Human arsenic exposure risk via crop consumption and global trade from groundwater-irrigated areas

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Abstract

While drinking water is known to create significant health risk in arsenic hazard areas, the role of exposure to arsenic through food intake is less well understood, including the impact of food trade. Using the best available datasets on crop production, irrigation, groundwater arsenic hazard, and international crop trade flows, we estimate that globally 17.2% of irrigated harvested area (or 45.2 million hectares) of 42 main crops are grown in arsenic hazard areas, contributing 19.7% of total irrigated crop production, or 418 million metric tons (MMT) per year of these crops by mass. Two-thirds of this area is dedicated to the major staple crops of rice, wheat, and maize (RWM) and produces 158 MMT per year of RWM, which is 8.0% of the total RWM production and 18% of irrigated production. More than 25% of RWM consumed in the South Asian countries of India, Pakistan, and Bangladesh, where both arsenic hazard and degree of groundwater irrigation are high, originate from arsenic hazard areas. Exposure to arsenic risk from crops also comes from international trade, with 10.6% of rice, 2.4% of wheat, and 4.1% of maize trade flows coming from production in hazard areas. Trade plays a critical role in redistributing risk, with the greatest exposure risk borne by countries with a high dependence on food imports, particularly in the Middle East and small island nations for which all arsenic risk in crops is imported. Intensifying climate variability and population growth may increase reliance on groundwater irrigation, including in arsenic hazard areas. Results show that RWM harvested area could increase by 54.1 million hectares (179% increase over current risk area), predominantly in South and Southeast Asia. This calls for the need to better understand the relative risk of arsenic exposure through food intake, considering the influence of growing trade and increased groundwater reliance for crop production.

1. Introduction

Long-term drinking of arsenic-contaminated groundwater is a serious risk to human health in many parts of the world [1, 2]. It is estimated that 94–220 million people globally are exposed to arsenic in groundwater above the World Health Organization (WHO) drinking-water guideline value (10 µg l⁻¹) [3]. Compared to the risk arising from drinking water, which has been reported and studied extensively [1–5], dietary intake of arsenic via food crops is relatively less explored but is increasingly recognized as a significant additional health risk [2, 4–6]. Long term ingestion of arsenic is reported to lead to several adverse human health effects, including cancer, skin lesions, developmental effects, cardiovascular disease, neurotoxicity, and diabetes [7]. There is a clear evidence that irrigation with groundwater contaminated with geogenic arsenic causes arsenic to accumulate in soil and subsequently in crops through the water-soil-plant uptake pathway (figure 1) [1, 4, 6, 8–13].

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Several studies have looked at arsenic uptake in crops from soil and its subsequent transfer to humans via dietary intake [1, 2, 4–7, 13–15]. The health risk from food intake of arsenic could be equivalent to or larger than that for drinking water [2, 16, 17]. Among the crops at risk of arsenic contamination, rice has received the most attention [2, 6, 14, 15]. This is due to the relatively high intrinsic susceptibility of rice to arsenic uptake [18], the prevalent practice of flood irrigation of rice paddy fields creating anaerobic conditions making inorganic arsenic readily available [4, 6], and the rice-rich diet in heavily arsenic-affected regions, notably Bangladesh and eastern India. Although the level of contamination in wheat and maize is found to be up to an order of magnitude lower than that of rice [18], they are the major staple cereal crops, along with rice, for much of the human population [19] and hence could pose a risk.

Previous arsenic food risk studies focused on the risk associated with the intake of inorganic arsenic in crops grown locally or procured from local markets [1, 2, 10, 12, 14]. This disregards the role of trade, which can transfer the risk geographically and can increase exposure even in low arsenic risk countries [13, 20]. This component may be significant given that most countries (∼80%) depend on imports for a bulk of their food supply (especially staple crops) or to meet intermittent supply shortfalls [21]. Although studies have been made on global virtual water flows [22] and global groundwater depletion embedded in trade [23], none have systematically looked at the global transfer of crop-embedded geogenic arsenic contamination derived from groundwater irrigation and associated human exposure and health risks. One study found that vegetables imported from Bangladesh had arsenic concentration 2–3 times higher than that of vegetables cultivated in the United Kingdom/EU [24]. These health concerns are increasingly relevant and important given that the global trade of agricultural exports between 2002 and 2012 increased by about 200% in terms of economic value, and 60% in physical terms, and has been projected to rise uninterruptedly [25].

The projected increase in food production due to population growth is anticipated to rely considerably on the expansion of irrigation-based agriculture as climate change manifests itself [26, 27]. Such expansion could be associated with higher arsenic exposure risk, as groundwater irrigation moves into areas with high arsenic hazard [4, 7].

In this paper, we provide a critical first-order global-level understanding of the magnitude and
distribution of potential crop production from groundwater irrigation in groundwater arsenic hazard areas and its transfer via trade. We combine the best available global data on crop production, irrigated areas and groundwater arsenic hazard areas with country-level trade flows to systematically estimate:

(a) Total crop production at risk of arsenic contamination;
(b) The role of international trade in transferring and redistributing risk and,
(c) The extent of crop areas at risk with respect to future groundwater irrigation expansion.

Estimating arsenic crop uptake based on water and soil arsenic concentrations comes with high uncertainty as arsenic uptake depends on the interplay of many agronomic and biophysical factors [4, 6, 7, 12, 13]. Hence, rather than estimating an absolute mass of crop contaminated with arsenic, we estimate the mass of crop at risk of arsenic contamination from the crop production in areas of high groundwater arsenic hazard.

