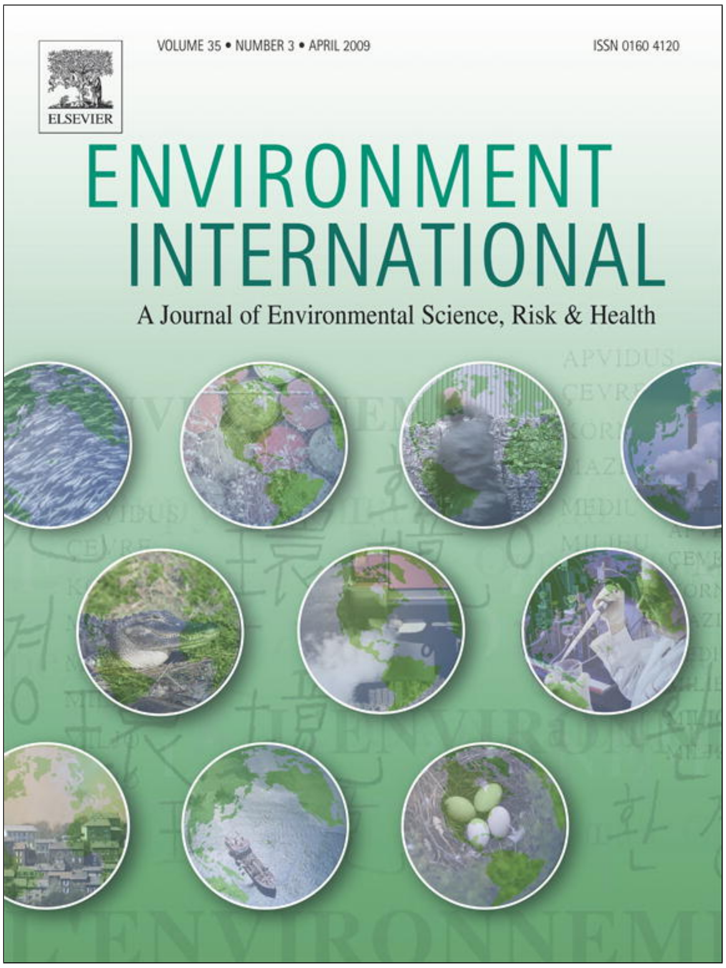
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Review article

Arsenic in groundwater: A threat to sustainable agriculture in South and South-east Asia

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A B S T R A C T

The problem of arsenic pollution of groundwater used for domestic water supplies is now well recognised in Bangladesh, India and some other countries of South and South-east Asia. However, it has recently become apparent that arsenic-polluted water used for irrigation is adding sufficient arsenic to soils and rice to pose serious threats to sustainable agricultural production in those countries and to the health and livelihoods of affected people. This paper reviews the nature of those threats, taking into account the natural sources of arsenic pollution, areas affected, factors influencing arsenic uptake by soils and plants, toxicity levels and the dietary risk to people consuming arsenic-contaminated rice.

Contents

1. Introduction . . . 647
2. Affected areas . . . 649
3. Causes of arsenic pollution . . . 649
4. Factors affecting arsenic availability . . . 650
5. Soil loading during irrigation . . . 651
6. Arsenic uptake by plants . . . 651
7. Accumulation in rice grain . . . 652
8. Toxicity to plants . . . 652
9. Toxicity to humans . . . 652
10. Conclusions . . . 653
Acknowledgment . . . 653
References . . . 653

1. Introduction

Natural arsenic (As) pollution of drinking water supplies has been reported from over 70 countries, posing a serious health hazard to an estimated 150 million people world-wide (Ravenscroft et al., 2009, and references therein). Around 110 million of those people live in ten countries in South and South-east Asia: Bangladesh, Cambodia, China, India, Laos, Myanmar, Nepal, Pakistan, Taiwan and Vietnam. It has recently been recognised that As-contaminated groundwater used for irrigation may pose an equally serious health hazard to people eating food from the crops irrigated (Williams et al., 2006), and that As accumulating in irrigated soils poses a serious threat to sustainable agriculture in affected areas (Heikens, 2006). Little is yet known about the extent and severity of these threats to human health and livelihoods. The objective of this paper is to draw attention to the nature of these looming threats and the studies needed to address them. It draws upon the authors' long field experience in Bangladesh

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Fig. 1. Distribution of arsenic contamination of groundwater in South and South-east Asia. Arsenic occurrence data from Ravenscroft (2007a) and map data from ESRI's ArcGIS 8.0. Projection: Robinson. Note the sizes of the areas shown should not be confused with the severity or number of people affected.

and reviews recent literature on As in soils and rice to assess what is currently known and not known on the subject.

Most studies we cite come from Bangladesh, because that is where most research has been carried out to-date. However, because of broadly similar agroecological and hydrogeological conditions, these results should be widely applicable to the alluvial plains of S and SE Asia where rice (paddy) is the main crop irrigated with groundwater. The similar geological and geochemical conditions of the aquifers from which irrigation water is drawn is demonstrated by studies from Bangladesh and West Bengal (e.g. McArthur et al., 2001, 2004), Nepal (Gurung et al., 2005), the Ganga Plains (Acharyya and Shah, 2006), Cambodia (Buschmann et al., 2007), Vietnam (Postma et al., 2007) and Taiwan (Liu et al., 2006a,b). In addition to the documented areas of arsenic pollution noted above, GIS-based geological–geochemical–hydrological models predict widespread pollution of groundwater in Indonesia, Malaysia, the Philippines and other regions where water supplies have not been tested for arsenic (Ravenscroft, 2007a,b).

2. Affected areas

Fig. 1 indicates the areas in S and SE Asia where As contamination of groundwater used for drinking water has been reported. No similar map can yet be drawn for areas within those countries where groundwater used for irrigation is contaminated. However, insofar as irrigation water and drinking water are drawn from the same polluted aquifers, it may be assumed – until proved otherwise – that the irrigation water is also polluted. In general, irrigation water is drawn from a slightly greater depth in the same aquifer, but in some cases it is known that potable and irrigation water are drawn from different aquifers. In Bangladesh and West Bengal, ca 90% of the groundwater that is abstracted is used for irrigation (Ravenscroft, 2003; Sanyal and Nasar, 2002).

