Plant Soil
https://doi.org/10.1007/s11104-020-04518-z

REGULAR ARTICLE

Soil arsenic but not rice arsenic increasing with arsenic in irrigation water in the Punjab plains of Pakistan

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Received: 14 January 2020 / Accepted: 27 March 2020

Abstract
Aim Irrigating rice with groundwater can lead to As accumulation in soil and rice grains. Matched sets of irrigation water, paddy soil, and rice grains were collected to assess the scale of the problem in the Punjab plains of Pakistan.
Methods From a total of 60 sites, irrigation water and rice grains as well as 103 soil samples were collected and analyzed in the laboratory. Irrigation water and 660 soil samples were also analyzed in the field using a field kit.
Results Concentrations of As in irrigation water (65 ± 32 μg/L) are higher in the floodplain of the Ravi River compared to the Chenab (13 ± 9 μg/L) and Jhelum (4 ± 5 μg/L) rivers, as well as the intervening Rechna (6 ± 6 μg/L) and Chaj doabs (0.8 ± 0.2 μg/L). Area-weighted mean soil As concentrations are 12 ± 3 mg/kg along the Ravi, 8.9 ± 2 and 8.1 ± 2 mg/kg along the Chenab and Jhelum, respectively, and 6.2 ± 0.2 mg/kg within the Rachna and 6.1 ± 0.1 mg/kg in Chaj doabs. The As content of polished grains export-quality basmati rice of 0.09 ± 0.05 mg/kg, however, is low across the entire area.
Conclusions Groundwater irrigation leads to elevated As concentrations in paddy soil of some rice-growing regions of Punjab but does not result in increased uptake of As in basmati rice grains.

Keywords Arsenic · Groundwater · Soil · Rice · Punjab

Responsible Editor: Fangjie Zhao.

Electronic supplementary material The online version of this article (https://doi.org/10.1007/s11104-020-04518-z) contains supplementary material, which is available to authorized users.

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Introduction

The northern Indus Plain of Pakistan is known as the rice-wheat belt, with rice grown in summer (Kharif) and wheat in winter (Rabi) (Hassan and Bhutta 1996). Pakistan ranks 10th globally in terms of rice production but is the world's 4th largest exporter at 4 million tons of rice per year (FAO 2017). On account of the semi-arid to arid climate of the country, an extensive network of canals was built starting in the nineteenth century to distribute water draining the Himalayas (Greenman et al. 1967). In northern Punjab, growing wheat during winter requires little irrigation (Naheed and Mahmood 2009), but rice requires about 1.6 m of water per season (Erenstein 2009). Supplemental irrigation is typically needed because the summer rains are insufficient. Since the 1960s, the canal irrigation system has gradually been supplanted by pumping groundwater from wells which numbered over half a million by 2000 and most of which are located in Punjab (Qureshi et al. 2010).

Unfortunately, the pumped groundwater can be contaminated with arsenic (As) in some parts of the country, including in northern Punjab which is the country's main rice growing region and where the present study was conducted (Farooqi et al. 2007; Javed et al. 2019; Nickson et al. 2005). Testing of over 30,000 drinking-water wells across 400 villages of northern Punjab on both sides of the border between Pakistan and India has revealed that As concentrations in groundwater are particularly elevated along the floodplain of the Ravi River, whereas the Sutlej, Chenab, and Jhelum floodplains are less affected (van Geen et al. 2019). This could be a concern for two reasons: the accumulation of As in paddy soil leading to a reduction in yield and the translocation of As to the rice grain resulting in human exposure.

Many studies, most conducted in Bangladesh, have shown that irrigating with groundwater that is elevated in As results in the accumulation of As in the upper ~20 cm of soil (Duxbury et al. 2009; Meharg and Rahman 2003; Panaullah et al. 2009; Van Geen et al. 2006). A few studies have shown that this accumulation of As significantly reduces rice production (Hossain et al. 2008; Huhmann et al. 2017; Panaullah et al. 2009). Most reports have focused instead on the accumulation of As in rice grains, concluding in some cases that high As concentrations in soil result in increased As concentrations in the grain (Azad et al. 2009; Khan et al. 2009; Rahaman et al. 2011; Rauf et al. 2011; Williams et al. 2006; Zhao et al. 2009), with others pointing to less conclusive results (Panaullah et al. 2009; Stroud et al. 2011; Van Geen et al. 2006). Given the growing evidence of the negative health impacts of exposure to As, including in early life, As accumulation in rice is a serious issue (Davis et al. 2012). Considerable attention therefore continues to be paid to rice varieties that accumulate less As in the grain (Halder et al. 2012; Williams et al. 2005), as well as changes in water or soil management that reduce the uptake of As by the rice plant (Duxbury and Panaullah 2007; Spanu et al. 2012).