2. Methods

The global risk analysis included spatial analysis to assess production of crops in arsenic hazard areas and their redistribution via trade was carried out in three steps:

(a) Determine crop production irrigated with groundwater in areas with a high hazard of arsenic in groundwater (concentration $>10 \mu g L^{-1}$), referred to as crop production from hazard areas $(\text{CropProd}_{\text{As}})$. This was done for 42 crops;
(b) Determine the contributions and pathways of $\text{CropProd}_{\text{As}}$ for rice, wheat and maize (RWM) in global crop trade as well as its contribution to total crop availability, domestic production and any net import, for each country;
(c) Assess future risk due to possible expansion of groundwater irrigation into areas with high hazard of groundwater arsenic.

Details of the datasets applied are given in table 1. The analysis of global crop production from hazard areas was carried out at a resolution of 5 arc min. For this, the groundwater arsenic hazard (item 3, table 1) map was resampled to 5 arc min using the average of all values in the finer 30 arc s grid. The analysis of future crop production risk was carried out at resolution of 30 arc min, for which all datasets were aggregated to 30 arc min resolution by averaging the values in the finer grids.

2.1. Global crop production from hazard areas

To determine crop production from hazard areas $(\text{CropProd}_{\text{As}})$ of crop $c$ in grid cell $g$ $(\text{CropProd}_{\text{As}(c,g)})$, a global dataset of the distribution and production of crops from the spatial production allocation model [28, 29] (SPAM) was used. This uses a cross-entropy approach to estimate crop distribution for 42 crops and two production systems within disaggregated units. SPAM data cover all crops reported by Food and Agriculture Organization (FAO), except explicit fodder crops (mostly grasses). The SPAM data were combined with FAO global spatial datasets of Global Map of Irrigation Areas (GMIA) that gives total irrigated area and their distribution between surface and groundwater irrigation [30]. The FAO map of surface and groundwater irrigation was used to disaggregate the SPAM map of total irrigated cultivated area into groundwater and surface water irrigated cultivated areas using a set of logical decision rules:

(a) If the FAO map shows no or partial groundwater irrigation in a cell and the corresponding SPAM cell has a larger irrigated area, the excess area in SPAM is presumed to be surface water irrigated.
(b) If the irrigated area in the SPAM cell is less than that of the FAO groundwater irrigated area (or zero), the SPAM cell’s irrigated area is used as the area of groundwater irrigated cultivated area (and the difference is assumed to be an error).

Thereafter, for each grid cell, the fraction $(F)$ of SPAM groundwater-irrigated cultivated area relative to total irrigated cultivated area was calculated. The fraction of groundwater irrigated area $(F)$ was then multiplied by the SPAM total irrigated harvested area $(\text{CropArea}_{\text{irr, total}(c,g)})$ of each crop $c$ to derive the groundwater-irrigated crop harvest area $(\text{CropArea}_{\text{GW, total}(c,g)})$. The SPAM irrigated crop production dataset $(\text{CropProd}_{\text{irr, total}(c,g)})$ and derived groundwater and surface-water irrigated harvested areas were then used to derive groundwater-irrigated $(\text{CropProd}_{\text{GW, total}(c,g)})$ and surface-irrigated $(\text{CropProd}_{\text{SW, total}(c,g)})$ crop production in million metric tons (MMT) (equation (1)).

This assumes that the crop productivity of groundwater is twice that of surface water [34, 35] due to higher reliability of groundwater and consequent higher investments in other crop inputs like fertilizers, pesticides, and seeds. Based on reviewed literature, cultivated areas irrigated with groundwater could be five to six times more productive than an area irrigated with the same volume of surface water [35]. To estimate crop production from groundwater and surface water irrigated areas, the share of irrigation water from groundwater is assumed to be equal to the proportion of groundwater-irrigated area:
2.2. Role of international trade in transferring arsenic risk from crop production in hazard areas

For each country i, the contribution of crop production from hazard areas (CropProd_{As(c,i)}) of crop c (considering only rice, wheat and maize), to global trade was assessed using the FAO trade matrix, which gives the quantity of all food and agriculture products imported and exported annually by all countries [31]. The traded mass of secondary products (crop derivatives) was converted to primary crop equivalent mass using extraction coefficients [23] (table S1 (available online at stacks.iop.org/ERL/16/124013/mmedia)). When evaluating the contribution of CropProd_{As(c,i)} to trade and domestic crop availability, the same proportion of CropProd_{As(c,i)} for the primary crop was also used for secondary products. This assumption was made due to only limited data being available on how arsenic concentration and bioavailability in various derivatives compare to those of primary crops. In any case, the majority of trade involves primary products (rice: 93%, wheat 73% and maize 63%) [31].

The average annual exports of crop c from country i, CropExport_{total(c,i)}, for the 5 year period 2003–2007, corresponding to SPAM data, which is for 2005, were determined by averaging the annual imports reported by trading partner countries for the period. Because import data were considered more reliable

| Item | Data | Resolution | Dataset, year, organization | Reference |
|------|------|------------|----------------------------|-----------|
| 1    | Crop distribution and production | 5 arc min | SPAM v2.0 2005 Harvest Choice, IFPRI | [28, 29] |
| 2    | Total irrigated and groundwater irrigated area | 5 arc min | Global map of irrigated area (GMIA, v 5.0), 2005, FAO and University of Bonn | [30] |
| 3    | Groundwater arsenic hazard | 30 arc s | Groundwater arsenic contamination (Global) 2020 Eawag | [3] |
| 4    | Country crop trade data | Country | Detailed crop trade matrix, 2003–2007, FAO | [31] |
| 5    | Groundwater recharge | 30 arc min | WaterGap, 1980–2009, Univ. Kassel | [32] |
| 6    | Groundwater salinity | 30 arc min | WHYMAP, 2004, BGR/UNESCO | [33] |