Surveys in Bangladesh have shown that there is great regional and local variability of As concentrations in groundwater. Pollution primarily affects Holocene aquifers at depths of between 20 and 120 m, mainly in a belt across the south-centre and east of the country (Fig. 2). Overall, it was estimated that, as of 1998–90, 25% of domestic wells provided water that exceeded the national drinking water standard of 50 ppb (μg/L) As and approximately twice that proportion exceeded the WHO guideline of 10 ppb As (Ravenscroft et al., 2005). Subsequent blanket surveys of the most affected areas have led to testing of nearly 5 million wells, predominantly using field-kits, from which it has been estimated that 20% of all wells in Bangladesh exceed 50 ppb (Johnston and Sarker, 2007). However, simple comparisons of these estimates should be avoided because they are affected by different analytical and sampling approaches and also, and this effect may be greater, by differences resulting from mitigation activities, whereby knowledge of the arsenic risk has led to a change in the nature of abstraction. Thus, the earlier survey probably provides the best description of the distribution of arsenic in groundwater, and the later testing better describes current exposure. Similar proportions (26%>50 and 58%>10 ppb) of polluted wells have been reported from West Bengal by Nickson et al. (2007). However, the proportion of wells within villages that exceed the national standard ranges between >90 and <10%. A survey of 456 irrigation shallow tubewells (STW) in five widely-separated upazilas (subdistricts) in Bangladesh showed that more than one-half produced water with >100 ppb As and 62 produced water with >200 ppb As; the highest recorded was 510 ppb (Islam et al., 2005). Arsenic concentrations as high as 1891 ppb have been reported in Bihar, India, (Ghosh et al., 2007) and 2629 ppb in Nepal (Shresta et al., 2003).

Irrigation with As-polluted groundwater particularly affects rice. Not only is rice the principal irrigated crop in most parts of S and SE Asia; as is described below, it is also the crop that is most susceptible to As toxicity and the most important food source of As in the human diet. In Bangladesh, it is mainly the dry-season rice crop (*boro*) that is irrigated. However, in some areas, supplementary irrigation is applied to the monsoon rice crops *aus* and *aman*, and it must be expected that this practice will increase in future years in order to increase crop yields and production to meet the demands of the increasing population. In seasonally-flooded areas, such as in Bangladesh, the possible effect of As added to soils by dry-season irrigation on a following rainfed or flooded rice crop also needs to be investigated.

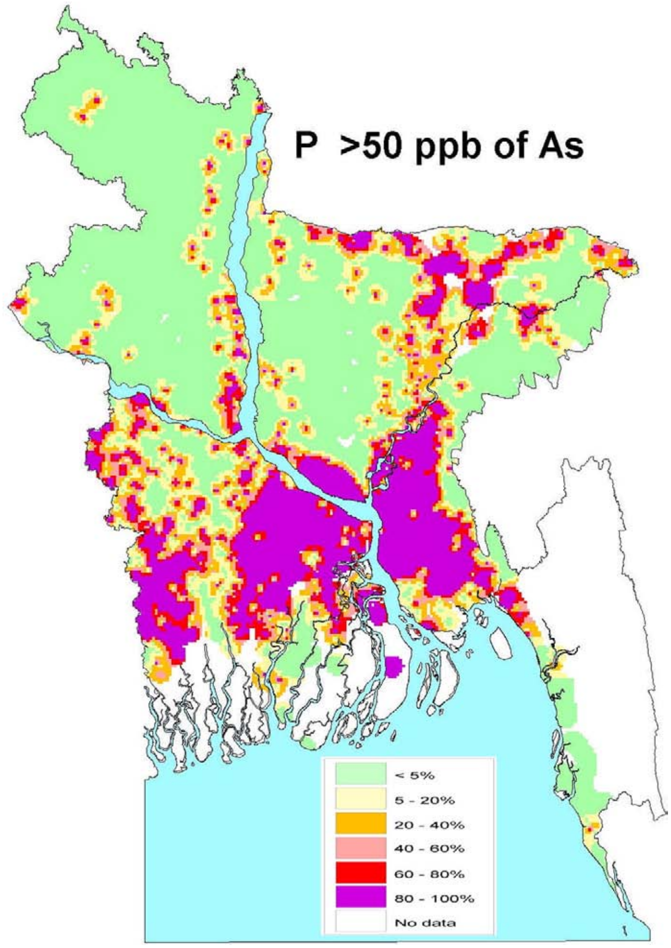

Fig. 2. Distribution of arsenic contamination in domestic tubewells in Bangladesh in 1998–99. The map shows the probability (P) of a well drilled to a depth of <150 m having a concentration >50 ppb As. After Ravenscroft et al. (2005). Projection: Bangladesh Transverse Mercator.

3. Causes of arsenic pollution

Ravenscroft et al. (2009) have described four geochemical mechanisms of natural As pollution: reductive dissolution; alkali desorption; sulphide oxidation; and geothermal activity. Reductive dissolution is by far the most important mode in S and SE Asia. It occurs where As adsorbed to iron oxyhydroxides in sediments is liberated into groundwater when microbial degradation of organic matter (e.g., in buried peat beds) reduces ferric iron to the soluble ferrous form (Nickson et al., 2000; McArthur et al., 2001). The As is contained in relatively-unweathered alluvial sediments derived from igneous and metamorphic rocks in the Himalayas and related young mountain chains (McArthur et al., 2004; Ravenscroft et al., 2005). Arsenic is not present in large amounts in these sediments: its importance lies in the toxicity of the element at very low concentrations to humans and many plants that absorb it. The high spatial variability of As concentrations in groundwater observed in Bangladesh appears to be related to regional and local variations in the

