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Identifying the Costs of a Public Health Success: Arsenic Well Water Contamination and Productivity in Bangladesh

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We exploit recent molecular genetics evidence on the genetic basis of arsenic excretion and unique information on family links among respondents living in different environments from a large panel survey to uncover the hidden costs of arsenic poisoning in Bangladesh. We provide for the first time estimates of the effects of the ingestion and retention of inorganic arsenic on direct measures of cognitive and physical capabilities as well as on the schooling attainment, occupational structure, entrepreneurship, and incomes of the rural Bangladesh population. We also provide new estimates of the effects of the consumption of foods grown and cooked in arsenic-contaminated water on individual arsenic concentrations. The estimates are based on arsenic biomarkers obtained from a sample of members of rural households in Bangladesh who are participants in a long-term panel survey following respondents and their coresident household members over a period of 26 years.

Key words: Arsenic, Productivity, Health, Genome.

JEL Codes: I15, I18, O1, I25.

1. INTRODUCTION

In the 1970s and 1980s, the government of Bangladesh, with the support and financing of the United Nations Children's Fund, promoted the digging of tube wells to provide clean drinking water and reduce the incidence of diarrheal disease. Prior to this, drinking water came from surface water sources, which were identified as a principal source of diarrheal disease. This shift in water sources has been attributed to having played a major role in the reductions in morbidity

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experienced in Bangladesh, particularly with respect to water-borne diseases. Indeed, despite little growth in rural wages and no change in average calorie intake (Pitt et al., 2012), there has been significant increases in average BMI by age and in height for the rural population of Bangladesh, as shown in Appendix Figures A1 and A2 for the period 1982 and 2008 based on panel survey data describing a representative population of rural households in 1982.

In the late 1990s, however, evidence indicated that groundwater, unlike surface water and by then the main source of water for drinking, irrigation, and cooking in Bangladesh, was contaminated by naturally occurring arsenic in 59 of the country's 64 districts. The contamination of groundwater by arsenic in Bangladesh is the largest poisoning of a population in history (Smith et al., 2000). As 95% of the country's population relies on well water, an estimated 57 million people have been chronically exposed to drinking water with arsenic levels exceeding the WHO standard of 10 μg/l, and 35 million people were exposed to arsenic levels above the country's government standard of 50 μg/l (British Geological Survey, 1999).

While there is now a large body of evidence that the consumption of arsenic-contaminated water is manifested in higher levels of morbidity and new symptoms (*e.g.* skin lesions), there is little evidence on the economic consequences of arsenic ingestion and retention in the body in Bangladesh. Moreover, in a low-income country where health levels are relatively low, the debilitating effects of arsenic on productivity are not easily identifiable because many of the symptoms (*e.g.* headaches, bloating, nausea, diarrhoea, breathing problems) are similar to those from other prevalent health causes. The causal effects of productivity are also difficult to identify given that arsenic levels in humans reflect consumption and time-allocation choices and much of the population does not work for wages. In this article, we exploit recent molecular genetics evidence on the genetic basis of arsenic excretion and unique information on family links among respondents living in different environments from a large panel survey within a theoretical framework incorporating optimizing behaviour to uncover the costs of arsenic poisoning in Bangladesh. In particular, we provide new estimates of the effects of the ingestion and retention of inorganic arsenic on direct measures of cognitive and physical capabilities as well as on the schooling attainment, occupational structure, entrepreneurship, and incomes of the rural Bangladesh population. We also provide new estimates of the effects of the consumption of foods grown and cooked in arsenic-contaminated water on individual arsenic concentrations.

The estimates are based on arsenic biomarkers obtained from a sample of members of rural households in Bangladesh who are participants in a long-term panel survey following respondents and their coresident household members over a period of 26 years. In the last round of the survey, each respondent in the survey aged 8 years and above provided clippings from all ten toenails. Toenail clippings are the preferred biomarkers for measurements of arsenic ingestion in environments in which exposure lasts more than a few months and where a significant share of arsenic exposure occurs through food consumption. Our new estimates of the causal impacts of arsenic exploit the new biomedical evidence on genetic linkages among kin in the ability to methylate arsenic, thus reducing its toxic effects, and data identifying family linkages among respondents living in separate environments (villages).

