FAOWATER Working Paper

Remediation of Arsenic for Agriculture Sustainability, Food Security and Health in Bangladesh

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Working Paper

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Foreword

Arsenic (As) in groundwater is a major health concern in Asia and the risks from using shallow tube wells (STWs) for drinking-water are well-known. At present, twelve countries in the Asian region have reported high As levels in part of their groundwater resources. Bangladesh has the highest percentage of contaminated STWs (~20 percent) and an estimated 30 million people are dependent on those wells for domestic purposes. The problem originates in arsenic-rich bedrock of the Brahmaputra river basin that filters drinking water pumped to the surface through millions of tube wells. Since an initial investigation on As accumulation in rice undertaken by FAO with support from the United Nations Development Programme (UNDP) in 2001, further scientific studies in the last couple of years have reported potential risks from As from dietary exposures. The most well-known concern is As entering the food chain, affecting food safety. This poses a potential dietary risk to human health in addition to the risk from drinking contaminated groundwater. Less well-known but potentially more serious is the risk of As to crop production. Continuous build up of As in the soil from As-contaminated irrigation water reduces crop yields in the long term.

As part of the green revolution, millions of STWs have been installed throughout Asia over the last three decades. This has resulted in a sharp increase of groundwater extraction for irrigation. In Bangladesh, of the four million ha under irrigation, 2.4 million ha are irrigated with approximately 900,000 STWs. It has been estimated that water extraction from the shallow aquifer for irrigation adds 1 million kg of As per year to the arable soil in Bangladesh, mainly in the paddy fields.

Management options of health risk prevention and agricultural sustainability should therefore focus on preventing and minimizing As input to soils and minimizing human exposures. Various management options are explored in the current FAO-Cornell remediation study. Optimizing water efficiency was shown to be a sound option to reduce As input while saving water; furthermore, aerobic growth conditions in paddy fields were shown to reduce bioavailability and uptake of As in rice. This current working paper reports the first successfully implemented field pilot study in the management strategy of arsenic in crop production and for sustainable environment. The final report on the overall arsenic issue in agriculture will be released in the near future. The remediation measures mentioned in this report are also applicable and useful as adaptive measures in coping with changing agriculture practice and responses to climate change. FAO welcomes comments, if any, from the readers and practitioners who use this report in their work. Comments should be addressed to: Chief, Water Resources Development and Management Unit, Land and Water Division, FAO, Viale delle Terme di Caracalla, 00100 Rome, Italy.

Acronyms

BARI	Bangladesh Agricultural Research Institute
BAU	Bangladesh Agricultural University
BCAMAE	The Bangladesh Consortium for Arsenic Management in Agriculture and the Environment
BGS	Bangladesh Geological Survey
BINA	Bangladesh Institute of Nuclear Agriculture
BRRI	Bangladesh Rice Research Institute
DPHE	Department of Public Health and Environment
DTW	Deep Tube Well
CIMMYT	International Maize and Wheat Improvement Center
FAAS	Flame Atomic Absorption Spectrometry
FAO	Food and Agriculture Organization of the United Nations
MSMA	Monosodium Methanearsonate
QTL	Quantitative Trait Loci
SRI	System of Rice Intensification
STW	Shallow Tube Well
UNDP	United Nations Development Programme
USAID	U.S. Agency for International Development
WHO	World Health Organization

Acknowledgements

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Introduction

Contamination of shallow groundwater aquifers with arsenic (As) has been reported in over 20 countries around the world (Nordstrom 2002) but is most serious in the Bengal Delta region of Bangladesh and West Bengal, India where the groundwater has been widely developed to supply drinking and irrigation water. An estimated 30 million people drink water from arsenic-contaminated tube wells in Bangladesh. Considerable efforts have been made to identify contaminated wells ($> 50\ \mu g\ L^{-1}$)[1] and to develop practical and acceptable water treatment systems for rural households (Chen et al., 2007; Kabir and Howard, 2007; Davis, 2006; Ahmed et al., 2006, 2005 & 2002; Hoque et al., 2006 & 2004). In addition to drinking water health risks, FAO was concerned about the potential levels of arsenic entering the food chain via absorption by crops from irrigated water. Because rice is the staple food in Bangladesh, and it is consumed in large quantities[2], arsenic-contaminated rice could aggravate human health risk when consumed along with As-laden drinking water. FAO in 2001 with UNDP initiated a study to examine arsenic accumulation in different parts of the rice plant from roots to straw and grain. This initial FAO study spurred a series of additional research conducted by USAID and other bilateral donors providing more substantive information indicating clear risks of arsenic in irrigation water and dietary exposure to arsenic via food. An international symposium on the behaviour of arsenic in aquifers, soils and plants and their implications for management was held in Dhaka in January 2005. The results confirmed the presence of high levels of arsenic in irrigated rice and vegetables.

In terms of water quantity used for rice in Bangladesh, the volume of water pumped for irrigation of winter (boro) season crops, especially for rice which uses 1 to 1.5 m depth of water per crop, is several orders of magnitude higher than that used for domestic purposes, introducing large amounts of As into the Bangladesh agricultural environment. Widespread use of As-contaminated irrigation water ultimately leads to issues of food security, food safety and degradation of the environment through:

1. Reduced agricultural productivity due to As toxicity to rice and possibly to animals when high As rice straw is used for feed.

2. Constraints on land use due to arsenic build up in soils, toxicity to rice and/or unacceptable quality of agricultural products.

3. Creation of spatial variability in soil As, Fe and P levels that make agricultural management of land difficult.

4. Enhanced exposure of humans to As through agricultural products containing elevated levels of As, especially rice, and through food system and environmental pathways of arsenic; e.g., high As animal products, dermal absorption while weeding rice paddies, use of high As straw and manure as fuel.