Previous reports on rice grown in Pakistan indicate relatively low As concentration in export-quality basmati, although these analyses were not paired with soil As measurements (Adomako et al. 2011; PCRWR 2014; Zavala and Duxbury 2008). In the present study, we explore the potential relationship between As in paddy soil and rice grains in a new setting by taking advantage of the recently documented difference in groundwater As levels across different floodplains and doabs of northern Punjab (van Geen et al. 2019). Along with irrigation water, transects of surface soil were collected from dozens of fields across the region and paired with rice samples obtained directly from the farmer cultivating each field. Motivated by the need for farmers to know the status of their field, we used a kit to analyze the As content of irrigation water and paddy soil in the field for comparison with laboratory measurements.

Materials and methods

The study area lies in northern Punjab ("five rivers") and is bound by the floodplain of the Jhelum River to the northwest and the floodplain of the Ravi River to the southeast (Fig. 1). The floodplain of the Chenab River divides the region roughly midway into the slightly elevated Chaj and Rechna doabs, a local word to describe the land between two rivers.

Sampling

From each of 60 individual rice fields irrigated by a single well, matched sets of irrigation-well water, and 10 surface soil samples were collected. Water was collected from the irrigation wells without filtration in 20 mL polyethylene scintillation vials with a PolySeal-lined cap (Wheaton no. 986706) and soil in polyethylene bags. Ten ~100 g soil samples scooped from the upper ~1 cm were evenly spaced along the diagonal across each field originating from the corner closest to the inlet of the irrigation water to the corner furthest away (Online Resource Fig. 1). For a subset of 10 fields in the floodplain of the Ravi River, a locally-made stainless steel core sampler (diameter 2.5 in., length 70 cm) was used to collect a soil profile to 60 cm depth in 10-cm intervals. About 1 kg of polished rice sample of the same 60 fields from the previous season was also obtained directly from the farmers and stored in polyethylene bags. Given that the harvest from each field was dried and threshed locally by each farmer, it is reasonable to assume that rice grains from different parts of the field had been well mixed and that the sample was therefore representative. A total of 60 water and 660 soil tests were conducted in the field using the ITS Econo-Quick kit (George et al. 2012). The same well water

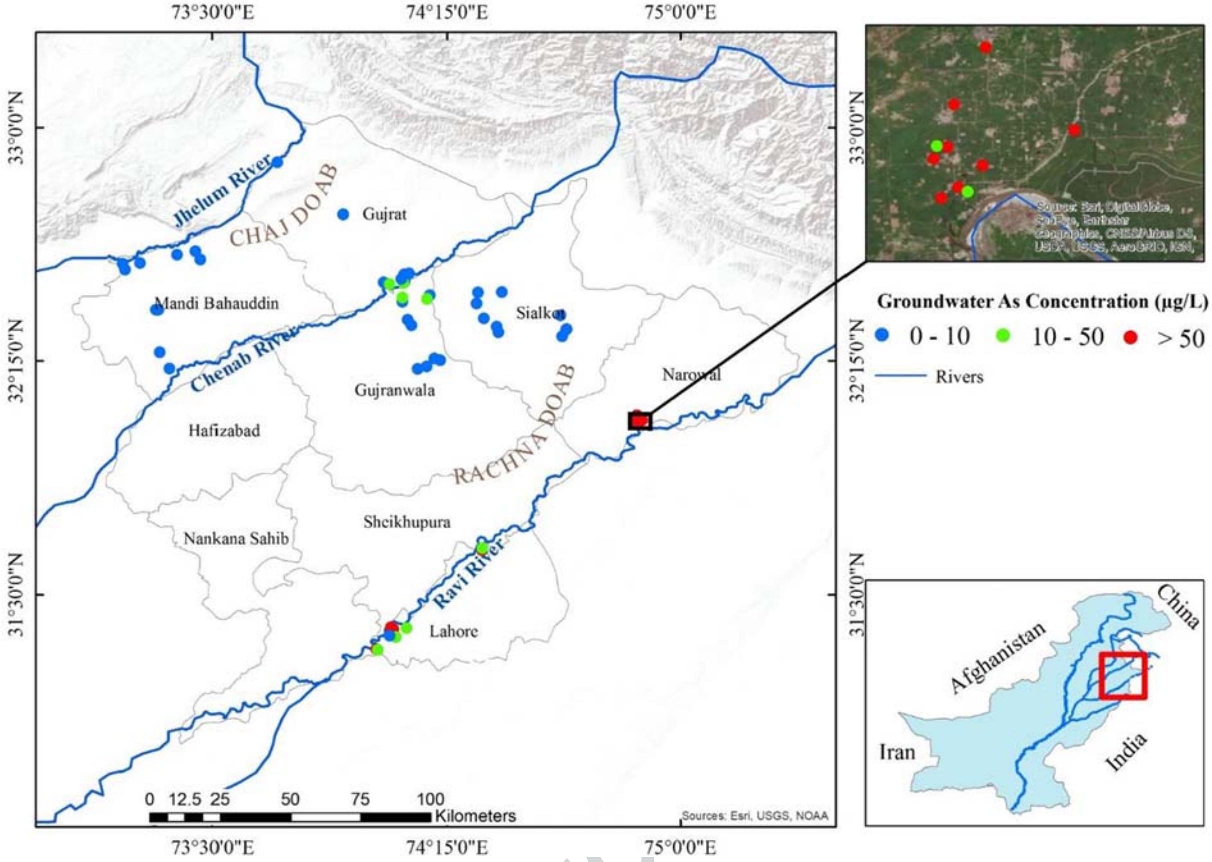

Fig. 1 Map of northern Punjab with the 60 study sites and the As content of water sampled from irrigation wells at each site

samples and a subset of 103 soil samples were also analyzed in the laboratory (Online Resource Table 1).