A large number of studies have related arsenic exposure in the environment, measured by well contamination, and diet to biomarkers for arsenic in humans (urine, blood, hair, and toenails) and to specific health outcomes. However, these studies have a number of deficiencies. Neither proximity to arsenic sources (wells) nor the ingestion of arsenic can be considered exogenous to the outcomes studied. First, especially given campaigns to identify wells that are contaminated, households can choose to avoid arsenic contamination by choosing surface-water sources for cooking and drinking that are less convenient, perhaps then risking the incidence of water-borne disease (Fields et al., 2011). Second, arsenic ingestion and retention are related to the nutrient composition of foods, which also reflect preferences and income constraints. Estimates of the

relative importance of drinking water and food consumption as sources of arsenic, based on the distribution of arsenic among wells in Bangladesh and the non-linear relationship between arsenic ingestion and exposure levels, suggest that dietary sources of arsenic are the most important route of arsenic exposure for two-thirds of the Bangladesh population (Kile et al., 2007). Moreover, specific foods differ in the degree to which they retain arsenic used in their cultivation and cooking and differ as well in the extent to which, via their nutritional composition, they enable the metabolism (detoxification) and subsequent excretion of arsenic, primarily through a process of methylation.[1]

An individual's retained arsenic in a country such as Bangladesh, where millions of wells have been tested and identified by their levels of arsenic contamination and where diet is both a source of arsenic and an aid to its metabolism, is clearly not an exogenous variable. But studies that carry out randomized nutrient supplementation that can reduce arsenic's burden by increasing the rate at which it is metabolized (methylated) do not identify the mechanisms by which such arsenic-reducing interventions improve health. Such supplements improve health and thus productivity by more than just reducing the toxic concentration of arsenic and its metabolites in body tissue.

There is little evidence on the effects of arsenic contamination on performance measures, and none on economic outcomes such as earnings or productivity.[2] In recent years, however, the specific set of inheritable genes associated with the abilities of humans to metabolize and secrete ingested arsenic have been identified, with field studies showing that retained arsenic levels are correlated within families consistent with genetic models. Genetic variation in abilities to methylate arsenic is thus an important component of the large variance in arsenic found in humans. Importantly, recent studies have shown, and we present additional evidence, that the genes associated with arsenic retention in Bangladesh do not predict measures of cognition or anthropometric outcomes in populations not exposed to arsenic. Variation in these genes across families thus provides a basis for the identification of the causal effects of arsenic retention on such outcomes where arsenic is present in the diet. This linkage, however, has not been exploited in studies examining the consequences of arsenic. Knowledge of both how arsenic retention directly and causally affects health and productivity outcomes and how diet affects arsenic retention is obviously critical to any cost–benefit analyses of governmental programs aimed at improving health and productivity.

In Section 2 of the article, we set out a simple model that highlights the distinct endogenous and exogenous components of an individual's retained arsenic. We show that whether or not agents are informed about the productivity effects of retained arsenic, it is not possible to sign the bias in correlational relationships between retained arsenic and productivity outcomes due to optimizing with respect to water choice. Section 3 describes the data and our measure of arsenic retention from the sample of toenail clippings in our rural sample. The data indicate very high levels of arsenic concentrations, exceeding average levels measured in U.S. respondents by almost 20 to 1, with concentrations exhibiting wide individual variation but spread almost uniformly across landholding groups.

In Section 3, we discuss alternative estimators for identifying the productivity effects of arsenic retention. In particular, we describe how we can use information on the measured retained arsenic

1. For example, Zablotska et al. (2008) and Heck et al. (2007), based on randomized field experiments, highlight the protective effects of folate-related nutrients and B-vitamins in samples from rural Bangladesh. Leafy vegetables are known to contain high concentration of folic acid. However, Hossain (2006), based on extensive tests in Bangladesh, reports that among the food products tested, leafy vegetables have the highest concentration of arsenic.

2. Asadullaha and Chaudhury (2011) find that proximity to contaminated wells is associated with lower test scores among school-age children, but identification rests on the assumption that proximity to water sources is random, and does not take into account that households may select their water sources endogenously.

of family members residing in different villages and estimates of the effects of food consumption on arsenic retention and ingestion to identify the causal effects of arsenic retention on a variety of outcomes at the individual and household level. To implement the method, we first obtain estimates of the causal effects of the individual consumption of seven food groups on arsenic concentrations based on individual-specific food consumption information, water source choice and smoking on the toenail-based arsenic measures. These show that diet matters for arsenic contamination, with the consumption of grains, the staple of the Bangladesh diet, significantly increasing, but tubers, in accord with the medical literature, reducing measured arsenic concentrations. We also find that using non-tube well water sources for cooking reduces arsenic concentrations by 18%.