Arsenic in sediments of the Bengal basin originated in minerals found in the Himalaya mountains and foothills. In the sediments, arsenic, together with phosphate ($PO4^{3-}$), appears to be primarily adsorbed on amorphous Fe oxyhydroxides (FAO 2006). The shallow groundwater is highly reduced leading to reductive dissolution of Fe oxyhydroxides and solubilization of As and $PO4^{3-}$. The distribution of As in the sediments is spatially heterogeneous, and results of a preliminary national scale survey of soils (current surface sediments), from a USAID Bangladesh

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[1] Bangladesh arsenic drinking water standard. However, WHO drinking water standard for arsenic is $10\mu g\ L^{-1}$.

[2] 450 g/person/day

project carried out by a consortium of National and International partners[3], found that As varied in a distinct pattern across Bangladesh (Figure 1).

Much of the country has soil arsenic levels < 5 mg kg^{-1}, an uncontaminated background level similar to many other countries (Mandal and Suzuki, 2002; Smith et al., 1998). However, soil arsenic is elevated above 5 mg kg^{-1} in the Ganges river basin, indicating that this river is a source of As contamination of the current land surface. The most affected area is just below the confluence of the Ganges and Brahmaputra rivers. The map is constructed from 394 sampling points; thus, for higher resolution, additional data points are necessary. A more detailed map may also elucidate elevated soil As levels in other regions of the country and is urgently needed to implement management strategies within the Ganges floodplain.

Figure 1. Kriged map of surface soil (0-15 cm) As content; the heavy red line delineates the 5 mg kg^{-1} boundary

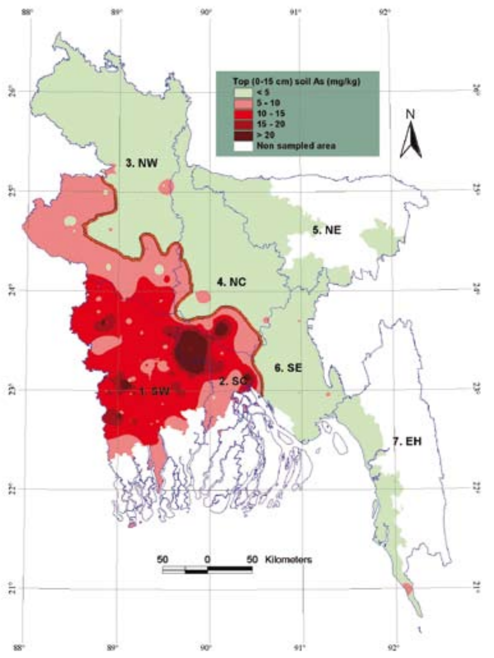
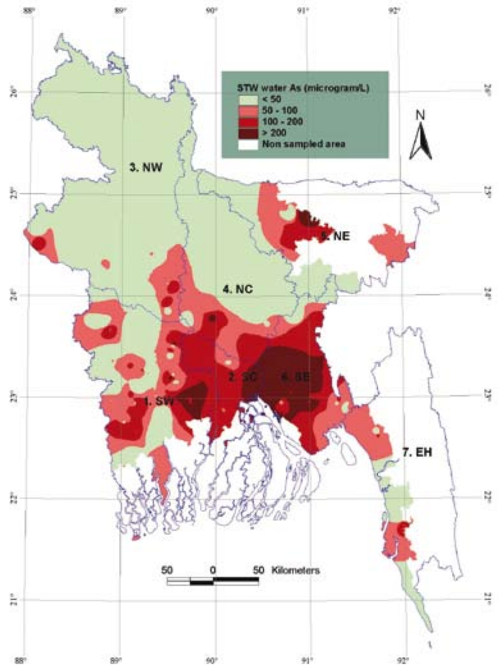


Figure 2. Kriged map of irrigation water As content in shallow tubewnells



A map for As in irrigation water (Figure 2) developed as part of the aforementioned national survey was very similar to the map generated by BGS/DPHE for arsenic in drinking water wells. The highest irrigation water As levels were found in the south central and south east regions of the country. *Boro* season rice is exposed to As from both soil and irrigation water, while the monsoon *T. Aman* rice is exposed to the natural soil arsenic in addition to any build up of As over time due to use of contaminated irrigation water. Soil As will be increased at the rate of 1 mg kg^{-1} per crop with 1.5 m of irrigation water containing 0.13 mg As L^{-1}, assuming no loss of As from the soil.

Research carried out by the BCAMAE in the command area of a single shallow tube well (STW)

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[3] Bangladesh Consortium for Arsenic Management in Agriculture and the Environment (BCAMAE) partners were BARI, BRRI, BINA, BAU, Cornell University, Texas A&M University and CIMMYT

in Poranpur village, Faridpur district in 2005 and 2006 established that reduced groundwater was rapidly oxidized after discharge from the well causing precipitation of amorphous Fe and Mn oxides (Figure 3), with concomitant adsorption and co-precipitation of As and P. The rapid re-oxidation of water coupled with the largely field to field water distribution method used in the command area raised soil As levels from a background of about 10 mg kg^{-1} to as high as 70 mg kg^{-1} and created a high degree of spatial variability in soil As levels which were higher near the tube well. Furthermore, yield of boro rice (BRRI dhan 29) was reduced from about 7.5 to 2.5 t ha^{-1} across a soil As gradient from approximately 12 to 68 mg kg^{-1}.

Figure 3. Irrigation water discharging from pump into concrete channel, showing orange Fe oxide deposition as water oxidizes

Farmers in the area complained of poor rice yields in both winter and summer (monsoon) seasons, and many were moving away from *boro* rice to wheat. However, they have no alternative to growing rice in the monsoon season, and farmers much preferred to grow rice in the *boro* season. Possible strategies for management of arsenic that would enable continuing rice production include:

1. Growing rice in an aerobic environment where As is adsorbed on oxidized Fe surfaces and is largely unavailable to rice. Arsenic may also be present as arsenate where uptake is suppressed by phosphate (Abedin et al., 2002), rather than arsenite found in flooded soils which is readily taken up through aquaporin channels (Meharg and Jardine, 2003) and is not affected by phosphate (Abedin et al., 2002).

2. Switching from As-contaminated shallow groundwater to non-contaminated surface or deep groundwater to avoid further build up of soil As. Unfortunately, the surface water option is limited and generally requires large irrigation development projects.

