Dominica	Guyana	539	0.1	30
Dominica	India	73	0.0	4
Dominica	Trinidad and Tobago	61	0.0	3
Dominica	United States of America	41	0.0	2
Ecuador	Peru	44822	4.4	7
El Salvador	Nicaragua	6534	0.6	3
El Salvador	United States of America	76404	8.0	40
Estonia	Cambodia	546	0.1	2
Estonia	Latvia	724	0.1	3
Estonia	Lithuania	577	0.1	2
Ethiopia	India	119013	10.5	6
Fiji	Australia	4056	0.7	37
Fiji	India	1856	0.2	9
Fiji	Thailand	5759	0.4	22
Fiji	Viet Nam	21745	3.7	211
Finland	Italy	9114	0.9	9
Finland	Spain	5231	0.6	6
France	Cambodia	55722	6.6	3
France	Italy	131132	12.3	5
France	Spain	45836	5.2	2
France	Thailand	81052	5.5	2
French Polynesia	Australia	2966	0.5	97
French Polynesia	Thailand	7131	0.5	98
Gabon	Cambodia	3967	0.5	17
Gabon	Thailand	55302	3.8	133
Gambia	Argentina	1800	0.3	8
Gambia	Brazil	17120	1.9	45
Gambia	India	19205	1.7	40
Gambia	Italy	1067	0.1	2
Gambia	Japan	6996	0.7	17
Gambia	Netherlands	1494	0.2	4
Gambia	Pakistan	26704	2.4	56
Gambia	Paraguay	2307	0.2	5
Gambia	Singapore	3319	0.2	4

Importing Country	Partner Country	Imports (ton)	iAs flow (kg/year)	EHR _{jk} (/100 000)
Gambia	Thailand	11077	0.8	18
Gambia	United Arab Emirates	1841	0.2	4
Gambia	Uruguay	8668	0.3	6
Georgia	Pakistan	5677	0.5	7
Germany	Belgium	55397	5.4	3
Germany	Cambodia	46347	5.5	3
Germany	Italy	119676	11.2	5
Germany	Netherlands	54297	5.5	3
Ghana	India	33726	3.0	6
Ghana	Thailand	164563	11.2	24
Ghana	United States of America	62387	6.5	14
Ghana	Viet Nam	216350	36.6	79
Grenada	Guyana	2064	0.2	48
Guatemala	United States of America	90311	9.4	25
Guinea	India	326028	28.8	77
Guinea	Lebanon	21346	1.8	5
Guinea	Myanmar	20820	1.4	4
Guinea	Pakistan	45410	4.0	11
Guinea	Singapore	16001	0.9	2
Guinea	Thailand	63626	4.3	12
Guinea	United Arab Emirates	75752	6.3	17
Guinea	Viet Nam	21523	3.6	10
Honduras	United States of America	142602	14.9	66
Hungary	Italy	12012	1.1	4
Iceland	Thailand	573	0.0	6
Iceland	United States of America	174	0.0	3
Indonesia	Thailand	368327	25.0	3
Indonesia	Viet Nam	770069	130.1	17
Iran (Islamic Republic of)	India	886618	78.3	32
Iran (Islamic Republic of)	Pakistan	78983	7.0	3
Iran (Islamic Republic of)	United Arab Emirates	195747	16.3	7
Ireland	Netherlands	3819	0.4	3
Ireland	United Kingdom	8923	0.9	7
Israel	Australia	30766	4.9	37
Israel	India	9315	0.8	6
Israel	Thailand	66651	4.5	34
Israel	United States of America	3998	0.4	3
Israel	Viet Nam	6793	1.1	9
Jamaica	Guyana	36869	3.6	56
Jamaica	Suriname	42601	1.8	28
Jamaica	United States of America	5440	0.6	9
Japan	Australia	42348	6.8	2
Japan	Thailand	277357	18.8	6
Japan	United States of America	322503	33.7	10
Jordan	Australia	20645	3.3	21