In the next sections, we examine the relationship between retained arsenic and measures of individual capabilities, schooling, health, and economic choices using as instruments measures of arsenic retention net of the influence of diet, water-source choices, and village fixed effects of separated family members. We find that OLS and within-household estimates significantly understate the negative effects of retained arsenic on cognition and physical strength. We also assess the validity of our identification strategy. We first show that the contemporaneous cognitive impairment from arsenic ingestion is the same for old and young. In contrast, however, we find that the negative effects on cognition are only manifested in lower schooling attainment and lower likelihoods of being in a skill occupation or running a non-farm business for those (young) cohorts of males who were of school age or who entered the labour force after the switch to arsenic-contaminated tube wells as water sources. Older cohorts' schooling attainment and occupation are unaffected. Using the same methods, we could find no effect of arsenic retention on BMI, height, or conventional morbidity symptoms for all age cohorts, consistent with the productivity effects of arsenic contamination being difficult to identify based on conventional symptoms.

In Section 7, we focus on the identification of the effects of arsenic on earnings and household productivity. The challenge for estimating earnings effects is that in Bangladesh less than half of the male labour forces are wage earners. Given that we have data on consumption expenditures for all households, we can avoid potential selectivity problems that plague estimates of earnings effects from improving health based solely on the earnings of wage workers. We discuss the conditions necessary for identifying the causal effects of retained arsenic by gender on earnings using household expenditure data and our instrumental-variables method and show that our data meet these conditions. Our IV estimates indicate that lowering the amount of retained arsenic among Bangladesh prime-age males to those levels in uncontaminated countries would increase earnings by 9%. We also find that retained arsenic in women affects whether the household obtains water from a non-tubewell source, consistent with arsenic reducing the productivity of women in home production. These latter results imply that improvements in water quality at the source would be less effective than measures that reduce the retention of ingested arsenic due to the endogenous response of households in their own efforts to reduce arsenic ingestion. In the conclusion, we summarize our results and quantify the productivity benefits from the provision of arsenic-free water to Bangladeshi households.

2. MODELLING THE EFFECTS OF ARSENIC CONTAMNINATION ON INDIVIDUALS

In this section, we describe a simple one-person model to fix ideas about how heterogeneity in water quality, preferences, health information, and abilities to methylate ingested arsenic combined with optimizing behaviour affect inferences about the relationship between an

individual's measured amount of retained arsenic[3] and measures of capabilities and economic outcomes. We also show that the dissemination of information on the true productivity effects of arsenic retention would lead to lower concentrations of retained arsenic and higher productivity

We assume, in accordance with the medical literature, that retained arsenic A_{ij} for individual i residing in household j depends on the consumption of specific foods, where $\boldsymbol{C_{ijx}}$ is a vector of consumed foods indexed by x; on the quality (arsenic content) of the water used for cooking and drinking ω_{ij}; and on the individual's endowed ability to methylate arsenic, given by μ_{ij}.

$$A_{ij} = A(\boldsymbol{C_{ijx}}, \omega_{ij}, \mu_{ij}) \tag{1}$$

We assume that $A_2 < 0$; $A_3 < 0$; and A_{22}, A_{33}, $A_{32} > 0$, so that higher ω_{ij} indicates less contamination by arsenic.[4] Consumed water quality depends on the quality of the water source e_j and the individual's purification effort t_{ij}:

$$\omega_{ij} = \omega(t_{ij}) + e_j, \tag{2}$$

where $\omega' > 0, \omega'' < 0$. t_{ij} may include time spent fetching water from alternative sources, time boiling or otherwise treating water from water sources that have biological contaminants but lower arsenic, such as surface water sources, and/or time spent collecting additional fuel needed for water boiling.[5]

The budget constraint is given by (3)

$$F_{ij} + (\Omega - t_{ij}) w_{ij} = \Sigma p_{jx} C_{ijx}, \tag{3}$$

where F_{ij} = non-earnings sources of income and the p_{jx} are local food prices. The individual's wage rate w_{ij} depends on the individual's capability or skill h_{ij}, which has a local per-unit rental price w_j, so that $w_{ij} = w_j h_{ij}$, and skill or productivity is affected (negatively) by retained arsenic and by a skill endowment r_{ij}:

$$h_{ij} = \mathrm{h}(A_{ij}, r_{ij}), \tag{4}$$

where $\mathrm{h}_A < 0$.