CropProd_{GW_total(c,g)} = \frac{2 \times \text{CropArea}_{GW_{total}(c,g)}}{1 + \text{CropArea}_{irri_{total}(c,g)}} \text{CropProd}_{irri_{total}(c,g)} \quad (1)

A global map of the probability of the concentration of arsenic in groundwater exceeding the WHO guideline of 10 µg L\(^{-1}\) \((\text{Prob}_{As(g)} (0.0 \leq \text{Prob}_{As(g)} \leq 1.0)) [3] \) was used to divide groundwater-irrigated harvested area \((\text{CropArea}_{GW_{total}(c,g)})\) into hazard \((\text{CropArea}_{As(c,g)})\) and non-hazard areas \((\text{CropArea}_{non-As(c,g)})\) (equation (2)). This was done assuming that the hazard area per cell is proportional to the probability of the concentration of arsenic in groundwater exceeding the guideline value for that cell \((\text{Prob}_{As(g)})\) (equation (2)). This was done for all 42 crops (equation (2)). This is then used to derive the associated crop production (in MMT), from hazard and non-hazard areas referred to as crop production from hazard areas \((\text{CropProd}_{As})\) and non-hazard areas \((\text{CropProd}_{non-As})\) using the same probability fraction (equation (2));

\[
\text{CropArea}_{As(c,g)} = \text{Prob}_{As(g)} \times \text{CropArea}_{GW_{total}(c,g)} \\
\text{CropArea}_{non-As(c,g)} = (1 - \text{Prob}_{As(g)}) \times \text{CropArea}_{GW_{total}(c,g)} \\
\text{CropProd}_{As(c,g)} = \text{Prob}_{As(g)} \times \text{CropProd}_{GW_{total}(c,g)} \\
\text{CropProd}_{non-As(c,g)} = (1 - \text{Prob}_{As(g)}) \times \text{CropProd}_{GW_{total}(c,g)} \quad (2)
\]

The harvested areas and production amounts were then summed by country. The contribution of crop production in hazard areas \((\text{CropProd}_{As(c,i)})\) to total crop production \((\text{CropProd}_{total(c,i)})\) for each country was determined as a percentage \((\text{CropProd(\%)}_{As(c,i)})\) (equation (3)):

\[
\text{CropProd(\%)}_{As(c,i)} = \frac{\text{CropProd}_{As(c,i)}}{\text{CropProd}_{total(c,i)}} \times 100 \quad (3)
\]
[23], export data reported by a country were used only to fill in missing data, e.g. if importing countries do not report imports but the country in question reports exports to that country. Total imports of crop c (rice, wheat or maize) by country i, \( \text{CropImport}_{c(i)} \), were determined by summing total exports from all other countries to the country in question. CropExport\(_{c(i)}\) was constrained by the estimated sum of total country production and imports (CropProd\(_{c(i)}\) + CropImport\(_{c(i)}\)).

The fraction of CropProd\(_{As(c,i)}\) in CropExport\(_{c(i)}\) of crop c from country i is assumed to be the same as that of the overall production (equation (3)) and is used to calculate CropExport\(_{As(c,i)}\) (equation (4)):

\[
\text{CropExport}_{As(c,i)} = \left( \frac{\text{CropProd}(\%)}{100} \right) \times \text{CropExport}_{c(i)}
\]

Like above, total imports of crop production from hazard areas (CropImport\(_{As(c,i)}\)) of crop c (rice, wheat or maize) by country i were determined by summing total exports from hazard areas from all other countries to the country in question. In countries where export (CropExport\(_{c(i)}\)) is more than internal production (CropProd\(_{c(i)}\)), due to channeling via intermediary countries in the case of indirect exports [36], CropExport\(_{As-total(c,i)}\) was modified to account for the redirecting of imports (equation (5)). We assume that the fraction of crop production from hazard areas in this excess CropProd\(_{c(i)}\) is the same as that in total imports \( \left( \frac{\text{CropImport}_{As(c,i)}}{\text{CropImport}_{c(i)}} \right) \):  

\[
\text{CropExport}_{As(c,i)} = \left( \frac{\text{CropProd}(\%)}{100} \right) \times \text{CropProd}_{c(i)} \\
+ \left( \frac{\text{CropImport}_{As(c,i)}}{\text{CropImport}_{c(i)}} \right) \times (\text{CropExport}_{c(i)} - \text{CropProd}_{c(i)}) \\
(\text{if} \text{CropExport}_{c(i)} > \text{CropProd}_{c(i)})
\]

A country’s total crop availability \( \text{CropAvail}_{c(i)} \) and crop availability from crops with arsenic risk \( \text{CropAvail}_{As(c,i)} \) were then determined using equations (6) and (7), respectively:

\[
\text{CropAvail}_{c(i)} = \text{CropProd}_{c(i)} + \text{CropImport}_{c(i)} - \text{CropExport}_{c(i)}
\]

\[
\text{CropAvail}_{As(c,i)} = \text{CropProd}_{As(c,i)} + \text{CropImport}_{As(c,i)} - \text{CropExport}_{As(c,i)}
\]

Finally, the percentage of total crop availability \( \text{CropAvail}_{c(i)} \) of crop c in country i grown in hazard areas was calculated (equation (8)) along with the proportion of that derived from imports (CropImport\(_{As(c,i)}\)) (equation (9)): 

\[
\text{CropAvail}_{As(c,i)}(\%) = \left( \frac{\text{CropAvail}_{As(c,i)}}{\text{CropAvail}_{c(i)}} \right) \\
\text{CropImport}_{As(c,i)}(\%) = \left( \frac{\text{CropImport}_{As(c,i)}}{\text{CropAvail}_{c(i)}} \right)
\]
CropAvail(%)_{As(c,i)} = \left( \frac{\text{CropAvail}_{As(c,i)}}{\text{CropAvail}_{Total(c,i)}} \right) \times 100 \tag{8}