Laboratory measurements

Water samples were acidified to 1% high-purity HCl (Fisher Scientific Optima) at least one week before analysis by high-resolution inductively-coupled plasma mass spectrometry (HR ICPMS) on a Thermo-Finnigan Element2 at Lamont Doherty Earth Observatory (LDEO) Laboratory of Columbia University, New York, USA (Cheng et al. 2004). This procedure has previously been shown to re-dissolve any iron oxides and therefore As that might have precipitated (Van Geen et al. 2007). An internal consistency standard containing 430 µg/L As and reference materials NIST1640a (8.08 ± 0.07 µg/L As) and NIST1643e (58.98 ± 0.7 µg/L As) were included with every run to ensure accuracy and precision of the method within <5%. The detection limit of the procedure is <0.1 µg/L based on the variability of the blank.

Soil samples collected in polyethylene bags were sun-dried and homogenized. Out of a total of 660 soil samples, a subset of 103 samples spanning the range of As concentrations were analyzed for As using an Innov-X Delta Premium field X-ray fluorescence spectrometer in the soil mode for a total counting time of 120 s. All soil As concentrations were above the detection limit of the XRF for As of ~3 mg/kg under these conditions. Soil standards 2709 and 2711 from the National Institute of Standards and Technology (NIST) were analyzed at the beginning and end of each of the two sample runs, and once in the middle of the longer run. The measured average and standard deviation for NIST 2709 of 16.9 ± 0.9 mg/kg ($n = 5$) matched the reference value of 17.7 ± 0.8 mg/kg and the measured average and standard deviation for NIST 2711 was 105 ± 4 mg/kg (n = 5) matched the reference value of 105 ± 8 mg/kg.

Polished rice grains were washed with deionized (DI) water and sun dried. Individual 7 g portions of rice were pulverized with a coffee grinder and transferred to a 200 mL glass beaker. The volume was raised to 70 mL with DI water and 1% HNO_3. The solution was then boiled for 20 min using a gas burner. Evaporation was compensated by adding DI water to raise the volume back to 70 mL, after which the digest solution was cooled in a water bath. A portion of each digest was saved in 20 mL polyethylene scintillation vials with a PolySeal-lined cap (Wheaton no. 986706) and analyzed by HR ICPMS after diluting 5-fold in a 1% HNO_3 solution containing a Ge spike for drift correction (Cheng et al. 2004). The remaining 50 mL was saved for analysis using a different kit (see below). In total, rice samples were digested and analyzed in triplicate from all 60 fields where irrigation water and soil samples were analyzed as well. For quality control, the same procedure was followed to measure the As content of rice flour obtained as Standard Reference Material 1568a from NIST. The mean As concentrations of 0.28 ± 0.02 mg/kg measured by analyzing 3 batches of SRM 1568b using the above procedure was consistent with its certified value of 0.285 ± 0.014 mg/kg.

Field kit measurements

Irrigation water samples were analyzed for As using the ITS Arsenic Econo-Quick Kit, which relies on the generation of arsine gas and a strip impregnated with mercuric bromide turning from white to yellow, orange, or brown depending on the level of arsenic (George et al. 2012). The second of the kit's 3 reagents, an oxidant to suppress potential interference by hydrogen sulfide, was not added. Each test strip was matched visually to the closest of a sequence of colors corresponding to 0, 10, 15, 50, 100, 200, 300, 500, and 1000 μg/L As provided by a reference card supplied with the kit. Paddy soil was also analyzed for easily mobilized As using the ITS Econo-Quick field kit using a modification of the procedure. Using a battery-powered balance, 0.5 g of wet soil was added to 50 mL of DI water in the kit's reaction vessel and subsequently handled as a water sample. For quality control, water standards containing 50 and 100 μg/L of total As prepared in deionized were analyzed each day in the field.

The method of Bralatei et al. 2015 was used in an attempt to measure the inorganic As (iAs) of rice with only two slight modifications: digesting 7 g of rice in 70 mL instead of 5 in 50 mL, and adjusting the volume back to 70 mL at the end to avoid the formation of a thick slurry. The 50 mL of saved digest was transferred to the reaction bottle, after which 2–3 drops of antifoaming agent were added followed by one sachet of sulfamic acid and one tablet of $NaBH_4$. The lead acetate filter was used to remove H_2S and the $HgBr_2$ holder for trapping the generated arsine. The sample was allowed to react for 20 min, after which the $HgBr_2$ holder was inserted in the digital reader. The reader was zeroed with a blank filter paper before each measurement. The iAs concentration in rice flour measured for NIST Standard Reference Material 1658b with the Arsenator averaged 0.04 ± 0.01 mg/kg ($n = 3$), i.e. only 40% of the certified value of 0.092 ± 0.01 mg/kg. For this reason, we make no attempt to interpret the average iAs concentration of 0.023 ± 0.01 mg/kg ($n = 60$ triplicates) measured in the Punjab rice samples.