The productivity effect of arsenic retention is the first partial of (4), h_A. The observed relationship between A_{ij} and h_{ij} (given water quality e_j and local prices p_{jx}) in environment j is, however,

$$\begin{aligned} \mathrm{d}h_{ij}/\mathrm{d}A_{ij} = \mathrm{h}_A + \mathrm{h}_A [\mathrm{A}_2 \omega' (\mathrm{d}t_{ij}/\mathrm{d}\mu_{ij})(\mathrm{d}\mu_{ij}/\mathrm{d}A_{ij}) \\ + (\Sigma \mathrm{A}_{1x} \mathrm{d}C_{ijx}/\mathrm{d}F_{ij})(\mathrm{d}F_{ij}/\mathrm{d}h_{ij})], \end{aligned} \tag{5}$$

if agents are knowledgeable about their own susceptibility to arsenic retention μ_{ij}. The bracketed term in expression (5) reflects the association between observed individual arsenic and the

3. Retained arsenic in this context is the concentration of arsenic in body tissue. The measure used in the empirical work is the arsenic concentration of toenails, the preferred biomarker of arsenic retained in human tissue.

4. The amount of retained arsenic depends on the quantity of water consumed. For simplicity, we assume that this is constant across individuals of given age and gender. Note that A_{1x} cannot be signed *a priori* for any food as foods are both a source of arsenic and, through the nutrients they contain, a potential aid to its metabolism.

5. In our survey data, 26.4% of households obtain their water for cooking from sources other than tube wells. Of these households, over three-fourths treat the water, the majority by boiling and the rest by an additive such as Aalum. As discussed below households using non-tubewell-sourced cooking water spend significantly more time fetching water and fuel.

endogenous components of arsenic retention. If variation in arsenic retention affects either the composition of goods consumed or water purification effort, the association between retained arsenic and measures of capabilities will not identify the causal effect of arsenic retention on productivity h_A. Similarly, the association between measures of the quality of water consumed and A_{ij} also reflects both behaviour and the technological relationship between water quality and retained arsenic A_2 from (1):

$$dA_{ij}/d\omega_{ij} = A_2 + h_A w_j \omega' dt_{ij}/dw_{ij}. \tag{6}$$

The bias terms in the associations (5) and (6)—the terms associated with the behavioural response to the exogenous components of arsenic *(As)* ingestion and retention—depend on how retained arsenic affects behaviour. But is it plausible that arsenic affects behaviour if agents are not fully informed about the amounts of arsenic they ingest or retain and whether and how arsenic affects their productivity? We now show that even if agents only know (i) that arsenic is a deleterious to health, (ii) which non-local water sources reduce arsenic ingestion, and (iii) how water purification effort affects arsenic retention the association between retained arsenic and productivity reflects choice behaviour. In this extreme case, agents are *un*informed about (i) the effects of *As* on productivity h, (ii) their own individual arsenic retention A_{ij}, and (iii) their own methylation efficiency endowment μ_{ij}. They only observe their own productivity.

For simplicity, we ignore for now the effect of the consumption of specific foods on arsenic ingestion and consider the consumption of only one aggregate consumption good C_{ij} with a unit market price. Changes in effort to reduce *As* in their consumption of water are thus the only source of endogeneity in this case. The utility function is

$$U = U(A^*_{ij}, C_{ij}; u_{ij}) U_1 < 0, U_2 > 0, U_{11} > 0, U_{22} < 0, \tag{7}$$

where A^*_{ij} = the agent's beliefs about his retained arsenic and we have added an individual-specific preference parameter u_{ij}.

What is the optimal time spent fetching water, given the beliefs of agents? The FOC is:

$$U_A A^*_2 \omega' = U_C w_{ij}. \tag{8}$$

Agents face a trade-off between consumption (good) and arsenic (bad) because effort reduces the time available for income earning. Note that if agents were fully informed about the economic consequences of arsenic retention the FOC is:

$$U_A A^*_2 \omega' = U_C(w_{ij} - A^*_2 \omega' h_1 w_j(\Omega - t_{ij})). \tag{9}$$

Comparing (8) to (9) indicates that lack of knowledge about the relationship between arsenic retention and productivity in the population leads to higher levels of contaminated water consumption (less water purification effort) than is optimal, if lowering arsenic retention actually increases productivity, as $U_C w_{ij} > U_C(w_{ij} - A^*_2 \omega' h_1 w_j(\Omega - t_{ij}))$. There is thus a productivity and health payoff to the dissemination of information about the economic consequences of arsenic retention.