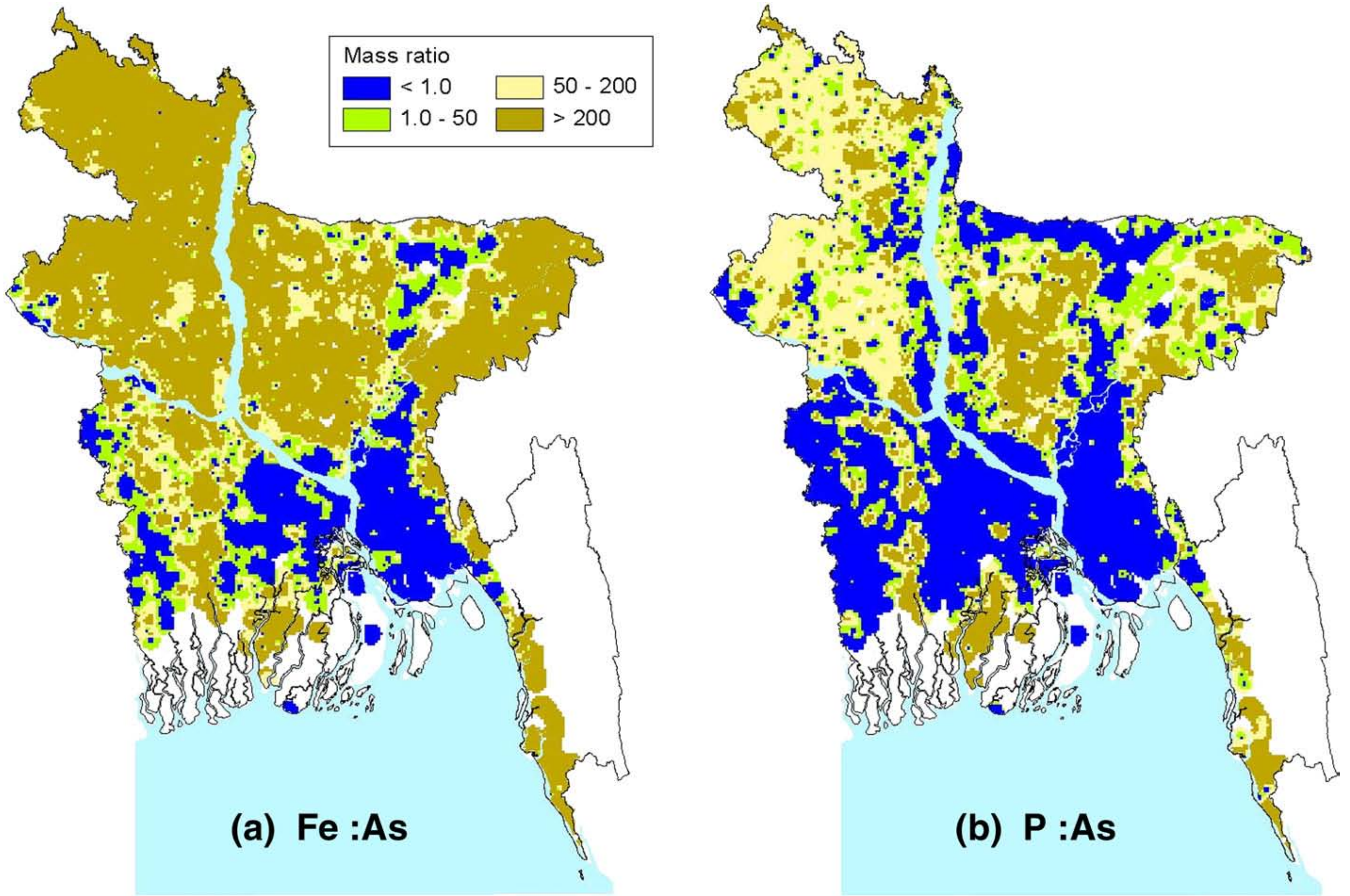

Fig. 3. Distribution of Fe:As and P:As ratios in Groundwater in Bangladesh. Mass ratios calculated from the same data set as Fig. 2. (DPHE, 1999; DPHE/BGS, 2001). Projection: Bangladesh Transverse Mercator.

amounts of organic matter in aquifer sediments, both laterally and vertically (DPHE, 1999). Observations in Bangladesh also show that there are great variations from place to place in iron–arsenic and phosphorus–arsenic ratios in groundwater (Fig. 3) that may be significant for As accumulation rates in soils, plant uptake and feasible mitigation measures.

4. Factors affecting arsenic availability

Many soil factors influence the amount of As available for plant uptake (Mahimairaja et al., 2005). They include redox potential, pH, the contents of organic matter, iron, manganese, phosphorus and calcium-carbonate, and soil microbes. The influence of some of these soil properties and constituents also varies significantly within the year in soils that alternate between anaerobic and aerated conditions, as occurs in seasonally-flooded soils and irrigated upland soils used for paddy cultivation. Table 1 shows the range of soil properties that can occur between adjoining ridge and basin sites within lateral distances of 0.5–1 km on the Ganges River Floodplain in Bangladesh. Similar ranges in properties occur in Bangladesh's other floodplain regions, except that the soils are not calcareous and the proportions occupied by soils of different texture vary. Thus there can be considerable regional and local differences in soil properties that affect As accumulation and availability, including within tubewell command areas. Diurnal and seasonal variations in microbiological activity within paddy fields (particularly by soil bacteria and algae) may also influence As accumulation and availability. These differences are additional to the differences in the As content of irrigation water applied to them. All these variable factors need to be taken into account in soil and crop sampling and in the interpretation and extrapolation of results.

Arsenic added in irrigation water is adsorbed to ferric oxyhydroxides in the topsoil (Roberts et al., 2007) where it gradually accumulates over time (Meharg and Rahman, 2003; Norra et al., 2005). Arsenic accumulation is most serious in soils used for transplanted rice (paddy) cultivation, where the topsoil is puddled to hold water on the surface. That is partly because of the large amounts of water used to irrigate rice – of the order of 1000 mm per crop – and partly because, under the anaerobic conditions in flooded paddy fields, the As is mainly present as As (III), the form that is most readily available to plant roots. In Bangladesh, As levels in unirrigated floodplain soils appear to be <10 mg/kg (Abedin et al., 2002) and similar to or lower in the topsoil than in the subsoil (Saha and Ali,

Table 1
Ishurdi-Pakuria association

Relief position	Flooding depth (m)	% of assoc.	Soil series	Topsoil			
				Organic matter %	Clay %	pH	$CaCO_3$ %
Ridge top	0	15	(Homesteads)				
Ridge top	0	10	Sara	1.5	18	7.9	8
Up slope	0–1	10	Gopalpur	1.8	36	7.6	2
Mid slope	0.3–1	30	Ishurdi	2.2	53	7.2	3
Lower slope	0.3–1	20	Pakuria	2.0	59	7.8	5
Basin margin	1–2	5	Garuri	2.9	53	6.2	0
Basin centre	2–>3	10	Ghior	3.7	64	5.4	0

Source: Report on reconnaissance soil survey of Sadar and Goalundo Subdivisions, Faridpur District, 1969. Soil Resources Development Institute, Dhaka.