Results

Distribution of As in irrigation water

The World Health Organization guideline of 10 μg/L for As in drinking water is not directly relevant to crop irrigation but still a useful benchmark. On the basis of laboratory measurements, 31 out of 60 samples of irrigation water contained ≤10 μg/L As, with 27 out of the remaining 29 samples containing ≤100 μg/L (Fig. 1). Concentrations of As in the two remaining irrigation wells, both in the Ravi floodplain, were marginally higher at 102 and 135 μg/L, respectively (Fig. 2a). The proportion of wells with >10 μg/L As is the highest in the Ravi floodplain (17 out of 20 wells), followed by the Chenab floodplain (5/9), the Rechna doab (4/19), the Jhelum floodplain (1/ 6), and the Chaj doab (0/6) (Online Resource Table 2). The floodplain was assumed to extent 8 km from either side of the river for this study, with more distant areas classified as doabs (Greenman et al. 1967).

Kit measurements in the field correctly classified irrigation wells relative to the WHO guideline for 27 out 31 wells containing ≤10 μg/L and 26 out 29 wells containing >10 μg/L based on ICPMS measurements. Nominal kit values over-estimated the actual As concentration by a factor of 4 ± 3 for As concentrations >10 μg/L (Fig. 2a).

Distribution of As in paddy soil

Average concentrations of As in soil samples measured by XRF increase roughly linearly from 6.1 ± 0.4 mg/kg

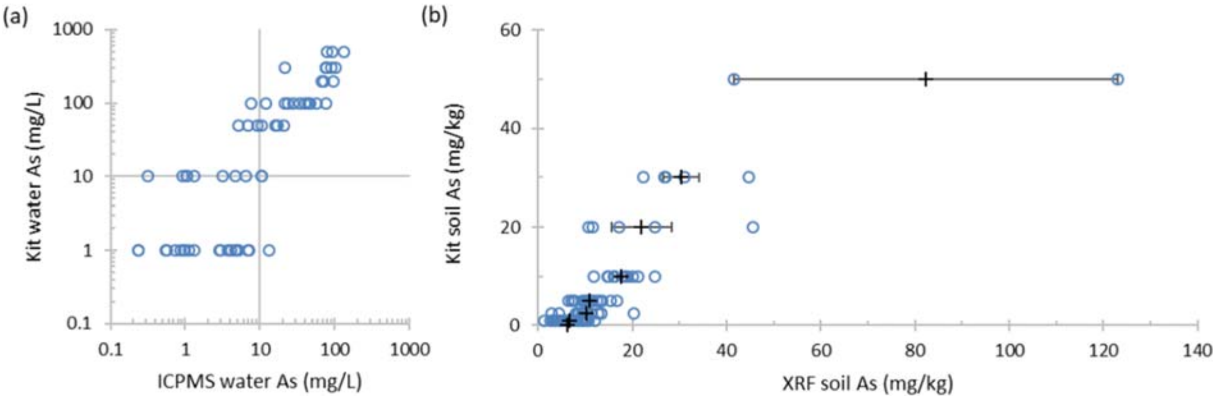

Fig. 2 Comparison of kit measurements in the field and with laboratory measurements of (a) well-water As concentrations ($n = 60$) by HR ICP-MS and soil As concentrations ($n = 103$) by XRF

for the lowest kit reading of 0 µg/L to 30 ± 4 mg/kg for a kit reading of 300 µg/L, which is equivalent to a leachable As concentration of ~30 mg/kg in the soil (Fig. 2b). The average of 82 mg/kg As in soil at the high end for the kit reading of 500 µg/L, equivalent to 50 mg/kg in soil, doesn't follow quite the same trend but is constrained by only two samples. Only a fraction of the total As is likely to be released by the kit during the 10 min reaction time. The almost one-to-one correspondence between total As measured by XRF and As released measured by the kit is therefore serendipitous and attributable to the kit overestimating the As concentration in the soil-water slurry. All kit soil measurements displayed and discussed hereon were converted to the average As concentration obtained for each kit value by XRF (Online Resource Table 3).