3. Identification or development of arsenic tolerant rice varieties, where arsenic uptake is also low.

Various research groups are looking at the possibility of growing rice more aerobically, in part because much of the rice production in the future will likely have to be with much less water as competing uses increase. The International Rice Research Institute (IRRI) leads a project aimed at developing "aerobic" rice varieties for the Indo-Gangetic Plains region, including Pakistan, India, Nepal and Bangladesh. The system of rice intensification (SRI) of Cornell University utilizes an alternating wet-dry water management for much of the season. Through the USAID-funded Soil Management Collaborative Research Support Program (SM-CRSP), raised bed and furrow system of crop production was shown to facilitate growing rice in a more aerobic soil environment (Figure 4), and this technology is being transferred to farmer groups in the Rajshai-Natore area. The results show that the raised bed system maintains or increases rice yields, reduces water use by 30-40% and improves fertilizer N efficiency while also lowering seed, tillage and labor costs. The raised bed represents a major shift in rice production practice but has been well received by farmers.

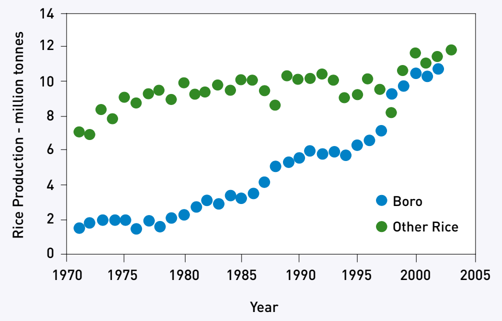
Figure 4. Farmer production of hybrid rice on raised beds and (inset) panicle size from conventional (L) and bed (R) production practices

Tolerance of rice to monosodium methanearsonate (MSMA) has been actively researched in the USA for more than 30 years. A Chinese indica variety (Zhe 533) has recently been found to be immune to panicle sterility (termed "straighthead disorder") that affects all USA rice varieties to some extent (Yan et al., 2005). An arsenate tolerance gene has also been identified (Dasgupta et al., 2004), but so far there is no report of tolerance to arsenite, which is likely the major form of As in paddy soils. The tolerance approach should be carefully considered as it could lead to continued loading of arsenic into soils via As-contaminated irrigation water, with probable disastrous long-term consequences for agriculture and human health. However, As tolerant rice varieties do have a use in environments that are already contaminated with As, or where As availability is high, especially if they also have low straw and grain As levels. Quantitative trait loci (QTL's) for accumulation of As in rice roots, shoots and grain have recently been identified (Zhang et al., 2007) suggesting that there may be genetic opportunities to reduce the As content of rice.

The "rice revolution" in Bangladesh was largely achieved by growth in the production of *boro* or winter season rice (Figure 5) using about a million shallow tube wells (STW) to supply groundwater irrigation. Today, *boro* rice supplies 50% of the country's food grain requirement. More recently, the government of Bangladesh has been promoting and subsidizing the development of "deep" tube wells as a more reliable source of irrigation water than the shallow tube wells, which are more frequently failing in the dry winter season. The BGS/DPHE survey of As in drinking water wells showed that groundwater As concentration decreased dramatically below 100 m depth (Ravenscroft et al., 2005). The "deep" tube wells for irrigation are generally on the order of 100m, and are still within the shallow groundwater aquifer. Some "very deep" tube wells with depths to approximately 300 m are also used for irrigation. Deep tube wells represent a large investment for farmer groups and, in contrast to shallow tube wells, are permanent. Consequently, it is important to characterize their As content and general water chemistry, and to understand how or whether this is likely to change over time.

Another As management option is to switch from boro rice to alternative cereal crops such as wheat and maize that require less water. This would be a good choice where availability of non-contaminated water is limited. The climate of Bangladesh is better suited to maize than to wheat. Maize production in Bangladesh has

Figure 5. Increase in rice production in Bangladesh



grown rapidly in the last five years in response to the demand for feed in the burgeoning poultry industry. Grain yields are high (average approximately 6 tons/ha) and leaf biomass is used for cattle feed. Maize production is currently concentrated in the northern part of Bangladesh, but it can be grown throughout much of the country. Wheat yield averages about 2 t/ha but requires fewer inputs of water and nutrients than maize. Wheat production has declined somewhat as maize production has grown, but there is renewed interest in wheat with recent commodity price increases.

Objectives of FAO-Cornell Project

The purpose of the project was to investigate several options for risk management of arsenic in crop production, with the following specific objectives:

1. To determine the impact of raised bed "aerobic" rice production management on yield and uptake of arsenic by rice across a soil arsenic gradient.

2. To determine the effect of soil arsenic on growth and uptake of arsenic by rice, maize and wheat in an outdoor net house pot study.

3. To assess the impact of soil arsenic on yield and arsenic content of wheat grown in farmer fields surrounding the rice experiment site.

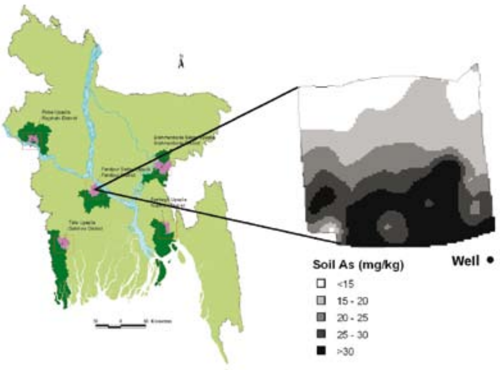
4. To evaluate the arsenic content and water chemistry of deep irrigation tube wells.

Methodology

Field Site

The 6 ha command area field site used for experiments with rice and sampling of farmer wheat and triticale production was located in the village of Poranpur of the Sadar Upazilla in Faridpur, a severely arsenic-affected district of the Gangetic Floodplain in central Bangladesh (Figure 6). The soil was a fine-textured (silty clay) Aquept (pH 7.5-7.9, organic C 1.3-1.8%). The previous cropping pattern at the study site was rain-fed monsoon rice (transplanted *Aman*) followed by irrigated winter rice (*Boro*). This site had previously been used for an experiment that showed As toxicity to rice.