2006). In irrigated areas, Duxbury and Zavala (2005) reported topsoil As levels >10 mg/kg at 48% of 456 STW sites studied, and Huq et al. (2006) reported that 21% of samples from a 24-upazila study had levels >20 mg/kg, with a highest level of 81 mg/kg.

Most recent studies show that virtually all the As added in irrigation water remains in the top 10–15 cm of soils, implying that little is lost to the atmosphere by volatilisation, leaching to deeper soil layers and removal in crops. However, Dittmar et al. (2007) reported similar topsoil As contents at the start of two successive irrigation seasons, and suggested that As added during the first irrigation season had been leached by floodwater during the following monsoon season; and, in a much earlier field trial on flooded rice soils in the USA contaminated with arsenical pesticides applied to previous cotton crops, Reed and Sturgis (1936) reported substantial loss of soil As between the start and end of the rice-growing period and suggested that this loss might be due to reduction of As to gaseous arsine. Further studies are needed to determine the factors that influence gains and losses of soil As under different environmental and management conditions. Those studies should include examining the role of algae in As methylation and recycling: flooded paddy fields can host a great number of algal species (Catling, 1993). Theoretically, under reducing conditions, arsenic might be sequestered by co-precipitation with sulphide minerals. However, this is greatly limited by the very low concentrations of sulphate in groundwater (e.g. McArthur et al., 2001).

Table 2 shows how As might accumulate in soil over time at different concentrations in irrigation water, assuming an annual water application of 1000 mm. A soil irrigated with 1000 mm of water containing 100 ppb As receives 1 kg/ha As per annum. The limited evidence at present suggests that the safe limit of soil As for rice lies somewhere in the range 25–50 mg/kg (Saha and Ali, 2006; Duxbury and Panaullah, 2007). In Table 2, boxes showing 25–50 and >50 mg/kg have been shaded to show when, in principle, these soil concentrations might be reached. Actual soil loading rates will vary with the amount of irrigation water applied, As concentrations in the water and losses due to volatilisation, leaching and crop removal. Because of the short period since As contamination of soils by groundwater irrigation was recognised, little information is available at present on As accumulation and removal rates. More extensive surveys and studies are needed taking into account the variability in soil factors described above.

5. Soil loading during irrigation

Not all the As delivered by tubewells actually reaches the fields irrigated. In most As-affected areas of S and SE Asia, groundwater is rich in iron (e.g. DPHE, 1999; Gurung et al., 2005; Postma et al., 2007). That iron is oxidised when the water is exposed to the air and is then precipitated as iron-hydroxides which adsorb As. Hossain (2005) reported that As concentrations at a 4-ha STW site near Faridpur, Bangladesh, decreased from 136 ppb at the well-head to 68 ppb at the end of the 100 m distribution channel, mostly within the first 30 m. On the other hand, at a STW site near Munshiganj, Bangladesh, Roberts et al. (2007) reported an As loss of only 21% (from 397 to 314 ppb) in a 152 m irrigation channel. More such studies are needed over a wider range of environmental conditions taking also into account differences in relief, soils and water quality (e.g., in Fe:As ratios).

Hossain (2005) reported that topsoil arsenic concentrations at the Faridpur site, which had been irrigated for about 20 years, ranged from 61 mg/kg in the field nearest the well-head to 11 mg/kg in a field near the far side of the command area. At the Munshiganj site referred to above, which had been irrigated for 15 years with an assumed annual water application of 1000 mm, Dittmar et al. (2007) reported that topsoil As concentrations varied considerably within fields. In one field studied in detail, As concentrations decreased gradually from 23.0 mg/kg near the field inlet to 11.3 mg/kg at the far corner of the field. With continuing irrigation, these differences within command areas and within fields are likely to increase with time, and should be taken into account in soil and crop sampling.

At the Munshiganj site, topsoil As contents had increased significantly above background levels over the 15 years of irrigation. However, as described above, Dittmar et al. (2007) reported that As contents at this site were similar at the start of two successive irrigation seasons, and suggested that As added during the first irrigation season had been leached by floodwater during the following monsoon season. These findings indicate that differences in soil accumulation rates can occur not only laterally but also between years. They point to the need for more study sites covering a wider range of environmental conditions and for relevant parameters to be monitored over a period of years.

Table 2
Potential effect of arsenic concentrations in irrigation water on soils with time

Years of irrigation	Arsenic in irrigation water (ppb)				
	50	100	250	500	1000
	Arsenic added to soil (mg/kg)				
1	0.28	0.56	1.4	2.8	5.6
5	1.4	2.8	7	14	28
10	2.4	5.6	14	28	56
20	5.6	11	28	56	110
30	8.4	17	42	84	170
50	14	28	70	140	280

Green shading <20 mg/kg; orange 20-50 mg/kg; red >50 mg/kg. (For interpretation of the references to colour in this table legend, the reader is referred to the web version of this article.)

6. Arsenic uptake by plants

Plant uptake of As from soils is complicated by a number of factors. In aerated soils used for crops such as wheat, maize and most vegetables, As is present mainly as As(V) and, as such, is likely to be in the solid phase. Therefore, in such soils, As in groundwater used for irrigation is quickly adsorbed by iron hydroxides and becomes largely unavailable to plants. In anaerobic soil conditions such as occur in flooded paddy fields, As is mainly present as As(III) and is dissolved in the soil-pore water (the soil solution) (Xu et al., 2008). It is thus more readily available to plant roots.

In seasonally-flooded soils in monsoon climates, soils change between the oxidised state in the dry season and the reduced state when the soils are submerged in the wet season. Similar changes occur in soils that are flood-irrigated for rice cultivation: topsoils are reduced during periods when they are kept flooded and become oxidised when they are allowed to dry out for crop harvesting or between crop seasons. Thus, As may be present in different forms in the same soil at different times of the year. Additionally, widespread observations during soil surveys in Bangladesh showed that, in most seasonally-flooded soils in that country, strong reduction occurs only in the topsoil and that subsoils down to a permanently-saturated lower layer remain at least partially aerated and oxidised during the period when the soil is submerged (Brammer, 1996). Rice roots may therefore be growing in both reduced and oxidised soil horizons.