For lack of a local regulatory standard, the subset of soil samples analyzed by XRF are classified relative to Japan's threshold of 15 mg/kg As for paddy soil (MOE 2016). For the subset of soil samples analyzed with the kit and by XRF, the classification relative to that threshold (0–15 mg/kg) was correct in 81 (88%) out 92 cases whereas 11 (12%) were not consistent with XRF measurements (Online Resource Table 4). All inconsistencies were underestimates by the kit relative to XRF. Converting all the soil measurements to concentrations based on XRF show that that 30% ($n = 200$) of soil samples from the Ravi, 4% ($n = 90$) from the Chenab, and 2% ($n = 60$) from the Jhelum floodplain do not meet this standard (Online Resource Table 5). In contrast, all 150 analyzed soil samples from Rechna and Chaj contained <15 mg/kg As. The kit did not detect any soil As for three-quarters of the samples from the Rechna doab ($n = 190$) and all samples from the Chaj doab (n = 90).

Most diagonal transects with elevated levels of As in soil show higher concentrations recorded closest to the current inlet of irrigation water (Fig. 3). For the 10 profiles close to the inlet in the Ravi floodplain, 22 out of 30 intervals in the 0–30 cm depth range contained >15 mg/kg As whereas only 3 out of 30 intervals in the 30–60 cm depth range did so (Fig. 4, Online Resource Table 6).

Concentration of As in rice grains

Average concentrations of As in rice based on triplicates for 60 samples ranged from 0.05 to 0.28 mg/kg (Fig. 5). Standard deviations for triplicates were < 0.05 mg/kg for 52 out of 60 sets of samples. The concentration of As in rice grain averaged over all 60 samples was 0.09 ± 0.05 mg/kg based on all 180 measurements. The lowest grain As concentrations of 0.06 ± 0.01 mg/kg (with standard error of the mean) were measured in the Jhelum flood plain for 6 sets of triplicates and the highest of 0.090 ± 0.01 mg/kg in the Ravi floodplain for 20 sets of triplicates. The 2-standard error intervals of these two averages overlap and their difference is therefore not statistically significant at the 0.05 level (Online Resource Table 7).

Discussion

Accumulation of As in soil

The observed pattern of highest soil As concentrations closest to the inlet of the irrigation water has been documented previously in Bangladesh and attributed to the

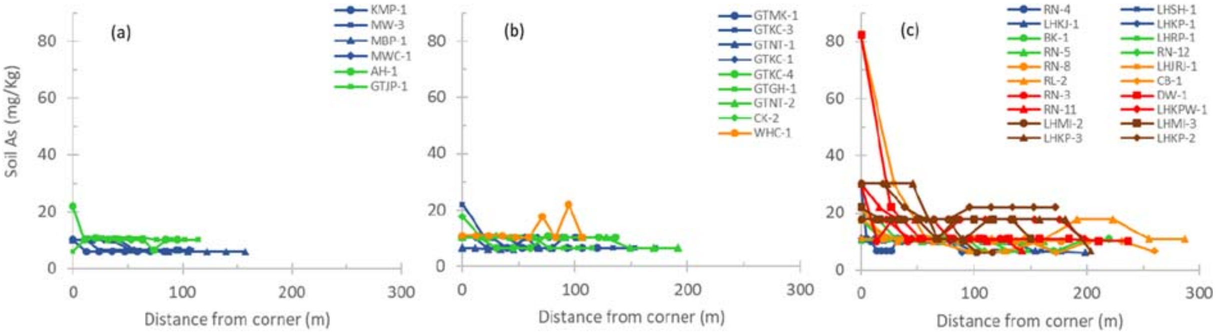

Fig. 3 Surface soil As concentrations for 10 equidistant points along a diagonal from corner of the field closest to the entry point of irrigation water to the opposite corner of the field in floodplains of the (**a**) Jhelum, (**b**) Chenab, (**c**) and Ravi rivers. Each colored line indicates a specific rice field and the points on the line show the concentrations for every single sample. Soil As concentration were measured with the ITS Econo-Quick kit in the field and converted to equivalent readings by XRF (Fig. 2 and Online Resource Table 3). The sites are ordered by increasing area-weighted mean soil As and represented by the different color and symbol combinations in sequence of blue<green<orange<red<brown and circles<square < triangles<diamonds based on area-weighted As

co-precipitation of As with iron oxyhydroxides after oxidation in contact with air (Dittmar et al. 2007; Roberts et al. 2007). A few fields in the Ravi and Chenab floodplains where soil As levels are higher away from the inlet may indicate that the position of the inlet was moved or that the field was reconfigured in the past (Fig. 3). The Ravi>Chenab>Jhelum>Rechna>Chaj sequence of geographic units based on average soil As content (Fig. 5) follows the Ravi>Chenab>Rechna>Jhelum>Chaj sequence based on the proportion of irrigation wells with >10 μg/L, with the exception of a switch in order between the Jhelum floodplain and the Rechna doab (Fig. 1). The As content of irrigation water therefore seems to determine the As content in excess of local background for paddy soil across the region.