Figure 6. Location of Poranpur field site and map of soil arsenic levels



The STW in this command area has been used for irrigation of boro season rice for the last 20 years. The As concentration in the water measured at different times from 2005-2007 ranged from 0.10-0.13 mg L^{-1}, with a 1:1 ratio between arsenite (As-III) and arsenate (As-V) species. The irrigation water was naturally reduced (Eh -70 mV) and also contained relatively high levels of reduced Fe (1.97-2.87 mg L^{-1}) and Mn (0.76-0.79 mg L^{-1}), together with phosphate (0.49-0.67 mg P L^{-1}). A single irrigation channel runs laterally in both directions from the STW, and individual fields are irrigated by allowing water to flow from field to field. The study utilized a soil As gradient from approximately 12 to 57 mg kg^{-1} to study the extent to which growing rice more aerobically on raised beds would prevent yield loss and lower plant As concentrations.

Rice Field Experiment

Paired plots for comparison of crop productivity and quality under conventional flooded (paddy) and raised bed and furrow conditions were established across a soil As gradient at As levels of 12.5, 26.3, 39.5 and 56.5 mg kg^{-1}. Plots were 5 m wide x 10 m long. Raised beds were 15 cm high, and 30 and 50 cm wide at the top and base, respectively, with 5 beds per plot. Two 45-day old seedlings/hill of BRRI dhan 29, a popular *boro* season variety, were transplanted on Jan 25, 2007 at a row to row and hill to hill spacing of 20 cm on both beds and the flat. Only 2 rows of rice were planted on each bed and plant density was much higher in the conventional treatment. Fertilizer was applied at the following elemental rates: N = 140, P = 25, K = 60, S = 20 and Zn = 4 kg/ha applied as urea, triple super-phosphate, muriate of potash, gypsum and zinc oxide, respectively. All nutrients were applied 2 days prior to transplanting and mixed with the soil, except for N, which was applied in three equal splits: one-third 2 days before transplanting, one-third 40 days after transplanting (DAT) and one-third 7-10 days before panicle initiation (60-70 DAT).

Conventional plots were continuously flooded to a depth of approximately 10 cm until drainage at 80% grain maturity about 2 weeks before harvest. In the raised bed-furrow system, enough irrigation water was kept in the furrows to just submerge the beds for seedling establishment and weed control during the first two weeks after transplanting. Thereafter, irrigation was scheduled to maintain a water head of about half the height of the beds never allowing the beds to be submerged throughout the growing season. A straw mulch was used to conserve moisture in the beds. Soil Eh in the raised beds and conventional plots was measured periodically by a pH meter equipped with a platinum electrode-glass electrode system. Rice was harvested between May 28 and June 3-4, 2007. The crop matured about 7-10 days later on the raised beds than in the conventional plots. Each raised bed and conventional plot was sub-divided into four "sub-plots" to measure variability. Twenty randomly selected hills from each "sub-plot" were cut at ground level and used for agronomic measurements and chemical analysis. A 5 m^2 area from the center portion of each sub-plot was harvested for determination of grain yield. Rice was threshed manually immediately after harvest and grain moisture content and weight were recorded. Grain yield was adjusted to 14% moisture. Rice straw and husked grain samples were analyzed for total As, Fe, Mn and P.

Nethouse Experiment

Rice, wheat and maize were also grown in pots in a nethouse placed adjacent to the rice field experiment (Figure 7). Plastic buckets 25 cm diameter x 30 cm high were filled with 10 kg dry wt of surface soil (0-15 cm) from the plots used in the rice field experiment with 3 replicates at each soil As level for each crop. A single maize plant, 2 hills (4 plants) of rice and 2 wheat plants were grown in an individual pot. Wheat (var. Bijoy) and maize (var. BARI maize 3) were seeded on Nov. 30, 2006 and 45 day-old seedlings of rice (BRRI dhan 29) were transplanted on Jan 25. The fertilizer nutrient rates were 100-12.5-25-10-2 mg kg^{-1} N-P-K-S-Zn for rice; 120-17.5-37.5- 10-2.5-1 mg kg^{-1} N-P-K-S-Zn-B for wheat, and 300-32.5-62.5-2.5-1 mg kg^{-1} N-P-K-S-Zn-B for maize. The nutrient sources were urea, triple super-phosphate, muriate of potash, gypsum, zinc oxide and boric acid. The rice was maintained continuously flooded, while maize and wheat were watered as required, using water from the tube well. Wheat was harvested at ground level on March 30, maize on May 6 and rice on May 21. Oven-dried straw and sun-dried grain weights were recorded. Straw and grain samples were preserved for total As, Fe, Mn and P analysis.

Figure 7. Nethouse at Poranpur site for pot experiments

Farmer Wheat Fields

Many farmers in Poranpur had switched from rice to wheat during the study season because of poor yields of *boro* rice. Thus, the area in the STW command area surrounding the rice trial was used to assess the effect of soil As concentration on wheat productivity (var. Shatabdi). For this purpose composite samples of surface soil (0-15 cm) and wheat grain and straw were collected from 41-1 m^2 areas for determination of soil As, wheat yield and As concentration in grain and straw. Wheat yield per ha was computed from the grain weight obtained from the one meter square area. The soil, straw and grain samples were analyzed for As.

Deep Tube Wells

Water was collected from 12 deep tube wells in Faridpur district after 10-15 min of operation, immediately filtered (0.45 micron) and a 90 mL aliquot dispensed into bottles containing 10 mL 2 M HCl. Water was analyzed for As, P, Fe and Mn.

