Arsenic Accumulation in Irrigated Paddy Soils and Possible Mitigation Methods

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Abstract

Irrigation with arsenic-contaminated groundwater is adding arsenic to soils in Bangladesh, India and some other countries in south and south-east Asia. The added arsenic gradually accumulates in the topsoil, and amounts now appear to be reaching levels toxic to rice in some soils that have been irrigated with highly-contaminated water for 10-20 years or more. Arsenic accumulations vary considerably between and within tubewell command areas. Practical mitigation and rehabilitation methods will vary from place to place according to local environmental, economic and cultural conditions, and many may be costly to apply. Possible methods include: water treatment; providing an alternative safe water supply; substituting alternative farming methods and soil treatments to reduce arsenic uptake by crops; and removing contaminated topsoils.

Arsenic accumulation

In a paper written over 70 years ago, Reed and Sturgis (1936) stated that "Arsenic toxicity in soils is no new problem" and described arsenic toxicity in rice grown on flooded soils in Louisiana, USA. Yet it is only in the past ten years that the potential hazard of arsenic toxicity in soils irrigated with arsenic-contaminated groundwater has slowly been recognised in Bangladesh and West Bengal; and, as Ravenscroft (this conference) has described, there seems to be little awareness as yet of this hazard elsewhere in South and Southeast Asia where soils are widely irrigated with contaminated groundwater.

Arsenic added to the soil in contaminated irrigation water stays mainly in the topsoil where it gradually accumulates with time. Only small amounts of the added arsenic appear to be taken out of the soil by crops, lost to the air by volatilisation or leached to lower soil layers. The problem of arsenic accumulation is particularly serious in soils where, as in most parts of South and Southeast Asia, rice is the main crop that is irrigated. Paddy soils – i.e., those on which rice is transplanted and grown in flooded fields – are particularly exposed to this hazard. That is because of the large quantity of water used to irrigate this crop – commonly 1000 mm compared with only about one-quarter this amount for dryland crops – and the fact that, under the anaerobic conditions in flooded paddy fields, the added arsenic is in a form that is readily available to plant roots, whereas arsenic is quickly immobilised in the aerated environment of soils used for dryland crops.

Soil arsenic toxicity levels for crops are difficult to establish. In fact, there is no single level that can be regarded as toxic to plants. The factors which influence the availability of arsenic to plants – such as redox potential, pH, organic matter content, and contents of other soil minerals such as iron, manganese, phosphorus and sulphur – vary greatly between soils, and some may vary within the year. Moreover, different plants take up or tolerate widely different levels of soil arsenic, and the same is true of different types and varieties of rice. Also, conventional methods of soil analysis involve drying soil samples, which means that laboratory results do not necessarily correlate satisfactorily with the saturated, anaerobic conditions in which rice roots are growing. The limited evidence available suggests that the safe limit of soil arsenic for rice might be ca 50 ppm. Some soils in Bangladesh that have been irrigated for 10-20 years now have >50 ppm arsenic in the topsoil compared with original levels probably less than 10 ppm, and the first indications of toxicity symptoms in rice have recently been reported.

Figure 1 shows how arsenic might accumulate in soil over time at different concentrations in irrigation water, assuming an annual irrigation application of 1000 mm. A crop irrigated with 1000 mm of water containing 100 ppb arsenic receives 1 kg of arsenic per hectare per annum.

That is equivalent to the addition of 0.56 mg/kg per year when mixed into 10 cm of cultivated topsoil. At this concentration, it could take several decades before significant changes in soil arsenic levels could be differentiated from an uncontaminated background of 5–10 mg/kg of arsenic. Assuming this background, the arsenic loadings in Figure 1 have been shaded according to the following tentative interpretative guide: <5 mg/kg: loading is indistinguishable from background; 5–15 mg/kg: marginal probability of distinguishing the loading from background; and >50 mg/kg: probably distinguishable from background. Actual loading rates will vary from place to place with the amount of irrigation water applied and arsenic concentrations in the water.

Not all of the arsenic in groundwater delivered from tubewells actually reaches the fields irrigated. In most arsenic-affected areas of the Bengal Basin, groundwater is rich in iron. On exposure to the air, this iron is oxidised and precipitated as hydroxides, which then adsorb arsenic. Hossain (2005) reported that arsenic concentrations in the irrigation water at one 4-ha tubewell site in Bangladesh that had been used for 15 years decreased from 136 ppb at the well-head to 68 ppb at the end of the distribution channel. He also found that, in fields near the well-head, the arsenic concentration in the topsoil was 61 mg/kg, but it decreased to <20 mg/kg (minimum 11 mg/kg) over the outer one-third of the command area (Figure 2). Therefore, the concentration of arsenic in water measured on delivery from a tubewell is not a reliable indicator of the amount of arsenic actually added to soils within different parts of a command area. This factor needs to be taken into account in soil, water and crop sampling within irrigation command areas.

Mitigation methods

Historically, most of the studies on arsenic-contaminated land and soils have been carried out in developed countries, either on mining or industrial waste sites or on aerated soils contaminated with arsenical pesticides or other treatments. However, few, if any, of the reclamation or mitigation methods used on such land and soils appear to be practical for small-scale rice farmers, and more appropriate methods need to be found. The need to test and propagate such methods is urgent: in some places, soils are already approaching arsenic levels that could reduce crop yields; and even before that threshold is reached, annually increasing soil arsenic levels are increasing arsenic levels in rice grown on affected soils and thus increasing the amounts of arsenic ingested by local consumers.