CropImport(%)_{As(c,i)} = \left( \frac{\text{CropImport}_{As(c,i)}}{\text{CropAvail}_{As(c,i)}} \right) \times 100 \tag{9}

2.3. Future risk from crop production expanding into areas with groundwater arsenic hazard

To assess the risk associated with any future shift from surface-water irrigation or rainfed cultivation to groundwater irrigation in arsenic hazard areas, the feasibility of using groundwater for irrigation was first assessed. This was determined using the groundwater recharge rate [32] and groundwater salinity [33]. Areas with groundwater recharge less than 50 mm yr\(^{-1}\) were considered too dry to sustain sufficient groundwater recharge for sustainable development. Groundwater quality suitable for irrigation was determined by considering salinity (total dissolved solids). Areas where salinity is greater than 5 g l\(^{-1}\) were excluded (~2.5% of worldwide land area). Irrigation water with salt content of 2–5 g l\(^{-1}\) can generally be used for salt-tolerant crops with permeable soils and good management practices, whereas higher concentrations are generally not suitable [37].

Future potential groundwater-irrigated RWM-cultivation areas were then compared with groundwater arsenic hazard areas. Overlapping areas, per crop c and grid cell g, were counted as potential risk areas (equation (10)) using the probability scaling as in equation (2) and summed by crop and country:

\[
\text{CropArea}_{\text{risk}(c,g)} = \text{Prob}_{As(g)} \times \text{CropArea}_{\text{rainfed}(c,g)} + \text{Prob}_{As(g)} \times \text{CropArea}_{\text{surface irrigated}(c,g)} \tag{10}
\]

2.4. Datasets

Table 1 summarizes the global datasets used in the analysis. Since the datasets of both crop production and irrigated areas (table 1, items 1 and 2) relate most closely to the situation in 2005, the aggregated analysis is ascribed to the year 2005. Furthermore, groundwater recharge (item 5) and the FAO datasets on crop trade by country (item 4) are averages from 1980 to 2009 and 2003–2007, respectively. The parameters given in the maps of groundwater arsenic risk (item 3) and the salinity map (item 6) are generally constant or slowly varying. We included 198 countries in our analysis based on data availability and the importance of trade.

3. Results

3.1. Crop production from groundwater arsenic hazard areas

Globally, the total harvested area irrigated with groundwater having arsenic risk (i.e. groundwater arsenic hazard areas or simply hazard areas) (CropArea\(_{As}\)) is 45.2 million hectares (Mha), producing (CropProd\(_{As}\)) annually 418.2 MMT dry mass of 42 main crops. This is 17.2% and 19.7% of the total harvested area and crop production of these 42 crops from irrigated areas, respectively. Relative to total crop production, including surface irrigated and rainfed areas, CropProd\(_{As}\) is 6.4%. Table 2 gives the top-ten food crops in terms of CropArea\(_{As}\) and CropProd\(_{As}\). Rice, wheat, maize, vegetables, and sugarcane contribute most significantly to CropArea\(_{As}\) and CropProd\(_{As}\). India, the USA, and China are the major producers of CropProd\(_{As}\). India is the top producer of sugarcane, wheat, rice, sorghum, and vegetables; the USA of potatoes, sugar beets and temperate and tropical fruits; and China of maize.

Wheat, rice, and maize are the top-three staple cereal crops in terms of global crop production in hazard areas (table 2). A much higher share of sugarcane in CropProd\(_{As}\) (38.2% of total production) relative to its share in CropArea\(_{As}\) (4.7% of total harvested area) is due to its much higher crop yield. Although sugarcane constitutes the greatest absolute amount of CropProd\(_{As}\) (160 MMT yr\(^{-1}\)), relatively little is known about its uptake of arsenic and subsequent propagation through derivative food products and trade. Furthermore, as sugarcane does not constitute a major staple crop, it was not included in the subsequent analysis.

3.2. Global rice, wheat and maize production from hazard areas

The total global cultivated area of RWM irrigated with groundwater in hazard areas (CropArea\(_{As-RWM}\)) is 30.2 Mha (table 2). This area annually produces 158.0 MMT dry mass of RWM, hereafter referred to as RWM crop production from hazard areas (CropProd\(_{As-RWM}\)). This represents 5.8% of the total cultivated area of RWM (16.8% of RWM-irrigated cultivated areas) and 8.0% of total RWM production by mass (18.0% of the total mass of irrigated RWM production). The total annual RWM crop production from hazard areas is broken down as follows: 57.2 MMT from rice (36.2%), 61.4 MMT from wheat (38.8%), and 39.4 MMT from maize (24.9%). Figure 2 depicts the global distribution of RWM crop production from hazard areas for each of the crops. Of particular note is the Indo-Gangetic Plains, which are a major producer of rice and wheat, the North China Plains producing wheat and maize, and the
Great Plains of the USA, which are a main source of maize.