We now show that even when the households are uninformed about arsenic productivity effects, using the model with information constraints, the remaining bias in (5), which depends solely on how retained arsenic affects water purification effort, cannot be signed:

Proposition 1 *The effect of retained arsenic on the demand for improved water via increased purification effort is ambiguous. The bias in the association between individual arsenic retention and productivity thus cannot be signed.*

Proof. Assume for simplicity that A and C are separable in U, then

$$\mathrm{d}t_{ij}/\mathrm{d}\mu_{ij} = h_1 \mathrm{A}_3[\mathrm{U}_C w_j/\Phi + \mathrm{d}t_{ij}/\mathrm{d}F_j w_{ij}(\Omega - t_{ij})], \tag{10}$$

where $\Phi = -[(\mathrm{A}_2\omega')^2\mathrm{U}_{AA} + \mathrm{U}_A\mathrm{A}_{22}(\omega')^2 + \mathrm{A}_2\omega''] < 0$ and $\mathrm{d}t_{ij}/\mathrm{d}F_j = \mathrm{U}_{CC}/\Phi > 0$

The first term in (10) is negative—lower arsenic retention increases market productivity and the opportunity cost of effort. The second term is the income effect, which is positive on purification effort—the increase in income (or C) lowers the marginal utility of consumption relative to that of arsenic. Thus, whether or not the population of Bangladesh is aware of arsenic effects on their own productivity the measured association between arsenic retention and productivity is not causal.

Improvements of the local water source (change in e_j) also affect behaviour, except that in principle, agents can be told the level of e_j so that there is an additional negative public-health information effect on efforts to reduce arsenic ingestion, which is embodied in the first term in brackets in (11):

$$\mathrm{d}t_{ij}/\mathrm{d}e_j = \omega'[(\mathrm{A}_2)^2\mathrm{U}_{AA} + \mathrm{U}_A\mathrm{A}_{22}]/\Phi + \mathrm{A}_2 h_1[\mathrm{U}_C w_j/\Phi + (\Omega - t_{ij})w_j \mathrm{d}t_{ij}/\mathrm{d}F_j]. \tag{11}$$

Given (11), the effect of an intervention that reduced arsenic in the local water source (by, say, drilling and testing a new tubewell) on income ($\mathrm{d}F_j/\mathrm{d}e_j = \mathrm{d}C_j/\mathrm{d}e_j$) may thus under or over-estimate the pure productivity effect, and the total welfare gain, of such an intervention, which is $(\Omega - t_{ij})\mathrm{h}_A\mathrm{A}_2 w_j$. The income effect inclusive of the behavioural response (11) is given by (12)

$$\mathrm{d}C_j/\mathrm{d}e_j = (\Omega - t_{ij})w_j \mathrm{h}_A\mathrm{A}_2(1 + \omega'(\mathrm{d}t_{ij}/\mathrm{d}e_j)) - (\mathrm{d}t_{ij}/\mathrm{d}e_j)w_{ij}, \tag{12}$$

which differs from the productivity effect by $-(\mathrm{d}t_{ij}/\mathrm{d}e_j)[(\Omega - t_{ij})w_j \mathrm{h}_1\mathrm{A}_2\omega\mathrm{N} + w_{ij}]$. If the increase in local water quality reduces water purification efforts, as is likely from (11), then consumption or income rises because more time is spent earning (the third term in (12)). On the other hand, the productivity-enhancing effect is attenuated, as embodied in the last term in (12).[6]

3. ESTIMATION OF INDIVIDUAL PRODUCTIVITY EFFECTS

3.1. *Least squares, and household and family fixed effects estimators*

Our first empirical objectives are to identify how concentrations of arsenic that result from the ingestion of arsenic-contaminated water causally affect health, human capital, and productivity at the individual level. Because we will be using family relationships as part of our identification strategy it is useful to add an index l to our notation to denote the family lineage of an individual. Linearizing the productivity function (4) and now decomposing the preference and genetic endowments into household, family, and individual components, we seek to identify the parameter δ in:

$$h_{ijl} = \delta A_{ijl} + \mathbf{Z}_{ijl}\beta_z + \beta_r(r_{ijl} + r_{jl} + r_j) + \beta_\mu(\mu_{ijl} + \mu_{jl} + \mu_j) + \beta_e e_j + \varepsilon_{ijl}, \tag{13}$$

where the l index identifies the individual's relationship with a family member, $\mathbf{Z}_{ijl}$, is a vector of observed exogenous attributes of the individual and household, and ε_{ijl} an iid error. As shown

6. Even if effort increases, the sign of the bias is ambiguous, as there are still two terms with opposite signs.

in equation (5) from the model, the parameter δ reflects not only the causal effect of *As* retention but also behaviour. Specifically, unobserved differences in productivity due to variation in r_{ijl} will be correlated with A_{ijl} because they will affect diet and water purification effort, as shown. And differences in a household's available water quality e_j will also be correlated with A_{ijl} via diet and time-allocation effects and may have direct effects on productivity. Finally, the genetic endowments that affect arsenic retention may also be linked directly to productivity. Thus, least squares estimation of (13) would not provide a consistent estimate of δ.