For rice, the situation is further complicated by the ability of the plant to carry oxygen from the air down its stem and discharge it through its roots. This creates an oxidised zone around individual roots in which iron is oxidised to the ferric state and forms a coating ('iron plaque') (Liu et al., 2006). In principle, this oxidised iron plaque should adsorb As and thus act as an As filter. However, most of the As in reduced paddy topsoils is present as As(III) which is readily adsorbed by iron, and plant studies show that rice plants take up As from soils in significant amounts (e.g., Meharg and Rahman, 2003). Liu et al. (2006) found that the amount of plaque deposited varied considerably between six rice varieties tested. Hu et al. (2005) found that adding phosphate greatly decreased plaque formation, and Hu et al. (2007) found that adding sulphur (as S or Na_2SO_4) increased plaque formation. All these studies were carried out in pots. More studies are needed – particularly field studies – to investigate the environmental, soil management and plant varietal factors that influence the amount of plaque formed and the effect of iron plaque on As uptake by rice plants.

Arsenic taken up from soils by rice accumulates in different proportions in different plant parts in the order roots > stem > leaf > grain (Abedin et al., 2002). For example, in pot trials in Bangladesh, Das et al. (2004) found 2.4 mg/kg As in rice roots, 0.73 mg/kg in stems and leaves, and 0.14 mg/kg in grain. Some dryland crops also take up significant amounts of As, and accumulate it differentially in various plant parts. Williams et al. (2006), who measured As contents of 37 vegetables, pulses and spices commonly grown in Bangladesh, found levels were highest in radish leaves (0.79 mg/kg), arum stolons, spinach and cucumber, and lowest (<0.2 mg/kg) in most fruits, vegetables and spices. Roychowdhury et al. (2002) also found great differences between 30 crops and food items from 34 As-affected households in West Bengal, India, *inter alia* reporting a significant difference between potato skins (0.526 mg/kg) and potato flesh (0.00728 mg/kg). In all studies, considerable differences were found between samples from different sites. It should be noted that the dryland crops tested generally provide a small proportion of the total diet. Rice poses by far the greatest threat from As in irrigation water and should be the primary focus for research studies, mitigation efforts and extension advice.

7. Accumulation in rice grain

Considerable differences in As uptake exist between rice varieties and between the kinds of rice grown in different countries. Williams et al. (2006) reported As levels ranging between <0.04 and 0.92 mg/kg in rice samples obtained from 299 markets in 25 (of 64) districts across Bangladesh; (the samples included several different rice varieties from irrigated and rainfed land and from areas with high and low-As tubewell water). Meharg and Rahman (2003) found rice grain contents ranging between 0.058 and 1.835 mg/kg As in 13 different rice varieties tested in Bangladesh, and comparative levels of 0.2–0.46 mg/kg As for raw rice in the USA and 0.063–0.2 mg/kg in Taiwan. Duxbury and Zavala (2005) reported mean concentrations of 0.032–0.046 mg/kg As for aromatic rice from Bangladesh, Bhutan, India and Pakistan. They also reported mean values of 0.181 mg/kg for the USA and 0.186 mg/kg for Spain, with a highest value of 0.753 mg/kg for a sample from Texas, USA. However, Williams et al. (2005) reported that the As in US varieties is predominantly present in a less harmful organic form (dimethylarsinic acid), whereas 80–90% of that in Bangladeshi rice varieties is in the arsenite form which is most toxic to humans. In a subsequent greenhouse study with japonica rice, (Xu et al., 2008) found that much less inorganic As was present in rice grown under anaerobic soil conditions than under aerobic conditions (20–44 v 91–100%), but that inorganic As contents were still 2.6–2.9 times higher in the flood-irrigated rice Differences between rice types and cultivars need to be taken into account in all studies where rice yields and amounts eaten are measured or compared.

There are conflicting reports on the correlation between soil and plant As levels. In samples from 330 STW sites in two upazilas in western Bangladesh, Jahiruddin et al. (2005) found that As concentrations in grain were poorly correlated with soil and water As; so did Miah et al. (2005) who sampled 270 STWs in 67 upazilas across the whole of Bangladesh. On the other hand, Farid et al. (2005) considered that correlations were good at 96 sampling points within a single STW site studied at Brahmanbaria, Bangladesh. In the only study where detailed field trials have been reported to-date, Duxbury and Panaullah (2007) found at a STW site near Faridpur, Bangladesh, that As contents of rice grain decreased with increasing soil-As level: from about 0.55 mg/kg As at 11.6 mg/kg soil As to about 0.35 mg/kg at 57.6 mg/kg soil As, but concentrations in grain increased as yields decreased. Similar, but more exaggerated, results were obtained in pot trials with soil samples from the same sites, except that grain As levels remained almost the same at 39.5 and 57.6 mg/kg soil As. Such trials need to be carried out under a wider range of environmental and agronomic conditions.

8. Toxicity to plants

There is no single level of soil As that is toxic to plants. Different plant species tolerate different amounts of As in soils; so do different rice cultivars. Some plants (known as hyperaccumulators) can tolerate very high levels of soil As (e.g., Ma et al., 2001). Various symptoms of As toxicity in rice have been reported. They include delayed seedling emergence, reduced plant growth, yellowing and wilting of leaves, brown necrotic spots on older leaves and reduced grain yields (Huq et al., 2006). A disease known as 'straighthead' (because of upright, empty panicles at maturity) or 'parrot beak' (because of misshaped grains) is considered to be an indicator of As toxicity in the USA and Australia (Williams, 2003). Straighthead disease was reported for the first time in Bangladesh in 2006 (Duxbury and Panaullah, 2007). On soils contaminated by arsenical pesticides in the USA, Yan et al. (2005) found considerable variation in varietal resistance at high soil-As levels, ranging from virtually no yield reduction in one Chinese cultivar to 80–90% reduction in four of ten US cultivars tested.

In Bangladesh, Duxbury and Panaullah (2007) reported rice yields in conventional paddy fields decreasing from 8.92 to 2.99 t/ha with soil-As levels increasing from 26.3 to 57.5 mg/kg. Complementary pot studies showed greater yield reductions at higher soil-As levels than in the field. In both trials, the popular modern rice variety BR29 was used. Duxbury and Panaullah's field results suggest that the practical limit for paddy cultivation might lie at soil-As levels between 25 and 50 mg/kg. However, differences in varietal tolerance described above need to be kept in view, and so do differences in soil management. Duxbury and Panaullah also reported results from rice grown on raised beds in which yields decreased from 8.24 t/ha at a soil As level of 26.3 mg/kg to 5.21 t/ha at 57.5 mg/kg As (i.e., 2.22 t/ha higher than in the flooded field at the highest As concentration). The limiting concentrations for soil-As for irrigated dryland crops in S and SE Asia remain to be determined.