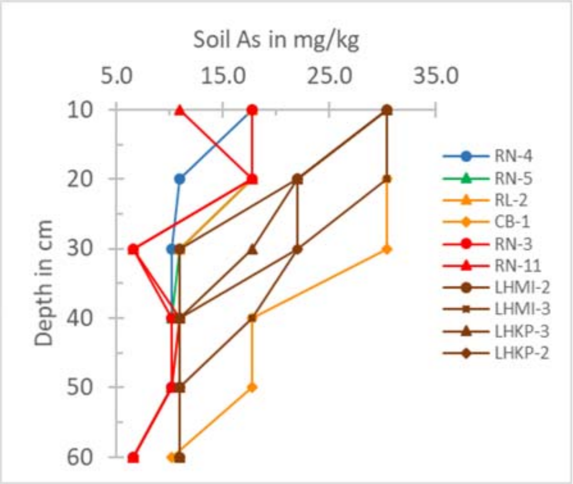

Fig. 4 Soil As in soil profiles close to the inlet of ten selected fields in Ravi flood plain. The soil As concentration was measured by ITS Econo-Quick field kit and converted based on mean XRF As for each kit bin. (Fig. 2 and Online Resource Table 6)

Groundwater has been used for growing rice in the region starting in the 1960s (Qureshi et al. 2010). In order to relate the duration of irrigation with groundwater to the accumulation of As in soil, each diagonal transect of soil As measurements was first converted to a representative field average by weighing the first 5 samples by 0.6, 5, 10, 15, and 20%, respectively, and by the same weights in reverse order for last 5 samples based on simple geometry (Online Resource Fig. 1). Subtracting a background concentration of 6 mg/kg As and assuming a bulk density of the soil of 1.5 g/cm^3, an excess inventory of As per surface area was calculated for each field. Farmers in the study area require an average of 1.6 m of water, groundwater and rainfall combined, to grow rice each season (Erenstein 2009). None of the farmers participating in this study reported using canal water to irrigate their rice field, either because they were too far away from a canal or because canal water did not reach them. Rainfall during the rice growing season across the study region between 1981 and 2010 averaged 0.4 m in the driest southwesterly portion of the study area to 0.7 m in the wettest northeasterly portion (Bokhari et al. 2017). By difference, the quantity of groundwater required in the driest area was therefore estimated at 1.2 m (22 sites), in the intermediate area at 1.0 m (27), and 0.9 m (11) in the wettest area. From these net requirements, the amount of As supplied by pumping groundwater for growing rice each year was calculated using the As concentrations measured for irrigation water in the laboratory.

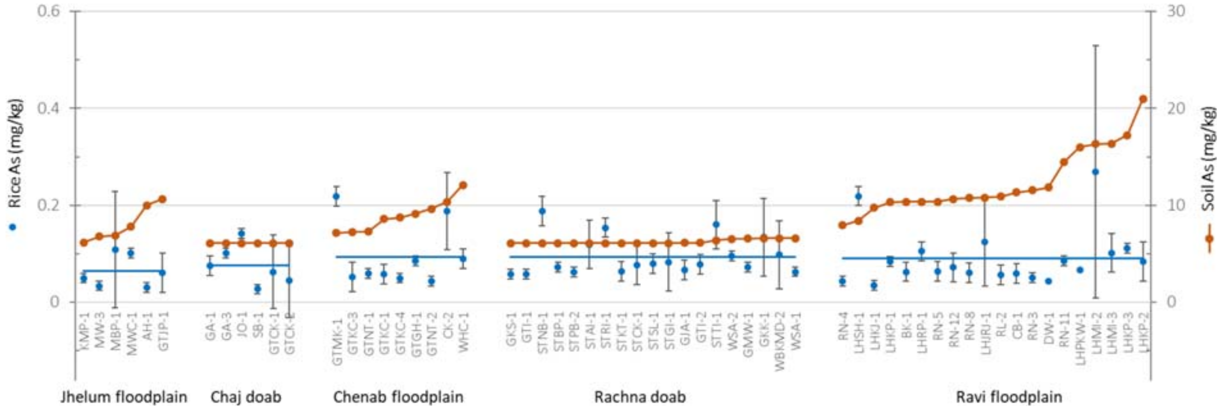

Fig. 5 Soil and rice As, sorted by soil As, in a geographical sequence from West to East: 1) Jhelum floodplain, 2) Chaj Doab, 3) Chenab floodplain, 4) Rachna Doab, and 5) Ravi floodplain. The blue circles show the mean rice As (mg/kg) of 3 batches in the same field, the error bars show the standard deviation between the 3 batches, and the blue horizontal line shows the mean rice As of each floodplain/doab

The comparison of excess As concentration per surface area for each field as a function of As supplied per surface area each year shows a generally increasing trend corresponding to an average duration of irrigation with groundwater of 26 ± 3 years (Fig. 6). Assuming the growth in the number of irrigation wells in Punjab from 1960 to 2000 (Qureshi et al. 2010) has continued and can be approximated by a linear trend, the average irrigation well would have been in use for about three decades. The match between these two independent estimates confirms that groundwater pumping is the main driver of As concentrations in paddy soil of Punjab exceeding background levels for the region. The implication is that continued irrigation of rice paddies with groundwater will result in further increases in As concentrations in paddy soil over broader areas.