Analytical Method

Standard analytical methods were followed for water, soil and plant samples. In all cases As was measured by flow-injection hydride generation-flame atomic absorption spectrometry (FI-HG-FAAS) following pre-reduction with KI and $NaBH_4$ to generate AsH_3 (Samanta et al., 1999). A Perkin-Elmer AAnalyst 200 instrument was used for FAAS. Fe and Mn were measured by FAAS and P by the molybdenum blue colorimetric procedure. Soil available P was measured following the Olsen extraction method (Olsen and Sommers 1982). Soil and plant samples were digested with HNO_3-H_2O_2 in a block digester at 110ºC prior to elemental analyses (Tang and Miller 1991). Soil samples were extracted with pH 3.0, 0.2 M ammonium-oxalate in the dark for determination of amorphous Fe and Mn oxides (Loeppert and Inskeep, 1996). Standard solutions were prepared using analytical grade chemicals. A secondary reference rice grain standard developed using NIST 1688a certified rice flour reference material was used in plant analysis.

Results and Discussion

1. Effects of Soil Arsenic on Rice

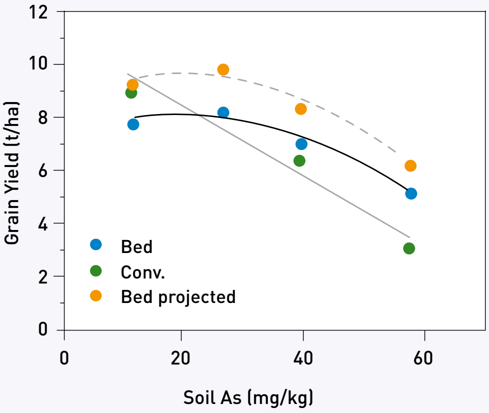
(i) Rice Productivity and Arsenic Content across a Field Soil Arsenic Gradient

Growth of rice in the conventional paddy was initially better than on raised beds, this was reversed over time (Figure 8). The growth duration was also 1-2 weeks longer on the beds.

Figure 8. Rice growth on raised beds and under paddy conditions at tillering (above) and crop maturity (below); soil arsenic in plots in the foreground is 58 mg kg^{-1}

Rough rice yield at 14% moisture declined more or less linearly from 8.9 to 3.0 t/ha across the soil arsenic gradient under conventional flooded paddy conditions. This result was similar to that obtained in the previous year. In contrast, yield of rice on the raised beds was much less affected by soil arsenic levels, declining from about 8 to 5.2 t/ha over the As gradient. In the current experiment, 5 beds were used in a space where there would normally be six beds so that potential productivity would be higher by this factor, shown as projected yield in figure 9.

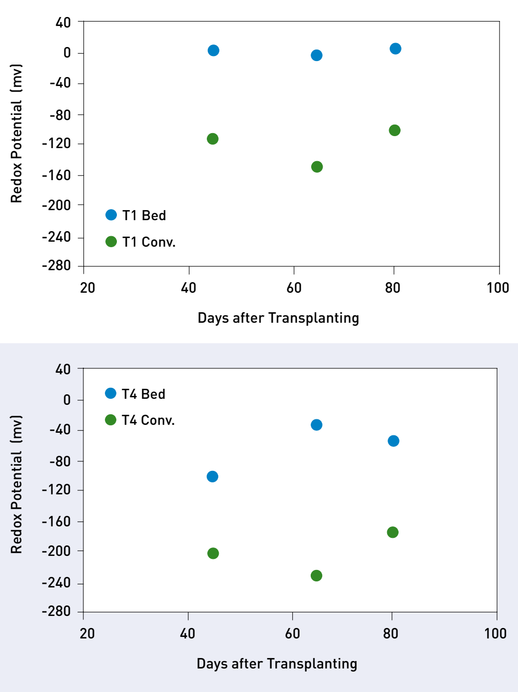
Figure 9. Rice yields for raised bed and conventional paddy production over a soil arsenic gradient



Soil As	Crop Yield - t/ha	
mg/kg	Conv.	Beds
11.6	8.92	7.77
26.3	8.11	8.24
39.5	6.38	6.97
57.5	2.99	5.21

Soil redox potential (Figure 10) in the surface soil (0-15 cm) was much lower in the conventional paddy than in the raised bed. However, redox values in the high arsenic plot (T4) were low enough that at least some Fe was reduced. With more experience it may well be possible to manage water to prevent Fe reduction and hence lower arsenic availability more than was achieved in the present study.

Figure 10. Soil redox potential (0-15 cm) in raised beds and flooded rice paddies



Production of rice on the raised beds also reduced the arsenic content of rice plants, consistent with lower As availability (Figure 11). As soil arsenic increased, the concentration of arsenic in rice straw increased linearly in both the bed and conventional treatments, but was 3-6-fold lower in rice grown on beds (Figure 11B). Arsenic in rice grain increased from 0.26 to 0.36 mg kg^{-1} on the beds, whereas it declined from 0.54 to 0.34 mg kg^{-1} in the conventional plots (Figure 11A). This difference in behavior implies that As toxicity interferes with translocation of As from vegetative tissues to grain. Thus there is a positive relationship between As in the straw and grain for rice grown on beds but a negative relationship for conventional flooded rice (Figure 12).

Figure 11A. Effect of soil As content on arsenic levels in rice grain

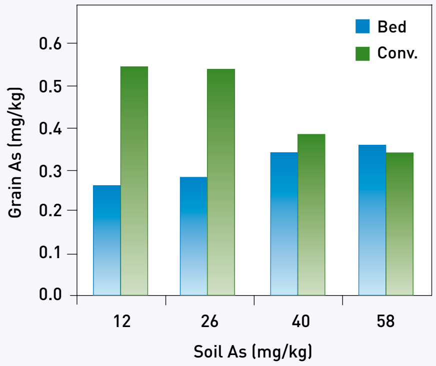


Figure 11B. Effect of soil As content on arsenic levels in rice straw

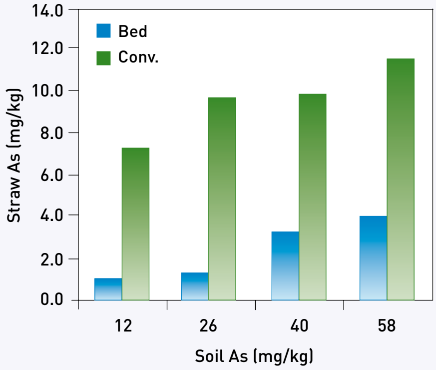
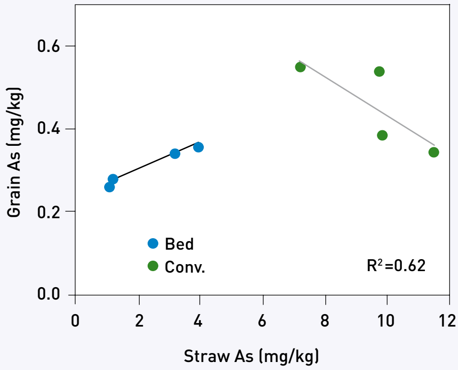