Importing Country	Partner Country	Imports (ton)	iAs flow (kg/year)	EHR _{jk} (/100 000)
Jordan	India	36049	3.2	20
Jordan	Pakistan	3731	0.3	2
Jordan	Thailand	10500	0.7	5
Jordan	United States of America	91232	9.5	61
Jordan	Viet Nam	2930	0.5	3
Kazakhstan	Russian Federation	18169	1.8	2
Kenya	Pakistan	479242	42.6	51
Kenya	Thailand	29781	2.0	2
Kenya	Viet Nam	29050	4.9	6
Kiribati	Australia	7361	1.2	441
Kiribati	China, Hong Kong SAR	124	0.0	5
Kiribati	China, mainland	711	0.1	26
Kiribati	Croatia	138	0.0	5
Kiribati	Fiji	88	0.0	3
Kiribati	Singapore	188	0.0	4
Kiribati	Switzerland	113	0.0	4
Kiribati	United States of America	681	0.1	27
Kiribati	Viet Nam	870	0.1	55
Kuwait	Australia	3076	0.5	6
Kuwait	Egypt	3342	0.2	3
Kuwait	India	174005	15.4	194
Kuwait	Pakistan	12580	1.1	14
Kuwait	Thailand	8105	0.5	7
Kyrgyzstan	China, mainland	2677	0.3	3
Kyrgyzstan	Kazakhstan	9702	0.8	9
Kyrgyzstan	Russian Federation	6317	0.6	7
Latvia	Cambodia	2209	0.3	5
Latvia	Lithuania	1483	0.1	3
Lebanon	Australia	4349	0.7	7
Lebanon	Egypt	4830	0.3	3
Lebanon	India	8232	0.7	7
Lebanon	Italy	13567	1.3	13
Lebanon	Russian Federation	2599	0.3	3
Lebanon	Thailand	14055	1.0	9
Lebanon	United States of America	5477	0.6	6
Lebanon	Viet Nam	2863	0.5	5
Lithuania	Cambodia	3091	0.4	5
Lithuania	Viet Nam	2281	0.4	5
Luxembourg	Belgium	1112	0.1	10
Luxembourg	France	404	0.0	2
Luxembourg	Germany	259	0.0	2
Luxembourg	Portugal	582	0.1	7
Madagascar	India	98560	8.7	13
Madagascar	Pakistan	149415	13.3	19
Madagascar	Viet Nam	12688	2.1	3

Importing Country	Partner Country	Imports (ton)	iAs flow (kg/year)	EHR _{jk} (/100 000)
Malaysia	Cambodia	37095	4.4	6
Malaysia	India	34998	3.1	4
Malaysia	Pakistan	135635	12.1	17
Malaysia	Thailand	268385	18.2	26
Malaysia	Viet Nam	501531	84.8	119
Maldives	India	19782	1.7	214
Maldives	Pakistan	2898	0.3	32
Maldives	Thailand	799	0.1	7
Mali	Brazil	9120	1.0	2
Mali	Côte d'Ivoire	78679	3.3	7
Mali	Senegal	121127	5.1	11
Malta	Italy	620	0.1	7
Malta	Pakistan	333	0.0	4
Malta	Thailand	359	0.0	3
Malta	United Kingdom	580	0.1	7
Malta	United States of America	160	0.0	2
Mauritania	Argentina	1832	0.3	4
Mauritania	Brazil	20739	2.3	25
Mauritania	India	4497	0.4	4
Mauritania	Japan	7589	0.8	8
Mauritania	Pakistan	38908	3.5	37
Mauritania	Senegal	4703	0.2	2
Mauritania	Thailand	55727	3.8	41
Mauritania	United States of America	3823	0.4	4
Mauritania	Viet Nam	4353	0.7	8
Mauritius	India	43518	3.8	175
Mauritius	Pakistan	10370	0.9	42
Mauritius	Thailand	4078	0.3	13
Mexico	United States of America	811077	84.7	24
Mongolia	China, mainland	18409	1.8	28
Mongolia	Russian Federation	4239	0.4	7
Mongolia	Viet Nam	4629	0.8	12
Montenegro	Italy	463	0.0	3
Montenegro	Viet Nam	321	0.1	4
Namibia	Brazil	975	0.1	3
Namibia	India	7710	0.7	16
Namibia	South Africa	4685	0.2	5
Nepal	India	445529	39.3	42
Netherlands	Cambodia	26769	3.2	2
Netherlands	India	48914	4.3	3
New Caledonia	Australia	4439	0.7	69
New Caledonia	Thailand	5723	0.4	38
New Caledonia	Viet Nam	261	0.0	4
New Zealand	Australia	14696	2.4	30
New Zealand	India	4242	0.4	5