Table 3 lists the top-ten countries of RWM crop production from hazard areas for each of the three crops. Global CropProdAsRice is dominated by India and Bangladesh (70.3% of total CropProdAsRice), while CropProdAsWheat is primarily attributed to India and China (75.1% of total CropProdAsWheat), and CropProdAsMaize to China and the USA (77.2% of total CropProdAsMaize). The contribution of CropProdAsRWM to the total country crop production (from irrigated and rainfed) of the three crops is significant in many countries (up to around 45%); for example for rice: Bangladesh (29.1%), Pakistan (24.3%), India (22.6%) and USA (20.2%); wheat: Bangladesh (45.5%), India (41.4%) Saudi Arabia (37.5%), Mexico (32.4%) and Pakistan (26.9%); and maize: Pakistan (22.2%) and China (14.1%). These are much higher than the global average production from hazard areas of 9.3% (rice), 10.0% (wheat), and 5.6% (maize) (table 3). The exposure risk from internal production in these countries is therefore high, though trade can increase or decrease this risk.

3.3. Role of international trade in transferring arsenic risk from crop production in hazard areas

The total global crop trade between 2003 and 2007 for rice, wheat and maize was estimated at 47.2, 175.3 and 150.8 MMT yr⁻¹, respectively (table 4). The part of global crop trade per crop coming from crop production in hazard areas (CropExport(%)AsRWM) amounts to 10.6%, 2.4% and 4.1% for rice, wheat and maize, respectively (table 4). In total, 15.4 MMT, or 9.7%, of total RWM originating from hazard areas is traded. The proportion of traded rice originating from hazard areas is slightly greater than the relative total production from hazard areas for rice (9.3%), whereas it is considerably lower than that for wheat (10.0%) and slightly lower than that for maize (5.6%) (table 3). This is because some of the large producers of rice with relatively high proportions of crop production from hazard areas (e.g. India, USA, and Pakistan; table 3, CropProd(%)AsRice) are also major exporters (table 4 and figure 3). Conversely, in the case of wheat, the USA is the only country among the top-five producers of wheat from hazard areas (table 3) that is also a major exporter (table 4). Furthermore, of the top-ten wheat-exporting countries, all except the USA have a very small proportion of their exports (<1.0%) originating from arsenic hazard areas (table 4). Likewise for maize, all of the top-ten major exporters, except China, have a very small proportion of their exports (<4%) coming from hazard areas (table 4).

Figure 3 summarizes for each of the three crops the direction of net crop trade flows from the five major exporters of crops from hazard areas to their top importers. The largest exporters for rice are India, the USA, Pakistan, Thailand and Australia; for wheat India, the USA, China, Pakistan and Mexico; and for maize the USA, China, France, Argentina and India. Although India, China, Pakistan and Mexico are not among the overall top-ten wheat exporters overall (table 4), they feature prominently in figure 3 due to a high fraction of their wheat export coming from hazard areas (table 3)
3.4. Country-level proportion of crop production from hazard areas

The proportion of RWM crops for consumption (domestic production + imports – exports) originating from groundwater irrigation in arsenic hazard areas (CropAvail(%)$_{As-RWM}$) was determined for each country. These were then grouped into large and small countries based on a population threshold of 1.5 million, as defined by the World Bank [38]. This was done to enable the analysis of the relatively low absolute quantities of exports and imports in small countries, for which trade can play an important role. Table 5 lists the top-ten large and small countries in terms of CropAvail(%)$_{As-RWM}$, indicating also the
Table 3. Top-ten countries in terms of annual crop production from hazard areas for RWM and the contribution of crop production from hazard areas to total country crop-specific production from irrigated and rainfed production.

| Country   | CropProd_{As-Rice} (MMT yr^{-1}) | CropProd(%)_{As-Rice} | Country   | CropProd_{As-Wheat} (MMT yr^{-1}) | CropProd(%)_{As-Wheat} | Country   | CropProd_{As-Maize} (MMT yr^{-1}) | CropProd(%)_{As-maize} |
|-----------|----------------------------------|------------------------|-----------|-----------------------------------|------------------------|-----------|----------------------------------|------------------------|
| India     | 30.2                             | 22.6%                  | India     | 28.9                              | 41.4%                  | China     | 19.6                             | 14.1%                  |
| Bangladesh| 10.0                             | 29.1%                  | China     | 17.2                              | 17.4%                  | USA       | 10.8                             | 3.8%                   |
| China     | 6.2                              | 3.5%                   | Pakistan  | 5.5                               | 26.9%                  | India     | 1.6                              | 11.1%                  |
| Pakistan  | 2.0                              | 24.3%                  | USA       | 1.9                               | 3.5%                   | Mexico    | 1.4                              | 6.8%                   |
| USA       | 2.0                              | 20.2%                  | Iran      | 1.4                               | 10.0%                  | Italy     | 0.7                              | 6.8%                   |
| Thailand  | 1.3                              | 4.3%                   | Saudi Arabia | 1.0                         | 37.5%                  | Pakistan  | 0.7                              | 22.2%                  |
| Philippines| 0.4                       | 3.2%                   | Turkey    | 1.0                               | 4.9%                   | France    | 0.5                              | 3.9%                   |
| Iran      | 0.4                              | 14.5%                  | Mexico    | 0.9                               | 32.4%                  | Argentina | 0.5                              | 3.2%                   |
| Nepal     | 0.4                              | 8.6%                   | Syrian    | 0.7                               | 15.2%                  | Spain     | 0.5                              | 12.7%                  |
| Japan     | 0.3                              | 3.6%                   | Bangladesh| 0.4                              | 45.5%                  | Egypt     | 0.4                              | 5.7%                   |
| Global    | 57.2                             | 9.3%                   | Global    | 61.4                              | 10.0%                  | Global    | 39.4                             | 5.6%                   |
Table 4. Top-ten countries in terms of total annual crop exports (MMT yr\(^{-1}\)) of rice, wheat and maize. For each crop, the proportion of exports grown in hazard areas is given as a percentage.