Figure 12. Relationship between arsenic in rice grain and straw for bed and conventional production methods



(ii) Productivity and Arsenic Content of Rice Grown in Pots

Productivity of rice grown under continuous flooding in pots containing surface soils (Figure 13; Table 1) was reduced somewhat more by high soil arsenic than it was in the field.

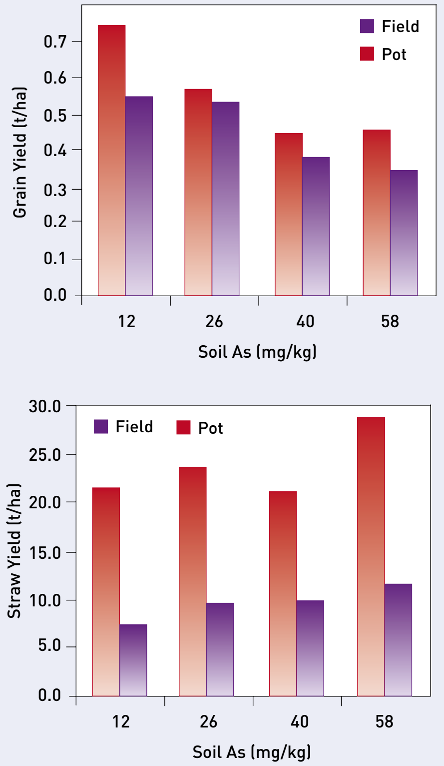
Figure 13. Effect of soil As concentration on rice growth in buckets (soil As increases from 12 to 58 mg kg^{-1} from L to R)

Table 1. Effect of soil arsenic on yield and arsenic concentration in rice grown in pots

Parameter	*Soil Arsenic (mg kg^{-1})*			
	11.6	26.3	39.5	57.6
Grain Yld (g/pot)	115	84	51	31
Grain As (mg/kg)	0.74	0.57	0.45	0.46
Straw As (mg/kg)	21.5	23.7	21.2	28.7

Additionally, higher plant uptake of As was found when rice was grown in pots compared to the field (Figure 14). Maximum As concentrations were 0.74 and 0.54 mg kg^{-1} for grain and 28.7 and 11.5 mg kg^{-1} for straw when rice was grown in the pots and field, respectively. Most likely, these results are found because the As concentration in soil in the field decreases somewhat with depth so that rice roots can escape high soil As by growing deeper, whereas soil As concentration was uniform in the pots.

Figure 14. Grain and straw As concentrations for rice grown in pots and the field



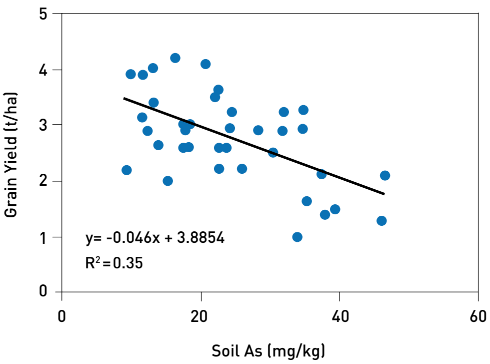
2. Effects of Soil Arsenic on Wheat

(i) Wheat Productivity and Arsenic Content in Farmer Fields

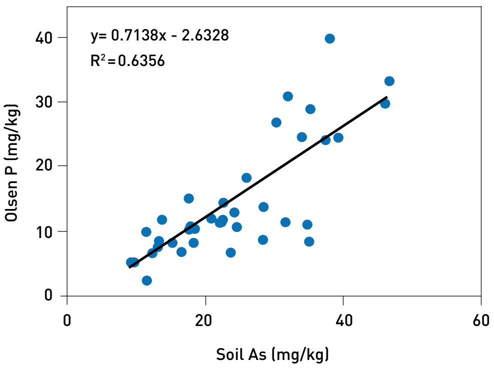
Wheat yields were negatively correlated with soil As (Figure 15), although it seems unlikely that As was the cause for reduced wheat yield as the availability of As is low under the aerobic soil conditions of wheat growth. Because irrigation water deposits both As and P in soils, these two parameters were also related (Figure 15) and consequently wheat yield was also negatively correlated with Olsen available P. It is possible that high soil P was interfering with Zn availability and that the relationship between yield and soil As and P was due to zinc deficiency in wheat. Also, the Shatabdi variety used is known to be susceptible to B deficiency. However, there are no data to evaluate these possibilities.

Figure 15. Relationships between soil arsenic and wheat yield (A) and available soil P (B)

A. Wheat Yield



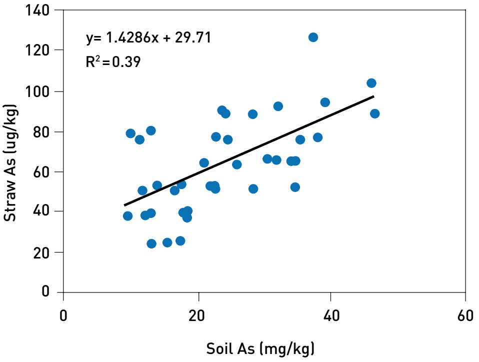
B. Soil P



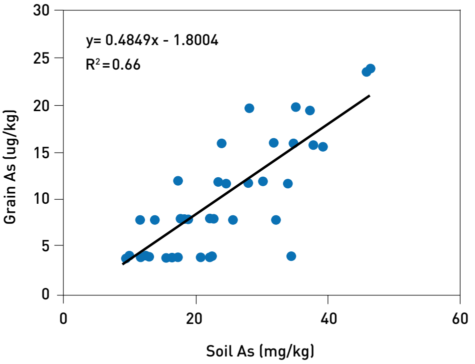
Positive correlations were found between soil As and both wheat straw and grain As concentrations (Figure 16), with As levels in straw and grain reaching approximately 0.1 mg kg^{-1} and approximately 0.02 mg kg^{-1}, respectively, which are 115 and 27 times less that the corresponding maximum values for rice grown across the field As gradient. The As gradient in the rice experiment reached a maximum of 57 mg kg^{-1}, whereas the maximum soil As concentration in the farmer wheat fields was 46 mg kg^{-1}.