Importing Country	Partner Country	Imports (ton)	iAs flow (kg/year)	EHR _{jk} (/100 000)
New Zealand	Pakistan	3440	0.3	4
New Zealand	Thailand	11890	0.8	10
New Zealand	United States of America	4705	0.5	6
New Zealand	Viet Nam	1093	0.2	2
Nicaragua	Brazil	70223	7.8	41
Nicaragua	Guyana	35562	3.5	18
Nicaragua	United States of America	32202	3.4	18
Niger	India	84710	7.5	14
Niger	Pakistan	87663	7.8	15
Niger	Thailand	128557	8.7	17
Niger	United States of America	12617	1.3	3
Nigeria	India	255739	22.6	7
Nigeria	Thailand	941971	63.9	20
Norway	India	2868	0.3	3
Norway	Italy	2717	0.3	3
Norway	Thailand	10024	0.7	7
Norway	Viet Nam	1158	0.2	2
Oman	India	54300	4.8	73
Oman	Pakistan	112501	10.0	152
Oman	Thailand	11822	0.8	12
Oman	United Arab Emirates	37750	3.2	48
Panama	Brazil	9726	1.1	10
Panama	Dominican Republic	13451	1.3	12
Panama	Guyana	24187	2.4	22
Panama	United States of America	60246	6.3	59
Peru	Brazil	29127	3.2	3
Peru	Uruguay	156482	4.7	5
Philippines	Thailand	200524	13.6	6
Philippines	Viet Nam	609097	102.9	43
Poland	Germany	46446	4.7	2
Portugal	Argentina	5485	1.0	3
Portugal	Cambodia	5755	0.7	2
Portugal	Guyana	34952	3.4	10
Portugal	Spain	33118	3.8	11
Republic of Korea	China, mainland	211668	20.4	16
Republic of Korea	Thailand	57386	3.9	3
Republic of Korea	United States of America	119904	12.5	10
Republic of Korea	Viet Nam	31199	5.3	4
Republic of Moldova	India	2133	0.2	3
Republic of Moldova	Pakistan	1616	0.1	2
Republic of Moldova	Russian Federation	1955	0.2	3
Republic of Moldova	Ukraine	2373	0.2	4
Romania	United States of America	26065	2.7	3
Russian Federation	Viet Nam	44749	7.6	2
Rwanda	Pakistan	35218	3.1	13