| Country | CropExport\(_{\text{Total-Rice}}\) | CropExport(%\(_{\text{As-Rice}}\)) | Country | CropExport\(_{\text{Total-Wheat}}\) | CropExport(%\(_{\text{As-Wheat}}\)) | Country | CropExport\(_{\text{Total-Maize}}\) | CropExport(%\(_{\text{As-Maize}}\)) |
|---------|-----------------------------------|----------------------------------|---------|-----------------------------------|----------------------------------|---------|-----------------------------------|----------------------------------|
| Thailand | 14.1                              | 4.3%                             | USA     | 30.3                              | 3.5%                             | USA     | 65.6                              | 3.8%                             |
| India   | 6.7                               | 22.6%                            | France  | 18.0                              | 0.1%                             | Argentina| 13.8                              | 3.2%                             |
| Viet Nam| 5.6                               | 0.6%                             | Canada  | 16.8                              | <0.01%                           | France  | 10.7                              | 3.9%                             |
| USA     | 5.2                               | 20.2%                            | Australia| 13.8                              | 0.3%                             | China   | 10.3                              | 14.1%                            |
| Pakistan| 3.8                               | 24.3%                            | Argentina| 11.0                              | 0.6%                             | Brazil  | 7.6                               | 0.4%                             |
| China   | 2.2                               | 3.5%                             | Russia  | 10.4                              | <0.01%                           | Netherlands| 3.0                              | 2.6%                             |
| Egypt   | 1.4                               | 4.1%                             | Germany | 9.0                               | <0.01%                           | Belgium | 3.0                               | 1.9%                             |
| Uruguay | 1.1                               | 2.6%                             | Kazakhstan| 6.2                              | 0.5%                             | Hungary | 2.8                               | 0.5%                             |
| Italy   | 1.0                               | 8.2%                             | Ukraine | 5.6                               | <0.01%                           | Germany | 2.4                               | 1.9%                             |
| Australia| 0.7                              | 29.4%                            | Italy   | 3.3                               | 0.4%                             | Ukraine | 2.3                               | <0.01%                           |
| Global  | 47.2                              | 10.6%                            | Global  | 175.3                             | 2.4%                             | Global  | 150.8                             | 4.1%                             |
share of availability for individual crops and the overall contribution of imports to availability. In all top-ten large countries, at least 10.0% of total RWM crop availability originates from hazard areas. Topping the list in terms of CropAvail(%)\textsubscript{As-RWM} for large countries are Bangladesh (27.7%), India (27.7%), and Pakistan (25.3%). Overall, rice and wheat contribute equally (average of 41.5% and 50.1%, respectively, for the ten countries) followed by relatively small contribution from maize (average of 8.4%). These figures and those reported hereafter are simple non-weighted country averages. The role of imports is highly variable, with an overall contribution of imports to CropAvail(%)\textsubscript{As-RWM} ranging from 0.1% to 100%. For Bangladesh, India, Pakistan, and China, which are major producers of RWM (table 3), the risk originates almost exclusively from domestic production, whereas for other large countries, including Middle Eastern countries (Saudi Arabia, UAE and Syria), Somalia and Haiti, a large part, up to 100%, of CropAvail(%)\textsubscript{As-RWM}, is imported.

In all top-ten small countries, at least 9.0% of total RWM crop availability originates from hazard areas. Topping the list in terms of CropAvail(%)\textsubscript{As-RWM} for small countries are the island states of Solomon Islands (19.4%), Kiribati (19.3%) and Bahrain (16.9%). Importantly, rice contributes the most to small countries CropAvail(%)\textsubscript{As-RWM} (average of 75.9%) followed by relatively small contributions from wheat (average of 13.0%) and maize (average of 11.3%). In contrast to large countries, 100% of CropAvail(%)\textsubscript{As-RWM} is imported for all top-ten small countries. This highlights the critical role of trade in exposing import-dependent countries to arsenic risk.

Figure 4 shows the frequency distribution plot of hazard area contribution (%) to domestic production and net crop (RWM) availability for 194 countries of the world. The influence of trade in redistributing risk is clearly visible. The results show that there are 118
| Country       | Percentage of RWM availability from hazard areas (CropAvail(%)$_{As-RWM}$) and share of each crop (%) | Imported percentage of RWM availability from hazard areas (CropImport(%)$_{As-RWM}$) |
|--------------|-------------------------------------------------------------------------------------------------|--------------------------------------------------------------------------------|
|              |                                                                                                 |                                                                                |
| Large countries |                                                                                                 |                                                                                |
| Bangladesh   | 27.7%                                                                                           | 5.2%                                                                           |
| India        | 27.7%                                                                                           | 0.1%                                                                           |
| Pakistan     | 25.3%                                                                                           | 0.4%                                                                           |
| Saudi Arabia | 19.7%                                                                                           | 31.1%                                                                          |
| United Arab Emirates | 14.0%                                                                                       | 100.0%                                                                         |
| Somalia      | 13.4%                                                                                           | 100.0%                                                                         |
| Oman         | 13.2%                                                                                           | 100.0%                                                                         |
| Syrian       | 10.6%                                                                                           | 22.8%                                                                          |
| Haiti        | 10.4%                                                                                           | 89.0%                                                                          |
| China        | 10.2%                                                                                           | 0.2%                                                                           |
| Small countries |                                                                                                 |                                                                                |
| Solomon Islands | 19.4%                                                                                       | 100.0%                                                                         |
| Kiribati     | 19.3%                                                                                           | 100.0%                                                                         |
| Bahrain      | 16.9%                                                                                           | 100.0%                                                                         |
| Maldives     | 16.8%                                                                                           | 100.0%                                                                         |
| Qatar        | 15.3%                                                                                           | 100.0%                                                                         |
| Micronesia   | 14.3%                                                                                           | 100.0%                                                                         |
| Comoros      | 13.4%                                                                                           | 100.0%                                                                         |
| Vanuatu      | 13.3%                                                                                           | 100.0%                                                                         |
| Bahamas      | 10.7%                                                                                           | 100.0%                                                                         |
| Mauritius    | 9.4%                                                                                             | 100.0%                                                                         |

**Table 5.** Top-ten large and top-ten small countries in terms of proportion of RWM availability (CropAvail(%)$_{As-RWM}$) from arsenic hazard areas and contribution of each crop. Proportion of CropAvail(%)$_{As-RWM}$ originating from imports (CropImport(%)$_{As-RWM}$) is given as a percentage.