Duxbury and Panaullah (2007) reported a negative correlation between As in rice grain and soil As – 0.54 mg/kg in rice at soil As 11.6 mg/kg versus 0.34 mg/kg (rice) at soil As 57.5 mg/kg – but a positive correlation between As in rice straw and soil. They attributed these different relationships to As toxicity interfering with translocation of As from vegetative tissues to grain. The relatively high grain As contents at relatively low soil As levels in this trial suggest that rice can accumulate significant amounts of As at levels well below those that are considered potentially toxic to plant growth. This finding needs to be kept in view in assessing the level at which soil As begins to pose a risk to human health for people eating crops grown on contaminated soils.

9. Toxicity to humans

The arsenic content of rice grain is important because of the large daily amounts of rice eaten by people in many parts of S and SE Asia (commonly assumed to be 450 g/day for a 60 kg adult in Bangladesh). Duxbury and Zavala (2005) pointed out that, when As in rice grain exceeds 0.11 mg/kg, it is possible for adults consuming 450 g of rice and 4 L of water per day at the 10 ppb WHO As water standard to exceed the FAO and WHO provisional tolerable dietary intake standard of 130 μg As per day for a 60 kg adult. For a person consuming water at the national standard of 50 ppb and rice containing 0.20 mg/kg As, daily intake of As would be more than double the recommended amount. These indicative calculations are confirmed by limited field studies. For example, Uchino et al. (2006), studying 37 families in West Bengal villages, found that total daily As intake of adults from food (rice + vegetables) and water was approximately 1.5 times the FAO–WHO guideline in villages where drinking water had < 10 ppb As, 2.7 times that guideline in villages with 10–50 ppb As in water and 6.1 times the guideline in villages with water > 50 ppb As. Food was the main source of As in families drinking water at the two lower As levels. Ravenscroft et al. (2009 and others cited therein) point out that international safety standards for both water and food do not adequately reflect the amounts of water and rice consumed in many tropical countries. Standards that are relevant for people living in S and SE Asia need to be established.

The As content of rice straw also needs to be considered where this is fed to livestock producing meat or milk for human consumption. Little information is yet available on this subject in rice-growing countries. However, the possibility of significant As uptake by animals is suggested by the findings of Nandi et al. (2005) who described a wide range of symptoms in cattle associated with high As intake in West Bengal, and found significantly more As in the hair of cattle in As-affected areas than in non-affected areas.

Arsenic is a potent carcinogen and it can cause deaths from a wide range of other serious diseases. Symptoms typically do not appear for 2–10 years from the start of chronic exposure, and they may also appear long after exposure ceases (Yuan et al., 2007). Although WHO (2004) note that there remains "considerable uncertainty and controversy over both the mechanism of carcinogenicity and the shape of the dose–response curve at low intakes", there is increasing evidence of both cancer (Smith et al., 2007) and non-cancer (Ahsan et al., 2006) effects at drinking water concentrations below 50 μg/L that appear to follow a linear dose–response relationship. Thus, following the precautionary principle, sustained efforts should be made to minimise As intake from all sources as soon as possible.

10. Conclusions

Irrigation with As-rich groundwater poses threats to sustainable agriculture and to human health in many countries of S and SE Asia. The extent and urgency of those threats urgently need to be assessed in affected countries so that appropriate countermeasures can be tested and introduced (Ravenscroft et al., 2009). Surveys are needed to identify tubewell sites where soils and rice grain are already As-contaminated or appear likely to become seriously contaminated within the next 5–10 years. Studies and field trials should take into account differences in soil, climatic, hydrological, biological, economic and cultural conditions between countries and within them. Soil and crop sampling need to take into account regional differences in environmental conditions and the complex patterns of soil As contamination between and within tubewell command areas. Although pot trials can provide useful preliminary information on soil and plant processes, field trials need to be used much more extensively: it is practically impossible to simulate the physical, chemical and biological environment of a paddy soil in a pot experiment. There is also an urgent need to develop a rapid, reliable, field method for measuring As levels in paddy soils in order to facilitate the survey and monitoring of soil As levels.

Increasing recognition of the implications of As in irrigation water and action to reduce its impacts will have profound consequences for water resources development and management (Ravenscroft et al., 2009). Where shallow aquifers are used for both irrigation and potable supply, irrigation pumping will contribute to the long term clean-up of the aquifers, albeit at the cost of transferring the health risk from drinking water to the food chain. Despite possible short-term (months to a few years) increases, the As concentrations in water wells must decrease in the long term. The rate at which As will decrease in groundwater compared to its accumulation in soils will vary greatly between regions, and should be a priority target for investigations. Except where As concentrations in shallow groundwater are observed to decline rapidly, the only permanent alternatives to non-irrigated cropping patterns will be to exploit deeper aquifers or surface-water sources. Until now, the deeper aquifers, whose resource potential is effectively unquantified, have only been used for potable supply, and it is highly uncertain whether they can form a sustainable source of irrigation water. Most surface-water sources have already been heavily exploited for irrigation. It is uncertain to what extent the remaining sources can provide a practical alternative in As-affected areas, and these problems may be exacerbated by climate change. Further discussion of these issues is beyond the scope of the present paper, but it is essential to recognise that agricultural mitigation of As-polluted soils cannot be divorced from water resources management.

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References

Abedin Md, Cresser MC, Meharg AA, Feldmann J, Cotter-Howells JC. Arsenic accumulation and metabolism in rice (*Oryza sativa L.*). Environ Sci Technol 2002;36:962–8.

Acharyya SK, Shah BA. Arsenic-contaminated groundwater from parts of Damodar fan-delta and west of Bhagirathi River, West Bengal, India: influence of fluvial geomorphology and Quaternary morphostratigraphy. Environ Geol 2006;53 (7):1553–61.

Ahsan H, Chen Y, Parvez F, Zablotska L, Argos M, Hussain I, et al. Arsenic Exposure from drinking water and risk of premalignant skin lesions in Bangladesh: baseline results from the Health Effects of Arsenic Longitudinal Study. Am J Epidemiol 2006;163: 1138–48.

Brammer H. The geography of the soils of Bangladesh. Dhaka: University Press Ltd; 1996.

Buschmann J, Berg M, Stengel C, Sampson ML. Arsenic and manganese contamination of drinking water resources in Cambodia: coincidence of risk areas with low relief topography. Environ Sci Technol 2007;41(7):2146–52.