Importing Country	Partner Country	Imports (ton)	iAs flow (kg/year)	EHR _{jk} (/100 000)
Saint Kitts and Nevis	Guyana	284	0.0	35
Saint Kitts and Nevis	Pakistan	25	0.0	3
Saint Kitts and Nevis	Saint Vincent and the Grenadines	65	0.0	8
Saint Kitts and Nevis	United States of America	559	0.1	73
Saint Lucia	Guyana	1639	0.2	24
Saint Lucia	India	310	0.0	4
Saint Lucia	Saint Vincent and the Grenadines	1956	0.2	28
Saint Lucia	United States of America	154	0.0	2
Saint Vincent and the Grenadines	Guyana	2972	0.3	106
Saint Vincent and the Grenadines	Uruguay	2428	0.1	27
Sao Tome and Principe	Brazil	91	0.0	2
Sao Tome and Principe	Cameroon	283	0.0	3
Sao Tome and Principe	India	415	0.0	8
Sao Tome and Principe	Indonesia	751	0.1	16
Sao Tome and Principe	Italy	225	0.0	5
Sao Tome and Principe	Japan	2176	0.2	48
Sao Tome and Principe	Lebanon	313	0.0	6
Sao Tome and Principe	Portugal	3158	0.4	88
Sao Tome and Principe	Spain	267	0.0	7
Sao Tome and Principe	Thailand	954	0.1	14
Sao Tome and Principe	Viet Nam	569	0.1	21
Saudi Arabia	Australia	26150	4.2	7
Saudi Arabia	India	939978	83.0	131
Saudi Arabia	Pakistan	138906	12.3	20
Saudi Arabia	Thailand	86319	5.9	9
Saudi Arabia	United States of America	117404	12.3	19
Senegal	Antigua and Barbuda	26262	2.6	8
Senegal	Argentina	28359	5.1	15
Senegal	Brazil	74623	8.3	25
Senegal	India	576396	50.9	151
Senegal	Pakistan	42038	3.7	11
Senegal	Thailand	177379	12.0	36
Senegal	Tunisia	15590	1.3	4
Senegal	United States of America	29760	3.1	9
Senegal	Uruguay	22838	0.7	2
Senegal	Viet Nam	68407	11.6	34
Serbia	Viet Nam	2928	0.5	3
Sierra Leone	Argentina	7047	1.3	7
Sierra Leone	Brazil	79559	8.8	45
Sierra Leone	India	43516	3.8	20
Sierra Leone	Pakistan	57345	5.1	26

Importing Country	Partner Country	Imports (ton)	iAs flow (kg/year)	EHR _{jk} (/100 000)
Sierra Leone	Paraguay	7573	0.7	4
Sierra Leone	Thailand	41758	2.8	15
Sierra Leone	Uruguay	67243	2.0	10
Slovakia	Czechia	9355	0.8	5
Slovakia	Italy	12039	1.1	7
Slovenia	Cambodia	1700	0.2	4
Slovenia	Italy	7657	0.7	15
Solomon Islands	Australia	32908	5.3	479
Solomon Islands	China, Hong Kong SAR	302	0.0	3
Solomon Islands	China, mainland	2661	0.3	23
Solomon Islands	Papua New Guinea	307	0.0	3
Solomon Islands	Thailand	558	0.0	3
Solomon Islands	United States of America	632	0.1	6
Solomon Islands	Viet Nam	1067	0.2	16
South Africa	Brazil	32031	3.6	4
South Africa	China, mainland	154717	14.9	15
South Africa	India	296050	26.1	27
South Africa	Thailand	442671	30.0	30
South Africa	Viet Nam	31976	5.4	5
Sri Lanka	Bangladesh	12500	1.9	3
Sri Lanka	India	146478	12.9	22
Sri Lanka	Myanmar	25893	1.8	3
Sri Lanka	Pakistan	27022	2.4	4
Sweden	Belgium	7629	0.7	4
Sweden	Cambodia	3259	0.4	2
Sweden	Germany	6177	0.6	4
Sweden	India	4960	0.4	2
Sweden	Italy	8829	0.8	5
Sweden	Netherlands	4890	0.5	3
Sweden	Thailand	11420	0.8	4
Switzerland	Brazil	54224	6.0	7
Switzerland	Italy	22240	2.1	2
Togo	India	31128	2.7	17
Togo	Pakistan	8824	0.8	5
Togo	Thailand	65365	4.4	28
Togo	Turkey	4914	0.4	3
Togo	Viet Nam	8086	1.4	9
Trinidad and Tobago	Brazil	8657	1.0	25
Trinidad and Tobago	Guyana	22425	2.2	57
Trinidad and Tobago	Paraguay	1426	0.1	4
Tunisia	India	10064	0.9	3
Turkey	Russian Federation	69303	7.0	4
Turkey	United States of America	136528	14.3	8
Uganda	Pakistan	93037	8.3	7
Ukraine	Pakistan	30083	2.7	2