Mitigation and rehabilitation methods that might be practical will vary from place to place according to local environmental, economic and cultural conditions. Possible methods are listed in Figure 3 and are reviewed briefly below.

<u>Water treatment</u>. The simple filtration methods used for domestic water supplies and more sophisticated methods used for treating urban supplies appear to be impractical for treating the enormous quantities of water used for irrigation (especially of rice) because of the cost, institutional needs and engineering involved. However, as was described earlier, considerable amounts of arsenic are co-precipitated with ferric iron in distribution channels before irrigation water reaches fields. Methods need to be tested to increase this reduction of arsenic contents by, for example, providing field or overhead settling tanks, increasing turbulence of flow in channels, adding ferric iron material to settling tanks or channels, or growing hyperaccumulator plants in settling tanks (see below).

<u>Alternative irrigation supply</u>. Wherever possible, an alternative source of arsenic-free irrigation water should be provided. Opportunities for substitution will differ between areas. In most affected parts of Bangladesh and West Bengal, exploiting deep aquifers (below about 150 m) will be the most practical method where groundwater availability and quality are proven to be satisfactory. Surface-water supplies might be used where they are not already fully exploited, and

it might be possible to construct dams in some hill valleys to create reservoirs for irrigating downstream floodplain land. However, these alternative irrigation sources are generally much more costly to provide, operate and maintain than existing shallow tubewells, and subsidies may need to be provided. The costs need to be weighed against the increasing health, social and economic costs of continuing irrigation with contaminated water.

Alternative farming methods. Arsenic in irrigation water applied to dryland crops grown on aerated soils is rapidly adsorbed by ferric iron; also, dryland crops need much less irrigation water than paddy rice. Therefore, substituting dryland crops such as wheat or maize for paddy rice, or growing rice as a dryland crop, could reduce the problem of arsenic contamination of soils and food crops. However, for the majority of farmers in south and southeast Asia, rice is by far the preferred crop option, culturally and economically, and much of the land currently irrigated is better suited to paddy rice than for dryland crops (including rice grown as a dryland crop). Additionally, on seasonally-flooded land, arsenic added and 'fixed' in aerated soils during dry-season irrigation might become available again to a following rice crop grown in the monsoon season. Research is in progress to breed arsenic-tolerant rice varieties, but the use of such varieties would not reduce the accumulation of arsenic in soils, so it might provide only a short-term interim measure until an alternative safe irrigation supply could be provided. Various ferric iron materials that adsorb arsenic have been tested for use on industrially-contaminated land, but the value of using such materials on paddy soils where the iron would be reduced seems doubtful, although locally-appropriate methods deserve testing. A practice long used in the southern United States, of allowing rice fields to dry out completely for 10–14 days prior to the panicle initiation stage, reduces arsenic uptake but also reduces potential crop yields, which might not be acceptable to small farmers.

Rehabilitation methods. Even where an arsenic-free irrigation supply can be provided, it will be desirable to reduce arsenic concentrations in affected soils to restore crop yields and/or reduce crop uptake of arsenic. High arsenic levels will persist in contaminated soils for many years because of the low rates of leaching and other losses. Substituting uncontaminated irrigation water should dilute arsenic concentrations in paddy topsoils during the growing season, and might enable normal rice production to be resumed immediately; and the addition of soil amendments such as ferric iron deserves testing.

The simplest and quickest way to remove the arsenic hazard in contaminated paddy soils is to remove the topsoil. This may seem a drastic solution, but the heavily contaminated layer is usually no more than 10–15 cm thick, and farmers in Bangladesh commonly sell soil for brick-making; soil is also widely removed for building road and flood embankments, footpaths, raised house plinths and house walls. Promotion of this technique for soil rehabilitation might need government or NGO support. This practice is only appropriate for silty and clayey soils in which topsoil removal would not expose a more permeable layer unsuitable for irrigated paddy cultivation.

The practicality of using plants which take up large amounts of arsenic from soils deserves study. Such plants (hyperaccumulators) include brake fern (*Pteris vittata*), some other ferns and Indian mustard. Arsenic taken up by such plants is removed from fields when the crops are harvested. The use of brake fern and mustard might be considered where it is impractical to provide a low-arsenic irrigation supply. Water hyacinth (*Eichhornia crassipes*) is a known hyperaccumulator, but it roots in water, so it could only be used to remove arsenic from irrigation water – e.g., in settling tanks – not from soils. The feasibility of using hyperaccumulating plants to rehabilitate paddy soils needs to be tested, together with methods to dispose safely of large quantities of plant residues with high arsenic contents and to reduce possible health risks to children, livestock and wildlife eating the plants or inhaling dust from burnt material.

References

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Figure 1. Effect of arsenic concentration and time on arsenic loading of soils from irrigation water

	Arsenic load in irrigation water (ppb)		
Years of irrigation	100	250	500
	Arsenic addition to soil mg/kg		
1	0.56	1.39	2.78
5	2.78	6.94	13.9
10	5.56	13.9	27.8
20	11.1	27.8	**55.6**
50	27.8	**69.4**	**138.9**

Figure 2. (From Hossain, 2005)

Figure 3. Possible arsenic mitigation methods

Type	Method
1. Water treatment	a. Filtration/chemical treatment b. Co-precipitation with iron
2. Alternative irrigation supply	a. Deep aquifer b. River/lake/pond c. Reservoir
3. Alternative farming method	a. Substitute dryland crops b. Grow dryland rice c. Use arsenic-tolerant varieties d. Soil amendments
4. Soil rehabilitation	a. 2a/b/c; 3d b. Remove topsoil c. Grow hyperaccumulator plants