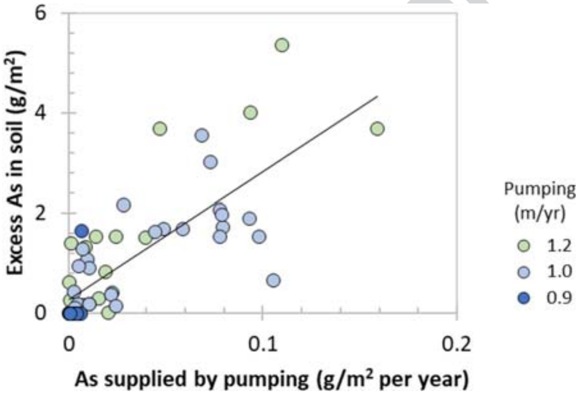

Fig. 6 Comparison of excess soil As concentrations in 60 study fields of Punjab with the annual As supply from pumping groundwater. Pumping rates were estimated by subtracting Kharif season rainfall divided in three categories (Bokhari et al. 2017) from the total of 1.6 m/yr of water required for growing rice in the region (Erenstein 2009). The slope and intercept of the least-squares regression line for all data combined are 26 ± 3 yr (1-sigma) and 0.3 ± 0.1 g/m2, respectively

Recent studies of boro rice varieties grown in Bangladesh indicate a loss in yield of 0.5–1.0 t/ha from an average of 3 t/ha for a 10 mg/kg increase in soil As (Huhmann et al. 2017; Panaullah et al. 2009). It is unclear to what extent the yield in basmati rice might be similarly sensitive to the build-up of As in paddy soil. The low As content of basmati rice doesn't necessarily mean the variety is less susceptible to yield loss from build-up of As in paddy soil, especially if levels continue to rise. The issue could potentially be addressed with an experimental design similar to that of Huhmann et al. 2017. Another approach would be to compare rice yield closest to the irrigation inlet with rice yield furthest away from the inlet, but within the same field in order to keep other factors such as soil type, water management, fertilizer input, and weeding as similar as possible.

Low As content of basmati rice

The patterns of As in irrigation water and paddy soil are clearly coupled geographically but are not accompanied by any such trend in the As content of rice (Fig. 5). Each of the five geographic units includes a few outliers with a slightly elevated average or a larger standard deviation for As concentrations in rice. The overall average of 0.09 mg/kg in total rice As for the region is consistent with 6 previous studies of basmati rice from Pakistan and India (Fig. 7). Studies of other varieties from India and Bangladesh, some market-based and some-field

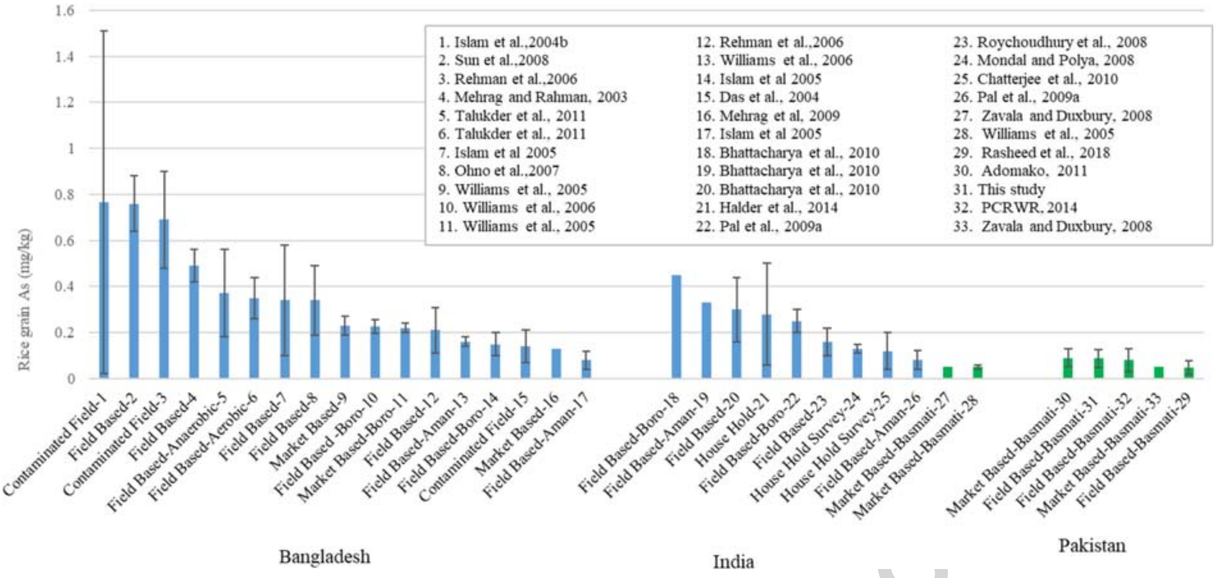

Fig. 7 Mean total As concentrations in rice reported by 33 studies conducted in Bangladesh, India and Pakistan. Blue bars combine various varieties, with the exception of basmati, which instead is shown as green bars. Error bar correspond to one standard deviation for the entire data set where listed or where it could be calculated

based, indicate a consistently higher average As content of rice, with even a few studies showing averages exceeding 0.5 mg/kg As (Fig. 7, Online Resource Table 8). About 40% of rice production in Pakistan is basmati, along with other varieties including IRRI-6, IRRI-9, KS-282, DR-82 and DR-83 that were not analyzed in this study (Memon 2013). Punjab province is the largest producer of basmati rice, whereas long-grain white rice of the IRRI type is grown mostly in Sindh province to the south.