Figure 16. Relationships between soil arsenic and wheat straw (A) and grain (B) arsenic concentrations

A. Straw



B. Grain



(ii) Productivity and Arsenic Content of Wheat Grown in Pots

Yield of wheat in pots was significantly reduced by 8% ($p < 0.05$) at the highest soil As level but not at levels up to 40 mg kg^{-1} (Table 2), suggesting that the substantial declines in yield with increasing soil As in farmer fields was caused by other factors. Grain and straw As concentrations increased progressively with increasing soil As, to a maximum of 0.1 and 3.3 mg kg^{-1} at the highest soil As level. These values were approximately 4 and 30 times higher than the maximum As concentrations found in the farmer wheat samples, again indicating the effect of constraining the root system to a high As soil.

Table 2. Effect of soil arsenic on yield and arsenic concentration in wheat tissues at harvest for wheat grown in pots

Parameter	*Soil Arsenic (mg kg^{-1})*			
	11.6	26.3	39.5	57.6
Grain Yld (g/pot)	10.8	10.6	10.5	9.9
Grain As (mg/kg)	0.03	0.05	0.07	0.10
Straw As (mg/kg)	0.16	0.53	1.13	3.30

3. Effects of Soil Arsenic on Maize

Maize growth and productivity in pots was reduced with increasing soil As (Table 3). Grain As levels were very low (0.02-0.03 mg kg-1) and higher concentrations of As were found in the leaf than the stem (max. values of 0.12 and 0.61 mg kg^{-1}, respectively). The yield reduction, which was modest (13 %), would probably not have been observed with free root growth in the field and As concentrations in grain and tissue would probably have been lower. Comparing pot data, the level of As in maize leaves at the highest soil As was 70- and 5-fold less than that found in rice and wheat straw, respectively, indicating that maize leaves would be a much safer feed for cattle.

Table 3. Effect of soil arsenic on yield and arsenic concentration in maize tissues at harvest

Parameter	*Soil Arsenic (mg kg^{-1})*			
	11.6	26.3	39.5	57.6
Grain Yld (g/pot)	118	112	99	103
Grain As (mg/kg)	0.02	0.02	0.02	0.03
Stem As (mg/kg)	0.08	0.10	0.10	0.12
Leaf As (mg/kg)	0.34	0.48	1.48	0.61

Figure 17. Effect of increasing soil As from 12 to 58 mg kg^{-1} (from L to R in picture) on maize biomass production

4. Water Chemistry of Deep Tube wells

Arsenic concentration in 12 deep tube wells (DTW) in Faridpur district averaged 181 µg L^{-1} (Table 4) which is almost twice the average from earlier survey of 100 STW's in this same district (0.097 ± 0.072 µg L^{-1}). Thus, development of DTWs, which are more permanent than STWs, would accelerate As contamination of soils and exacerbate problems of arsenic in the food system and the environment. The average deep tube well water was also higher in P but lower in Fe and Mn than the STW (Table 4).

Table 4. Faridpur District deep tube well characteristics and water chemistry

Village	Union	Depth ft	Year of Installation	Area (ha)	Water Chemistry As	P	Fe	Mn
					mg L^{-1}			
Bonogram	Koizuri	300	1987	20	0.170	1.14	4.66	0.119
Someshpur	Koizuri	250	1989	15	0.183	1.63	5.32	0.159
Tambulkhana	Koizuri	298	1989	22	0.204	1.51	3.99	0.079
Betbaria	Koizuri	275	1980	24	0.162	1.48	3.33	0.119
Betbaria	Koizuri	260	1989	10	0.209	1.56	3.99	0.119
Gadadhordangi	Aliabad	248	2004	20	0.222	1.53	3.99	0.159
Gerda	Gerda	270	2003	20	0.219	1.19	4.66	0.079
Ekra	Gerda	275	1978	12	0.120	3.74	5.32	0.079
Gerda	Gerda	275	1980	13	0.204	1.88	4.66	0.079
Sachia	Koizuri	300	1990	16	0.212	1.35	3.33	0.079
Dhuldi Rajapur	Machhar	350	1977	24	0.102	1.60	2.66	0.159
Machhar Koarpur	Machhar	351	1991	20	0.165	1.19	3.33	0.198
				Mean	**181±**	**1.65±**	**4.10±**	**0.12±**
					0.039	**0.69**	**0.84**	**0.04**
				Shallow tube well Mean	**0.097±**	**0.91±**	**5.04±**	**0.71±**
				(n=100)	**0.072**	**0.57**	**4.07**	**0.40**

Conclusions

The main conclusions from the research were:

1. Production of rice on raised beds is a viable strategy to minimize the effects of soil contamination with As on *boro* season rice productivity, and to reduce the As content of both grain and straw. Previous experience has shown that irrigation water inputs are reduced by 25-40% with raised bed culture, saving both water and reducing arsenic loading to soil. The more aerobic conditions of the raised bed reduced arsenic content of straw to one-sixth of that found with the conventional rice paddy at soil As levels < 25 mg and to one-third when soil As was > 25 mg kg^{-1}, thereby substantially reducing arsenic exposure of animals consuming rice straw. The As content of brown rice from raised beds was halved from 0.5 to 0.25 mg kg^{-1} at soil As levels < 25 mg kg^{-1}, but was similar to that in conventional paddy at higher soil As levels. Human intake of As from daily consumption of 400g rice containing 0.5 mg As kg^{-1} is equal to that from 4L of water containing 0.05 mg L^{-1}, indicating that intake of As from rice needs to be considered when setting drinking water standards. Raised bed culture can reduce human health risk associated with As intake from rice exposure route.