Importing Country	Partner Country	Imports (ton)	iAs flow (kg/year)	EHR _{jk} (/100 000)
United Arab Emirates	Australia	5354	0.9	3
United Arab Emirates	India	735860	65.0	203
United Arab Emirates	Pakistan	181196	16.1	50
United Arab Emirates	Thailand	53999	3.7	11
United Arab Emirates	Viet Nam	29500	5.0	16
United Kingdom	India	169305	14.9	8
United Kingdom	Italy	69491	6.5	4
United Kingdom	Pakistan	74318	6.6	4
United Kingdom	Spain	108955	12.4	7
United Republic of Tanzania	Pakistan	30719	2.7	2
Vanuatu	Australia	5755	0.9	225
Vanuatu	China, mainland	1012	0.1	24
Vanuatu	Fiji	343	0.0	8
Vanuatu	Singapore	432	0.0	6
Vanuatu	Thailand	419	0.0	7
Vanuatu	United States of America	927	0.1	24
Vanuatu	Viet Nam	914	0.2	38
Venezuela (Bolivarian Republic of)	Argentina	54621	9.8	8
Venezuela (Bolivarian Republic of)	Brazil	102840	11.4	10
Venezuela (Bolivarian Republic of)	Guyana	149825	14.6	13
Venezuela (Bolivarian Republic of)	United States of America	157781	16.5	14
Yemen	India	211504	18.7	40
Yemen	Oman	23857	2.0	4
Yemen	Pakistan	74646	6.6	14
Yemen	Thailand	145594	9.9	21
Zimbabwe	Pakistan	43111	3.8	13
Zimbabwe	South Africa	35421	1.5	5
Zimbabwe	Thailand	37663	2.6	9
Zimbabwe	United Arab Emirates	13880	1.2	4
Zimbabwe	Viet Nam	6314	1.1	4

The estimated daily dietary exposure (mg/kg BW/day) can be calculated from EHR shown in Table S8 by dividing by the cancer slope factor for arsenic, equal to 1.5 (mg/kg/day)⁻¹.

Table S8. Embedded health risk (EHR) in rice (1: 100 000). Ranked by EHR_j

Country	Rice in national market A= (1-β) EHR _{ij}	Imported rice B= βEHR _j *	A+B= TEHR _j	β
Bangladesh	148	2	150	0.021
Vietnam	141	0	141	0.015
Cambodia	110	1	111	0.007
Indonesia	76	2	78	0.022
Philippines	65	5	69	0.052
Republic of Korea	57	4	59	0.070
Kiribati	0	57	57	1.000
Solomon Islands	0	53	53	1.000
Thailand	46	0	46	0.001
China, mainland	44	1	45	0.012
Guyana	44	0	44	0.000
Malaysia	23	17	40	0.290
Panama	27	11	38	0.280
India	36	0	36	0.000
Japan	34	2	36	0.060
Fiji	6	29	35	0.760
Senegal	4	30	34	0.751
Vanuatu	0	33	33	1.000
Nepal	28	4	32	0.095
Oman	0	29	29	1.000
United Arab Emirates	0	29	29	1.000
Sri Lanka	25	3	28	0.058
Côte d'Ivoire	7	21	28	0.536
Madagascar	24	4	27	0.070
China, Hong Kong SAR	0	27	27	1.000
Peru	26	1	27	0.078
China, Taiwan Province of	25	2	27	0.073
Costa Rica	18	9	27	0.325
Nicaragua	17	8	25	0.304
Benin	1	22	23	0.889
Mauritius	0	23	23	0.997
Kuwait	0	23	23	1.000
Cabo Verde	0	22	22	1.000
Brazil	20	1	21	0.051
China, Macao SAR	0	20	20	1.000
Mauritania	5	14	19	0.587
Saudi Arabia	0	19	19	1.000
Suriname	17	0	17	0.005
Belize	15	1	16	0.069
Ghana	3	13	16	0.593