A number of studies have suggested that the As content of rice is related to the As content of paddy soil (Azad et al. 2009; Khan et al. 2009; Rahaman et al. 2011; Rauf et al. 2011; Williams et al. 2006; Zhao et al. 2009), however other studies did not observe such a connection (Adomako et al. 2009; Bhattacharya et al. 2010; Panaullah et al. 2009; Stroud et al. 2011; Van Geen et al. 2006). One reason for the inconsistency may be that the efficiency of the transfer of As from soil to grain varies and is sensitive to a number of factors including soil As, the variety of rice, and the irrigation regime (Williams et al. 2007). The results reported here confirm the low levels of As in basmati rice regardless of where it is grown. Growing varieties of basmati rice that do not accumulate as much as As could therefore be explored to replace, for instance, the main varieties currently grown in Bangladesh.

Table 1 Comparison of intake of As from rice and water (µg/day)

Rice As (mg/kg)	Rice consumption (g/day)		Water As (µg/L)	
	50	500	10	100
0.09	4.5	45	30*	300*
0.30	15	150		

*for 3 L of water/day30

Human exposure to as from well water relative to Rice

The new rice data combined with a recent well-water survey conducted across the Punjab plains provide a measure of exposure to As to compare with other rural populations in South Asia (Table 1). According to Akram and Henneberry 2016, rice consumption at 50 g/day is supplanted by wheat, at least in urban areas of Pakistan and, therefore, ten times lower than rice consumption in Bangladesh. In rural Pakistan, however, the consumption of rice may be comparable to Bangladesh (Akram and Henneberry 2016). The As content of wheat flour is generally much lower than in rice (Zhao et al., 2010) and therefore not considered in this analysis. Rasheed et al. 2018 report higher levels of As in wheat grains from Pakistan, but this was prior to milling and therefore not representative of actual intake. A quarter of wells in rural Punjab do not meet the WHO guideline of As in drinking water of 10 µg/L (van Geen et al. 2019) but that proportion is probably about twice as high in rural Bangladesh (Pfaff et al. 2017). The daily As intake of a farmer in Punjab from eating 50–500 g/day of basmati rice and drinking water from a well that just meets the WHO guideline is therefore on the order of 34–75 μg/day (Table 1). That figure would be closer to 450 μg/day for a farmer in Bangladesh eating a local rice variety that is elevated in As and drinking water containing 100 μg/L As. Under these two end-member scenarios, the intake of As from well water is comparable or dominates the intake from rice (Table 1). Given that, in addition, exposure through water is all inorganic As whereas a sizeable fraction of As in rice can be in a less toxic organic form (Meharg et al. 2009), helping rural populations of South Asia with access to low As water for drinking and cooking should remain the highest priority. Once that goal has been achieved, further reductions in exposure will be achieved by avoiding rice varieties with a particularly high As content in both Bangladesh and India, particularly in areas outside Pakistan where rice dominates the diet (Fig. 7).

Conclusion

Using matched water, soil, and rice As measurements from a considerable number of sites distributed across the Punjab plains of Pakistan, this study confirms that groundwater pumping is the main contributor of As concentrations in some paddy soil of Punjab. The contamination of paddy soil with As is currently limited in the region but is likely to increase in severity and geographic extent over time. The accumulation of As in paddy soil of the Punjab plains is not linked to a measurable increase in the uptake of As in rice grains of basmati rice. After reducing exposure from drinking well-water along the Ravi River, the main concern in the region could potentially become the loss in rice yield resulting from further accumulation of As in soil over time. This is why the ITS Econo-Quick arsenic kit could be useful to farmers by helping them determine the As content of both their irrigation water and their paddy soil.

Q5 **Funding information** This study was funded by U.S.-Pakistan Centre for Advanced Studies in Water (USPCASW), Mehran University of Engineering Sciences and Technology (MUET), Jamshoro, Sindh, Pakistan, Research grant Project No. 5, USAID under the Pakistan-U.S. Science and Technology Cooperation Program grant no NAS 2000006111, US NIEHS grant P42 ES010349, and US National Science Foundation (NSF) grant No ICER1414131. Asif Javed was also supported by a visiting fellowship to Columbia University from the Higher Education Commission (HEC) of Pakistan. This is LDEO contribution no. XXX.

Compliance with ethical standards

Competing interests None.

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