**Figure 4.** Distribution plot showing contribution (%) of RWM grown in hazard areas to country domestic production and net crop availability for 194 countries of the world.
countries where domestic production from hazard areas is non-zero (>0.1%). However, the contribution of production from hazard areas in countries’ net crop availability is non-zero in 193 countries. Similarly, the number of countries where more than 5% of net crop availability comes from hazard areas is 50, compared to 36 countries where domestic production from such areas is more than 5%. Globally, for 105 countries, import contributes 90% or more of country total crop availability from hazard areas.

3.5. Potential risk from future irrigated groundwater crop production expanding into arsenic hazard areas

Crop production from surface water irrigated and rainfed cultivated areas overlying groundwater arsenic hazard areas may be at future risk if these are converted into groundwater irrigation, e.g. due to growing food demands and greater seasonal variability in water availability due to climate change. Possible new hazard areas of groundwater irrigation with RWM are 54.1 Mha, an increase of 179% over current conditions (30.2 Mha). The majority of future risk areas are currently under rainfed cultivation (41.6 Mha or 77%), with surface water irrigated areas making up the remainder (12.5 Mha or 23%). About 43% of future risk areas are presently cultivated for rice (23.2 Mha). Given their relatively low arsenic exposure risk, current wheat and maize areas can be regarded as low risk areas in terms of irrigation shift unless converted to other crops, such as rice.

Of the 23.2 Mha of rice area under future risk, 13.6 Mha (59%) is currently rainfed and 9.6 Mha (41%) is irrigated with surface water. Table S2 gives the top-ten countries in terms of present rainfed and surface-water irrigated rice cropland areas that could potentially be converted into groundwater irrigation in hazard areas. Of the top-ten countries of potential future risk in rainfed areas, eight countries are in South Asia (Bangladesh, India, and Nepal) and Southeast Asia (Cambodia, Indonesia, Myanmar, the Philippines, and Thailand) (figure 5).
for India and Thailand, these countries are not major rice exporters currently (table 4), and so their future risk relates primarily to domestic consumption. Future rice-risk areas in surface water irrigated regions are dominated by China followed by India and Southeast Asian countries (Bangladesh, Indonesia, Philippines, Thailand, and Vietnam) (figure 5, table S2). In China, the risk region is located in Southern China and covers ~21% of the present surface-irrigated area of the country (table S2). Both India and China are among top-ten exporters of rice (table 4), indicating that future exposure risk affects domestic populations as well as importing countries.

4. Discussion

Our study shows that there are two main pathways of human exposure risk to arsenic from crop intake, i.e. crops produced domestically, and crops traded internationally, with contribution from the latter not traditionally accounted for [4–7, 14–17, 39–42]. Crops produced domestically represent the main risk pathway for countries where extensive groundwater irrigation exists in extensive arsenic hazard areas. These include the South Asian countries of Bangladesh, India, and Pakistan. Exposure from crops in these countries comes in addition to that of drinking water, which can be comparatively high [3, 5, 6].

In addition, international crop trade plays a significant role in redistributing risk globally. Almost 10% of RWM production from hazard areas (15.4 MMT) is traded internationally, with rice disproportionately traded more than wheat and maize, due to large exporters of rice having relatively high proportions of crop production from hazard areas (e.g. India, USA, and Pakistan). The trade pathway represents the main exposure route for many countries, which rely heavily on crop imports. This includes the Middle East and small countries. Globally, 105 countries have 90% or more of RWM availability from hazard areas originating from imports. The significant role of trade in redistributing risk calls for expanding arsenic risk assessments both at an international scale but also at a national and subnational scale, to understand the origin and proportions of available crops from hazard areas and possible precautionary measures. Traditionally, research has focused on arsenic-affected regions, particularly in Bangladesh and West Bengal, India [16, 17, 39], where sources are well-known, or as part of country-specific arsenic risk assessments in developed countries, e.g. USA [40], Sweden [41] or Europe [42], but with limited attention to the importance of trade.

Though wheat and maize are less prone to arsenic uptake relative to rice [18], a high proportion of production coming from hazard areas and high consumption of wheat and maize can increase the exposure risk. This calls for expanding traditional risk assessment approaches [e.g. 1, 9, 10, 14] to account for all main staple crops while understanding the relative risk from various crops in diets in different contexts.

As population growth leads to increased food demand, and the effects of climate change are progressively manifested through increasing variability in water availability, crops in hazard areas may increasingly become irrigated with groundwater, which could lead to long-term adverse impacts on human health through various food distribution pathways. Results show that such future groundwater irrigation expansion into presently rainfed or surface water irrigated areas could increase the current RWM cultivation in hazard areas by 179%. The risk from such expansion is already imminent in multiple places. For example, in Cambodia, increasing crop arsenic risk from the expanding use of groundwater to mitigate drought and boost cropping intensity in rainfed areas has been documented as a cause of concern [43]. Similarly, in hazard areas of rainfed rice cultivation in eastern India, policies on promoting the development of groundwater irrigation to alleviate endemic poverty, increase food productivity and production [44, 45], and indirectly avoid further groundwater depletion from intensively irrigated production in northwestern India [46], need to factor in this potential risk. Thus, any future crop intensification and irrigation strategies must consider this risk.