Country	Rice in national market	Imported rice	A+B= TEHR _j	β
	A= (1- β) EHR _{ij}	B= β EHR _j *		
Colombia	15	1	16	0.064
Bolivia (Plurinational State of)	14	2	16	0.074
Egypt	16	0	16	0.011
Gabon	0	15	15	0.978
Mali	12	2	14	0.140
Venezuela (Bolivarian Republic of)	8	5	13	0.367
Saint Vincent and the Grenadines	0	13	13	1.000
Iran (Islamic Republic of)	8	4	12	0.428
Jordan	0	12	12	1.000
Saint Kitts and Nevis	0	12	12	1.000
New Caledonia	0	11	11	1.000
Ecuador	10	1	11	0.028
Bahamas	0	11	11	1.000
Cameroon	1	10	11	0.842
Portugal	6	4	10	0.442
Jamaica	0	10	10	0.999
Togo	3	7	10	0.551
Israel	0	10	10	1.000
Trinidad and Tobago	1	9	10	0.941
Australia	8	1	9	0.230
Argentina	9	0	9	0.005
Honduras	2	7	9	0.796
South Africa	0	9	9	0.997
Yemen	0	8	8	1.000
Nigeria	5	3	8	0.233
Burkina Faso	2	6	8	0.702
Canada	0	7	7	1.000
Afghanistan	5	2	7	0.276
Kenya	0	6	6	0.887
Pakistan	6	0	6	0.004
El Salvador	2	5	7	0.748
New Zealand	0	6	6	1.000
Lebanon	0	6	6	1.000
Chile	3	3	6	0.492
Niger	1	5	6	0.833
Turkey	3	2	5	0.340
Spain	5	1	6	0.112
Antigua and Barbuda	0	5	5	1.000
United Republic of Tanzania	5	0	5	0.032
Mongolia	0	5	5	1.000
Albania	0	5	5	1.000

Country	Rice in national market	Imported rice	A+B= TEHR _j	β
	A= (1-β) EHR _{ij}	B= βEHR _j *		
Belgium	0	5	5	1.000
Dominica	0	4	4	1.000
Zimbabwe	0	4	4	0.996
United States of America	4	0	4	0.067
Kyrgyzstan	2	2	4	0.504
Kazakhstan	3	0	3	0.065
United Kingdom	0	3	3	1.000
Guatemala	1	3	4	0.793
Mexico	1	3	3	0.786
Bermuda	0	3	3	1.000
Sweden	0	3	3	1.000
Italy	3	0	3	0.101
Rwanda	1	2	3	0.427
Paraguay	3	0	3	0.005
Russian Federation	2	1	3	0.234
Namibia	0	3	3	1.000
Denmark	0	3	3	1.000
Greece	2	0	2	0.106
Malta	0	3	3	1.000
France	0	2	2	0.828
Czechia	0	2	2	1.000
Luxembourg	0	2	2	1.000
Finland	0	2	2	1.000
Norway	0	2	2	1.000
Slovenia	0	2	2	1.000
Cyprus	0	2	2	1.000
Austria	0	2	2	1.000
Uruguay	2	0	2	0.002
Algeria	0	2	2	0.997
Belarus	0	2	2	1.000
Iceland	0	2	2	1.000
Lithuania	0	2	2	1.000
Germany	0	2	2	1.000
Botswana	0	2	2	1.000
Ukraine	1	1	2	0.362
Republic of Moldova	0	2	2	1.000
Ireland	0	2	2	1.000
Netherlands	0	2	2	1.000
Uganda	1	1	2	0.415
Croatia	0	1	1	1.000
Slovakia	0	1	1	1.000

Country	Rice in national market	Imported rice	A+B= TEHR _j	β
	A= (1-β) EHR _{ij}	B= βEHR _j *		
Estonia	0	1	1	1.000
Georgia	0	1	1	1.000
Switzerland	0	1	1	1.000
Latvia	0	1	1	1.000
Romania	0	1	1	0.687
Malawi	1	0	1	0.006
Montenegro	0	1	1	1.000
Bosnia and Herzegovina	0	1	1	1.000
Azerbaijan	0	1	1	0.845
Hungary	0	1	1	0.746
Zambia	0	1	1	0.342
Bulgaria	0	1	1	0.475
Tunisia	0	1	1	1.000
Serbia	0	1	1	1.000
Poland	0	1	1	1.000

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