Catling DH. Rice in deep water. London: Macmillan; 1993.

Das HK, Mitra AK, Sengupta PK, Hossain A, Islam F, Rabbani GH. Arsenic concentrations in rice, vegetables, and fish in Bangladesh: a preliminary study. Environ Internat 2004;30: 383–7.

DPHE. Groundwater studies for arsenic contamination in Bangladesh. Rapid Investigation Phase. Final Report. Mott MacDonald International Ltd and British Geological Survey. Report prepared for Department of Public Health Engineering (Bangladesh) and Department for International Development (UK); 1999.

DPHE/BGS. Arsenic contamination of groundwater in Bangladesh. Department of Public Health Engineering and British Geological Survey. BGS Technical Report WC/00/19 (4 vols); 2001.

Dittmar J, Voegelin A, Roberts LC, Hug SJ, Saha GC, Ali MA, et al. Spatial distribution and temporal variability of arsenic in irrigated rice fields in Bangladesh. 2. Paddy soil. Environ Sci Technol 2007;41(17):5967–72.

Duxbury JM, Zavala YJ. What are safe levels of arsenic in food and soils. CIMMYT/USGS. 2005. Symposium on the Behaviour of Arsenic in Aquifers, Soils and Plants: Implications for Management, Dhaka, Jan. 16–18, 2005. Centro Internacional de Mejoramiento de Maíz y Trigo and the U.S. Geological Survey; 2005.

Duxbury JM, Panaullah G. Remediation of arsenic for agriculture sustainability, food security and health in Bangladesh. Working paper, Water Service, FAO, Rome; 2007.

Farid ATM, Sen R, Haque MA, Panaullah GM, Meisner CA, Loeppert RH, et al. Arsenic status of water, soil, rice grain and straw of individual shallow tube well command area of Brahmanbaria. CIMMYT/USGS. 2005. Symposium on the Behaviour of Arsenic in Aquifers, Soils and Plants: Implications for Management, Dhaka, Jan. 16–18, 2005. Centro Internacional de Mejoramiento de Maíz y Trigo and the U.S. Geological Survey; 2005.

Ghosh A, Singh SK, Bose N, Chowdhary S. Arsenic contaminated aquifers: a study of the Ganga levee zone in Bihar, India. Symposium on Arsenic: the geography of a global problem, Royal Geographical Society, London, 29th August; 2007. http://www.geog.cam.ac.uk/research/projects/arsenic/symposium/S3.5 A Ghosh.pdf

Gurung JK, Ishiga H, Khadka MS. Geological and geochemical examination of arsenic contamination in groundwater in the Holocene Terai Basin, Nepal. Environ Geol 2005;49(1):98-113.

Heikens A. Arsenic contamination of irrigation water, soils and crops in Bangladesh: Risk implications for sustainable agriculture and food safety in Asia. Bangkok: FAO; 2006. ftp://ftp.fao.org/docrep/fao/009/ag105e/ag105e00.pdf

Hossain MB. Arsenic distribution in soil and water of a STW command area. CIMMYT/USGS. 2005. Symposium on the Behaviour of Arsenic in Aquifers, Soils and Plants: Implications for Management, Dhaka, Jan. 16–18, 2005. Centro Internacional de Mejoramiento de Maíz y Trigo and the U.S. Geological Survey; 2005.

Hu Y, Li JH, Huang YZ, Hu HQ, Christie P. Sequestration of As by iron plaque on the roots of three rice (*Oryza sativa* L.) cultivars in a low-P soil with or without fertilizer. Environ Chem Health 2005;27:169–76.

Hu ZY, Zhu YG, Li M, Zhang LG, Cao ZH, Smith FA. Sulphur (S)-induced enhancement of iron plaque formation in the rhizosphere reduces arsenic accumulation in rice (*Oryza sativa* L.) seedlings. Environ Pollut 2007;147(17):387–93.

Huq SM, Shila UK, Joadar JC. Arsenic mitigation strategy for rice, using water regime management. Land Contam Reclam 2006;14.4:805–13.

Islam MR, Jahiruddin M, Rahman GKMM, Miah MAM, Farid ATM, Panaullah GM, et al. Arsenic in paddy soils of Bangladesh: levels, distribution and contribution of irrigation and sediments. CIMMYT/USGS. 2005. Symposium on the Behaviour of Arsenic in Aquifers, Soils and Plants: Implications for Management, Dhaka, Jan. 16–18, 2005. Centro Internacional de Mejoramiento de Maíz y Trigo and the U.S. Geological Survey; 2005.

Jahiruddin M, Islam MR, Shah MAL, Rashid MA, Rashid MH, Ghani MA. Arsenic in the water-soil-crop systems: PETRE-BRRI-BAU-AAS study. CIMMYT/USGS. 2005. Symposium on the Behaviour of Arsenic in Aquifers, Soils and Plants: Implications for Management, Dhaka, Jan. 16–18, 2005. Centro Internacional de Mejoramiento de Maíz y Trigo and the U.S. Geological Survey; 2005.

Johnston R, Sarker MH. Arsenic mitigation in Bangladesh: national screening data and case studies in three upazilas. J Env Sci Health 2007;42(12):1889–96.

Liu WJ, Zhu YG, Hu Y, Williams PN, Gault AG, Meharg AA, et al. Arsenic sequestration in iron plaque, its accumulation and speciation in mature rice plants (*Oryza sativa* L.). Environ Sci Technol 2006;40:5730–6.

Ma LQ, Komar KM, Tu C, Zhang W, Cai Y, Kennelley ED. A fern that hyperaccumulates arsenic. Nature 2001;409:579.

Mahimairaja S, Bolan NS, Adriano DC, Robinson B. Arsenic contamination and its risk management in complex environmental settings. Adv Agron 2005;86:1-82.

McArthur JM, Ravenscroft P, Safiullah S, Thirlwall MF. Arsenic in groundwater: testing pollution mechanisms for sedimentary aquifers in Bangladesh. Water Resour Res 2001;37:109–17.

McArthur JM, Banerjee DM, Hudson-Edwards KA, Mishra R, Purohit R, Ravenscroft P, et al. Natural organic matter in sedimentary basins and its relation to arsenic in anoxic groundwater: the example of West Bengal and its worldwide implications. Appl Geochem 2004;19:1255–93.