Estimating (13) after differencing across household members (household fixed effects), would eliminate the influence of all household-level determinants of productivity and arsenic retention, in particular eliminating the effects of local water quality e_j (proximity to clean water sources). However, this would not eliminate differences in the individual productivity endowments that might affect diet and time allocation or individual genetic variation linked to both arsenic retention and productivity. And the biases from measurement error in A_{ijl} would be amplified.

A variant of the household fixed effects estimator is the household/family fixed effects estimator, which differences across individuals linked genetically (in the same genetic lineage) within a household. Differencing across family members i and k within a lineage l in household j yields:

$$h_{ijl}-h_{kjl}=\delta(A_{ijl}-A_{kjl})+\Delta\boldsymbol{Z}_{ij}\boldsymbol{\beta}_z+\beta_r(r_{ijl}-r_{kjl})+\beta_\mu(\mu_{ijl}-\mu_{kjl})+\Delta\varepsilon_{ijl}, \tag{14}$$

where Δ is the difference operator. Variation in the endowments r_{ij} and μ_{ij} are reduced relative to the household fixed effects approach, but not eliminated, and consequently variation in A_{ij} would be more related to individual variation in endogenous diet and less to exogenous genetic variation, and measurement-error attenuation bias would remain an issue.

3.2. *Instrumental-variables approaches from RCT's*

Randomized interventions at the village level, such as the construction of a deep well to improve e_j, cannot be used as an instrument for individual arsenic stock because the new well will directly alter the allocation of time of all family members, for example, and thus affect labour market and other outcomes directly for any individual. Even randomized individual-specific interventions that reduce arsenic ingestion or increase arsenic retention cannot be used as instruments to identify δ. For example, the randomized distribution of nutrition supplements across individuals, which have been shown to increase arsenic metabolism and excretion (as in Gamble *et al.*, 2007), would have direct effects on health and productivity in addition to any effects via the stock of arsenic. Such an intervention thus would not identify the arsenic-health or productivity mechanisms. What is required is exogenous variation in a variable that directly affects arsenic retained in the body, given a person's exposure to arsenic in the environment, and has no other direct effects on the outcomes of interest.

3.3. *Using molecular genetics*

Our strategy for the identification of δ exploits exogenous individual variation in genes that influence an individual's ability to metabolize arsenic, as embodied in μ_{ijl} in the model and the consequent genetic linkages among family members in that ability. Recent evidence indicates that genetic variations (polymorphisms), apart from the nutritional determinants of arsenic concentrations in humans, are a major cause of the substantial inter-individual variation in arsenic metabolism (methylation) within the same exposure area (Vahter, 2000). Methylation of arsenic facilitates its excretion from the body. Arsenic is transformed in the body, and the end-products of

the methylation process are metabolites—monomethylarsonic acid (MMA) and dimethylarsinic acid (DMA)—that are readily excreted in urine. The enzymes that are required for this chemical process have also been identified and linked to four specific genes.[7]

The genetic origins of arsenic metabolism suggest that the ability to methylate is correlated among family members, and there is evidence of this in human populations. For example, in Chung et al. (2002) families from Chile were selected based on their long-term exposure to very high levels of arsenic in drinking water (735–762 μg/l). The intra-class correlation coefficients showed that 13–52% of the variations in the methylation patterns were from being a member of a specific family. Obviously, these correlations could arise due to similarity in diets and to common environmental factors. However, methylation patterns are correlated more strongly between siblings than between father-mother pairs within a household, after adjustment for total urinary arsenic, age, and sex.

If we had individual information on the existence of the alleles associated with arsenic methylation we could use the existence of the relevant genes as an instrument for arsenic retention in (13). The key identifying assumption would then only be that $\beta_\mu = 0$, that the genes associated with arsenic methylation do not have any direct effects on measures of productivity (*e.g.* that those individuals genetically more immune to arsenic retention are no smarter or stronger in settings where arsenic is not consumed). We will present evidence for this orthogonality assumption below. In the absence of this genetic information, we use as an instrument for an individual's retained arsenic an estimate of the individual's genetic ability to metabolize (methylate) arsenic. This is based on a non-co-resident family member's ability to do so net of common factors in the environment and dietary choice. Thus, we exploit the intra-family correlations in methylation ability and our ability to link family members living apart due to the long-term panel nature of our data.