2. Wheat and maize can be successfully grown as alternative crops to *boro* season rice, reducing irrigation water inputs considerably. Deep rooting of these upland cereal crops should be facilitated in order to reduce exposure to high surface soil As, plant uptake of As and potential As toxicity.

3. Water management techniques such as the introduction of alterative crops and promotion of water conservation and irrigation techniques are useful adaptive measures in coping with changing agriculture practice and responses to climate change.

4. Based on pot studies, wheat and maize grain contained approximately 7- and 25- times less As than rice grain and human intake from these sources (and chicken intake from maize) would be very low. Similarly, maize leaves would be a safer animal feed than either rice or wheat straws, which contained 70- and 5-times more As, respectively.

5. "Deep" irrigation tube wells (approx. 300 ft) in Faridpur district contained twice as much As as shallow tube wells, so the development of these larger and more permanent irrigation systems would accelerate soil contamination with As and exacerbate problems with As transport in the food chain.

Human Health Risk Assessment

Paddy rice is the staple food for Asia, and it provides 73% of total caloric intake and is consumed in large quantities, average approximately 450 g/adult/day, is reported for Bangladesh (Meharg 2005). Vast quantities (approximately 90%) of groundwater from shallow tube wells in Bangladesh are pumped to irrigate rice during dry season, and are estimated to be around 4 million hectares affecting 2/3rd of the country's soil. Once arsenic is in the soil it accumulates in this matrix with potential land degradation in the long term, impacting crop yield.

Currently, the drinking water standard for arsenic is 0.01 µg/liter (or 10 ppb) (WHO 2004, USEPA 2006) based on excess cancer risk of 6 in 10,000 persons developing skin cancer, as skin is the target organ for arsenic, as well as other associated cancers such as the lung and bladder in chronic exposures. In Bangladesh, the established guideline value is 50 ppb [or, 10 ppb x 5], corresponding to 6 in 10,000 persons times 5, or 30 more cases of skin cancer in every 10,000 people (or, 3 in 1,000 persons) over a lifetime cancer risk for drinking water alone with 50 ppb arsenic using linear multistage models for cancer development. These values have not accounted for additional risks from food stuffs.

In order to conduct a comprehensive quantitative risk assessment, information through dietary status and consumption patterns for various food categories are needed in calculating daily intakes from various human exposures to arsenic. The consumption of fodder from animals may pose another indirect human exposure route via meat consumption. These indirect pathways have yet to be studied; furthermore, micronutrient deficiency is common among women and children in developing countries, and the interaction of arsenic with selenium may aggravate further micronutrient deficiency among the most vulnerable subpopulations. It has been reported that while arsenic is toxic by itself, it also interacts with selenium, resulting in excretion of their mutual metabolite (Gailer et al. 2000). This confounding excretion of selenium can be a health concern as selenium, an essential micronutrient, supports antioxidation, chemoprevention and immunocompetence, and low selenium status is found with occurrence of illnesses such as diabetes (Can et al. 2005), some cancers (Clark et al. 1996), and viral infections (Beck et al. 1994) including poliovirus (Broome et al. 2004), HIV (Baum et al. 2000), and avian H5N1 influenza.

Future Applied Research Needs

1. Evaluation of the effectiveness of raised bed rice culture on rice productivity and As content in the monsoon season when irrigation water is generally not used.

2. Identification of rice varieties that perform well on raised beds with even less water by interfacing with existing research programs aimed at developing varieties that are productive in an aerobic environment. The goals of this approach would be to maintain yield potential while realizing further benefits in terms of water conservation, reduced As loading of soils and reduced As content of rice grain and straw.

3. Evaluation of the sensitivity of rice varieties to As toxicity in order to develop recommendations for As affected areas.

4. Quantification of irrigation water savings in conjunction with farmer adoption of raised beds for *boro* season rice.

5. Improved resolution of the maps of As in soil and STW irrigation water in the Gangetic floodplain to better identify critical areas for targeting As management practices.

6. A broader assessment of the As content and water chemistry of deep and very deep (up to 300m) irrigation tube wells in the Gangetic floodplain and elsewhere in Bangladesh in order to characterize their water quality and suitability for irrigation purposes. This information is needed for development of science-based groundwater use policies.

7. A broad assessment of wheat and maize productivity in farmer fields affected by As, including identification of the cause for the negative correlation of wheat yield with soil As in farmer fields at Poranpur.

8. Groundwater conservation measures using monsoon rainwater harvesting and treatment for groundwater recharge to dilute arsenic toxic constituents with high quality water and augment overall water supply.

9. Obtain dietary data to support comprehensive quantitative human health risk assessment.

10. Evaluate the potential of phosphate, an analogue of arsenate (AsV), to compete for sorption sites on iron hydroxides and for uptake by plants; thus applying balanced fertilization in reducing As uptake.

11. FAO technical assistance in disseminating and mobilising As risk management in agricultural systems; in capacity building of aforementioned research to field implementation via farmer training and community strengthening; in developing participatory and integrated approaches to As risk management; and in extending water-soil-crop management practices applied in the current study to climate change adaptation mechanisms.

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Arsenic contamination in groundwater has been reported in more than 20 countries around the world and, in many, shallow groundwater is used for both irrigation and drinking purposes. In Bangladesh arsenic threatens the health of up to 30 million people through arsenic-laden groundwater transfer to crops and directly via drinking water. The problem originates in arsenic-rich bedrock of the Brahmaputra river basin that filters irrigation and drinking water pumped to the surface through millions of tube wells. The current FAO Working Paper examines remediation options with respect to food safety and yield implications and reports FAO's successful development of water-soil-crop management practices in mitigating arsenic problem in agriculture.