Meharg AA, Rahman M. Arsenic contamination of Bangladesh paddy field soils: implications for rice contribution to arsenic consumption. Environ Sci Technol 2003;37(2):229–34.

Miah MMA, Rahman MS, Islam A, Paul DNR, Farid ATM, Jahiruddin M, et al. Nationwide survey of arsenic in soils, water and crops in Bangladesh. Behaviour of arsenic in aquifers, soils and plants: implications for management. Arsenic Symposium, Dhaka, January 2005. (Abstracts). CIMMYT, Dhaka; 2005.

Nandi D, Patra RC, Swarup D. Arsenic residues in hair samples from cattle in some arsenic affected areas of West Bengal, India. Bull Environ Contam Toxicol 2005;75:251–6.

Nickson RT, McArthur JM, Ravenscroft P, Burgess WG, Ahmed KM. Mechanism of arsenic poisoning of groundwater in Bangladesh and West Bengal. Appl Geochem 2000;15: 403–13.

Nickson RT, Sengupta C, Mitra P, Dave SN, Banerjee AK, Bhattacharya A, et al. Current knowledge on arsenic in groundwater in five states of India. J Environ Sci Health 2007;42(12):1707–18.

Norra S, Berner ZA, Agarwala P, Wagner F, Chandrasekharam D, Stuben D. Impact of irrigation with As rich groundwater on soil and crops: a geochemical case study in West Bengal Delta Plain, India. App Geochem 2005;20.10:1890–906.

Postma P, Larsen F, Hue NTM, Duc MT, Viet PH, Nhan PQ, et al. Arsenic in groundwater of the Red River floodplain, Vietnam: controlling geochemical processes and reactive transport modeling. Geochim Cosmochim Acta 2007;71(21):5054–71.

Ravenscroft P. An overview of the hydrogeology of Bangladesh. In: Rahman AA, Ravenscroft P, editors. Groundwater Resources and Development in Bangladesh—background to the arsenic crisis, agricultural potential and the environment. Bangladesh Centre for Advanced Studies. Dhaka: University Press Ltd; 2003.

Ravenscroft P. Predicting the global distribution of natural arsenic contamination of groundwater. Symposium on Arsenic: the geography of a global problem, Royal Geographical Society, London, 29th August; 2007a. http://www.geog.cam.ac.uk/research/projects/arsenic/symposium/S1.2_P_Ravenscroft.pdf

Ravenscroft P. Predicting the global extent of arsenic pollution of groundwater and its potential impact on human health. Report for UNICEF, New York; 2007b.

Ravenscroft P, Burgess WG, Ahmed KM, Burren M, Perrin J. Arsenic in groundwater of the Bengal Basin, Bangladesh: distribution, field relations and hydrogeological setting. Hydrogeology J 2005;13:727–51.

Ravenscroft, P., Brammer, H., Richards, K.S. Arsenic pollution: a global synthesis. Wiley-Blackwell, U.K; 2009.

Reed JF, Sturgis MB. Toxicity from arsenic compounds to rice on flooded soils. J Am Soc Agron 1936;28.6:432–6.

Roberts LC, Hug SI, Dittmar J, Voegelin A, Saha GC, Ali MA, et al. Spatial distribution and temporal variability of arsenic in irrigated rice fields in Bangladesh. 1. Irrigation water. Environ Sci Technol 2007;41(17):5960–6.

Roychowdhury T, Uchino T, Tokunaga H, Ando M. Survey of arsenic in food composites from an arsenic-affected area of West Bengal, India. Food Chem Toxicol 2002;40: 1611–21.

Saha GC, Ali MA. Dynamics of arsenic in agricultural soils irrigated with arsenic contaminated groundwater in Bangladesh. Sci Tot Environ 2006;379(2–3):180–9.

Sanyal SK, Nasar SKT. Arsenic contamination of groundwater in West Bengal (India): build-up in soil-crop systems. Paper presented at International Conference on Water Related Disasters, Kolkata, 5–6 December, 2002; 2002.

Shresta BR, Whitney JW, Shresta KB, editors. The state of arsenic in Nepal – 2003. Kathmandu: National Arsenic Steering Committee, Environment and Public Health Organisation; 2003.

Smith AH, Steinmaus C, Yuan Y, Liaw J, Hira-Smith MM. High concentrations of arsenic in drinking water result in the highest known increases in mortality attributable to any environmental exposure. Presented at the Royal Geographical Society Annual International Conference, London, 29th August; 2007. http://www.geog.cam.ac.uk/research/projects/arsenic/symposium/S1.4 A Smith et al.pdf

Uchino T, Roychowdhury T, Ando M, Tokunaga H. Intake of arsenic from water, food composites and excretion through urine, hair from a studied population in West Bengal, India. Food Chem Toxicol 2006;44.4:455–61.

WHO. Guidelines for drinking-water quality. 3rd edition. Geneva: World Health Organization; 2004.

Williams P. Investigating links between minerals in rice grain and straighthead. Final report. Leeton, NSW 2705, Australia: Cooperative Research Centre for Sustainable Rice Production; 2003.

Williams PN, Islam MR, Hussain SA, Meharg AA. Arsenic absorption by rice. CIMMYT/USGS. 2005. Symposium on the Behaviour of Arsenic in Aquifers, Soils and Plants: Implications for Management, Dhaka, Jan. 16–18, 2005. Centro Internacional de Mejoramiento de Maíz y Trigo and the U.S. Geological Survey; 2005.

Williams PN, Islam MR, Adomako EE, Raab A, Hossain SA, Zhu YG, et al. Increase in rice grain arsenic for regions of Bangladesh irrigating paddies with elevated arsenic in groundwaters. Environ Sci Technol 2006;40:4903–8.

Xu XY, McGrath SP, Meharg AA, Zhao FJ. Growing rice aerobically markedly decreases arsenic accumulation. Environ Sci Technol 2008;42(15):5574–9.

Yan W, Dilday RH, Tai TH, Gibbons JW, McNew RW, Rutger JN. Differential response of rice germplasm to straighthead disease by arsenic. Crop Sci 2005;45:1223–8.

Yuan Y, Marshall G, Ferreccio C, Steinmaus C, Selvin S, Liaw J, et al. Acute myocardial infarction mortality in comparison with lung and bladder cancer mortality in arsenic-exposed Region II in Chile from 1950 to 2000. Am J Epidemiol 2007 doi:10.1093/aje/kwm238.