5. Uncertainties and future research

Our assessment involves two major sources of the uncertainty: (a) quality and reliability of the data used and (b) methodological assumptions and simplifications made. Although the best available published global datasets were used (section 2, table 1), which have undergone extensive testing and validation, they come with assumptions and uncertainty. The datasets on gridded crop production (SPAM) [28, 29] and irrigation (GMIA) [30] are associated with uncertainty due to regional variations in quality and reliability of subnational statistics, other underlying datasets (e.g. cropland cover), and the downscaling methodological approaches used [28, 29, 47, 48]. SPAM builds extensively on cross-comparison with and supersedes other global agricultural production datasets (M3-Crops, MIRCA and GAEZ data) [29, 47]. SPAM (v2.0) has a more detailed collection of subnational statistical data, has been extensively validated using multiple approaches, and with more versions planned, provides the flexibility to update the analysis in the future [28, 29, 47]. Similarly, the irrigated area map (GMIA v5) has been extensively validated and has updated the inventory of subnational irrigation statistics [30], but uncertainty from regional variability in the availability and reliability of underlying subnational statistics remains [30, 48].
The most recent arsenic hazard map at the global scale [3] was used to define arsenic hazard areas. This map indicates arsenic hazard areas based on a compiled global dataset of arsenic observations and machine-learning modeling [3]. The accuracy of the global arsenic prediction model against test observations is high (e.g., area under curve, AUC of 0.89 [3]), but there remain parts of the world with very sparse observations (e.g., Africa and Russia) where the model predictions are associated with relatively higher uncertainty. The global crop trade dataset [31] was averaged over five years (2003–2007) to smooth out annual variability in trade data. However, our exposure risk assessment accounting for the role of trade does not factor in subnational level variability in contributing to international trade. It also does not account for any internal trade or redistribution of crops. For large countries, such as the USA, India or Pakistan, disregarding this introduces uncertainties in trade flows of crops and associated risk. For example, the Indian government’s procurement of rice for export comes mostly from the states of Punjab, Haryana, and Andhra Pradesh (~52% of procurement in 2017–18) [49]. These states have relatively low arsenic concentrations in groundwater compared with the Ganges Basin states of Uttar Pradesh, West Bengal, and Bihar [50], from where only 14% of procurement for export derives [49].

Global analysis requires making certain assumptions and simplifications. We assume, backed by strong published evidence, that crops grown in areas, and irrigated, with arsenic-contaminated groundwater have a higher probability of being contaminated with arsenic, and that the probability is proportional to the groundwater hazard [1, 4, 6–8]. However, several local factors can impact arsenic uptake, for example crop type and variety, irrigation method and technology, well depth, soil type, etc [4, 6, 7, 12, 13]. Better understanding the relative significance of and accounting for these factors may improve risk estimation. Research in this field may also point to technological and agronomic innovations, which may significantly change the estimation of future risk. The future exposure risk may also be affected by demographic, socio-economic, climate change and policy directions, which could significantly affect future risk areas.

Our study is a first step to understand and assess the magnitude of global arsenic exposure risk from crops grown in groundwater-irrigated hazard areas as well as plausible major risk source areas and trade pathways. Critical future research areas include: (a) assessing arsenic concentration in exported/imported crops (especially rice and for countries with a large dependence on trade); (b) creating improved maps of arsenic contamination risk in groundwater through better and higher-frequency/higher density monitoring of arsenic concentration in groundwater with focus on less densely mapped but anticipated high risk zones; (c) assessing intra-country production and trade patterns to understand the spread of risk within large countries with the highest risk and from where export derives (e.g., India, USA) and (d) better understanding of the transfer of risk via other large commodities such as sugar or vegetables, derived/processed food products (especially wheat) and from animal products.

6. Conclusion

This study provides a first-order global assessment of the distributed human exposure risk to arsenic through crops irrigated with groundwater in areas of probable high arsenic content (hazard areas), with a focus on the major staple crops of RWM. Annually, 158 MMT of RWM is produced in hazard areas, which corresponds to 18% of the total irrigated production and 8% of total (irrigated plus rainfed) production by mass of RWM. Our results show that domestic production combined with international trade of these crops derived from hazard areas leads to significant human exposure risk to arsenic from crop intake globally. Domestic production is the main source of exposure risk for countries where extensive groundwater irrigation exists in arsenic hazard areas (India, Bangladesh, and Pakistan), whereas international trade is the main source of risk exposure for countries relying heavily on imports to meet their crop demands. These include Middle Eastern and small countries.

The analysis points to the need for a thorough consideration of future arsenic risk from the expansion of groundwater irrigation in arsenic hazard areas. The analysis points to the need for global studies on the relative risk to human health from intake of arsenic-contaminated crops, as propagated through domestic or traded production as well as from drinking water. Such understanding can lead to enhanced global collaboration and policy development on the most promising mitigation approaches and guidelines for addressing all aspects of the risk chain, from groundwater and soil contamination, to crop uptake, human diet, and global trade risk propagation.

Data availability statement

The data that support the findings of this study are available upon reasonable request from the authors.

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Author contributions

Karen G Villholth conceived the research question and led the project. Mohammad F Alam conducted the spatial and non-spatial data analysis, Joel Podgorski provided critical insights on method design and result interpretation. Mohammad F Alam wrote the initial draft of the paper, with substantial contributions from all authors.

Conflict of interest

The authors declare no competing interests.

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