Using the notation of the model, the covariance between measured arsenic retention of two family members i and k residing in two different households j and y is

$$\begin{aligned}\operatorname{cov}(A_{ijl}, A_{jyl}) = {} & \operatorname{var}(\mu_l)\mathrm{A}_3 + \operatorname{cov}(e_j, e_y)\mathrm{A}_2 + \operatorname{cov}(w_j, w_y)\mathrm{A}_2\omega' \mathrm{d}t/\mathrm{d}w \\ & + \operatorname{cov}(u_{ijl}, \mu_{kyn})\mathrm{A}_1 \mathrm{d}C/\mathrm{d}u + \operatorname{cov}(P_j, P_y)\mathrm{d}C/\mathrm{d}P, \end{aligned} \tag{15}$$

where μ_l is the common genetic component of μ_{ijl}. As seen in (15), as long as local prices and the quality of water sources are spatially correlated, and if preferences among family members

7. Arsenite methyltransferase catalyzes the oxidative methylation of arsenic to forms of MMA. This enzyme is encoded on a gene called AS3MT on human chromosome 10. Engström et al. (2007) found that a significant part of the variation in urinary metabolites of arsenic in an Andean population is due to polymorphism in the AS3MT gene, as did Rodrigues et al. (2012) for a Bangladeshi population. Agusa et al. (2011) review 18 human case studies on this gene and find that two polymorphisms of the AS3MT gene were consistently related to arsenic methylation efficiency regardless of the populations examined for the analysis. Variants of the glutathione–S–transferase (GST) enzyme have also been identified as catalyzing the methylation of arsenic. The glutathione S–transferase omega–1 variant of this enzyme is encoded by the GSTO1 gene and the glutathione S–transferase theta–1 variant is encoded by the GSTT1 gene. Kile *et al.* (1995) and Mccarty et al. (2007) based on Bangladesh populations and Chanda et al. (2011) based on the population of West Bengal, India find that individuals possessing GSTT1–null genotypes (lacking the genes normal function) had significantly more arsenic in their toenails in contrast to GSTT1 wild–type (typical allele for a gene) individuals, after controlling for drinking water contamination.

Arsenic metabolism involves methylation to MMA and DMA by a folate–dependent process. Methylenetetrahydrofolate reductase (MTHFR) is a key enzyme in the metabolism of folate that has been strongly linked to both arsenic metabolism and toxicity in laboratory and animal studies. Steinmaus et al. (2007) and Ahsan et al. (2007) find that variations in the MTHFR genes modulate health effects of arsenic exposure in Argentina and Bangladesh, respectively. Ahsan et al. (2007) estimate that the proportion of skin lesions in their study population that is attributable to polymorphisms in the MTHFR gene is 7.5 percent, and the proportion due to polymorphisms in the GSTO1 gene is 8.9 percent.

for foods are also correlated even if living apart, using the actual arsenic levels among spatially separated kin as an instrument for an individual's retained arsenic would not be appropriate for identifying δ. We need to isolate that component of A_{ijl} that is unexplained by exposure to either environmental arsenic or by endogenously determined individual-specific nutritional intakes but that contains the genetic component of methylation ability u_l.

To remove from the measured arsenic those components that are endogenously determined through food and water choice and that reflect common environmental sources of arsenic from the measured arsenic, we first estimate the individual-specific production function for arsenic concentrations (1) using the measures of A_{ijl} taken from the toenail clippings. Assuming a Cobb–Douglas form for that function, and taking logs, we estimate the equation

$$\text{Log}A_{ijl} = \boldsymbol{N}_{ijl}\boldsymbol{\alpha} + \mu_{jl} + \mu_{ijl} + e_j + u_j + v_{ijl}, \tag{16}$$

where $\boldsymbol{N}_{ijl}$ is a vector of person-specific and endogenous family inputs, including the log of individual foods consumed and the log of smoking, and $\boldsymbol{\alpha}$ is a vector of coefficients. Evidence suggests that women methylate arsenic at higher rates than men, so we also include a gender dummy variable in (16).[8] Given the logarithmic form, we thus allow for the possibility that for given food intakes and thus the digestion of arsenic, retained arsenic concentrations will be proportionally higher among men. We will also estimate (16) by gender to assess if the effects of diet on arsenic concentrations vary across males and females and not just their choice of foods. A second shifter variable in (16) is an indicator of whether or not the water used for cooking came from non-well sources. Cooking without well water should contain less arsenic and so should mediate the influence of all foods cooked in water on digested arsenic levels.

Equation (16) contains five sources of unobserved heterogeneity highlighted in the model: The first is the genetic component of arsenic methylation ability that is shared among a lineage or kin group μ_l, the second the individual-specific component of that ability. There is also a component that represents the unobserved exposure to environmental arsenic from local drinking and cooking water, e_j, a household error component u_j, and an iid error term v_{ijl}.

To obtain consistent estimates of the $\boldsymbol{\alpha}$, the effects of variation in diet and other behaviours on retained arsenic, we need to take into account that food intakes are affected by variation in both water quality e_j and in individual methylation ability. To control for environmental water quality in the local choice set of households, we include in (16) a complete set of village dummy variables. To deal with the correlation between the $\boldsymbol{N}_{ijl}$ and u_j and μ_{ijl}, we estimate (16) by instrumental variables. As in Pitt et al. (1990, 2012), we assume that village-level variables such as food prices, wages, weather, and access to water sources as well as the exogenous individual characteristics of the household members and the households and their interactions affect food consumption P_{jx}. Here, however, because we are controlling for a village fixed-effect, we obtain identification of the parameters of the arsenic production function solely from individual and household characteristics that affect food consumption choices but do not affect retained arsenic levels directly and their interactions with the village-level variables. The excluded instruments for the individual food and water choices are the schooling of the respondent, the value of the landholdings of the household, the household head's schooling and age and the set of village dummy variables—which capture all of the village-level factors affecting individual choices—interacted with the household head's age and schooling. Identification of the nutrient effects on individual-specific arsenic concentrations

8. Women methylate more efficiently than do men as a consequence, in part, of the protective effect of estrogen (Lindberg *et al.,* 2007).

thus exploits the large number of villages in our sample, the existence of extended families in Bangladesh, and the information in our data containing individual food intakes.[9]

The estimates of the $\boldsymbol{\alpha}$ are of direct interest. First, we can quantify to what extent the individual consumption of fruits and green leafy vegetables, for example, which the literature suggests are a source of arsenic ingestion and also mediate the effects of arsenic ingestion via arsenic metabolism and excretion, affect arsenic concentrations in the body, given exposure to arsenic via water sources (impounded in the household fixed effect). For these estimates to be credible based on the short-period information on food intakes, it is important that the measure of individual arsenic concentrations, based on the toenail assays, reflects relatively recent, and not lifetime, accumulation, so that it is not necessary to have the complete life history of food intakes. The toenail-based measure mainly reflects arsenic ingestion and excretion in recent months, not years (Kile et al., 2005).[10]

We use the residuals from (16) for genetically linked but non-co-resident family members as instruments for A_{ijl} in (13) to identify δ. These contain the genetic component of arsenic μ_{ijl}, plus any measurement error, and the household fixed effect u_j. By using residuals from non-coresident family members who have resided in a different village at for least one year, we minimize the influence of the household component. Our panel data contain many households residing in separate villages whose family links are identified. This is because of the panel design of the survey, which followed all household members who left the households in a prior round, and because for almost every household in our original 1982 sample a relative had left the household between 1982 and the second round of the survey in 2002. Household division is common in Bangladesh because of the cultural practice of patrilocal exogamy, whereby most women marry outside the village where they were born. This is reflected in our data—between the 1982 and 2002 rounds, for example, 88% of girls age 5–15 in 1982 had left their original household and village and 10% of the boys left the village. Because as part of the survey design we include both the originally sampled households and any household containing any individual from the original households no matter where the location in Bangladesh, we have as much information on family members who remained together as we do for those who are no longer co-resident.

After estimation of (16), we compute $\mathrm{E}(\mu_l|A_{ijl} - \boldsymbol{N}_{ijl}\boldsymbol{\alpha}$ for all members of lineage l) for all sampled respondents who have a non-co-resident family member residing in another village. The short-run nature of the arsenic concentration measure is again important—the fact that the separated family members once shared a common arsenic source should not be reflected in the toenail-based measure of arsenic as long as the family members divided at least a year prior to the survey. However, if there is measurement error in $\boldsymbol{N}_{ijl}$, then in lineages with small numbers of observations, this expectation will also be measured with error that may not be of the classical variety in subsequent estimation. If this measurement error is uncorrelated across member in a lineage, then it will be useful to estimate the expectation $\mathrm{E}(\mu_{ln}|TN_{ijl} - \boldsymbol{N}_{ijl}\boldsymbol{\alpha}$ for all members of lineage l except person ijl). The covariation between a non-coresident family member's μ_{ln} and respondent arsenic retention A_{ijl} is thus $\mathrm{A}_3\mathrm{var}(u_{ln})$.

There are two main challenges to this procedure. First, the estimates may be sensitive to mis-specification of the production function. One source of mis-specification is functional form

9. In principle, we could have interacted all of the individual and household characteristics with the set of village dummy variables, but the issue of having too large a number of instruments biasing the IV coefficients becomes more likely given we have 607 villages.

10. Kile et al. (2005) collected toenail and drinking water samples from forty-eight families ($n = 223$) every three months over a two-year period. The team created a weighted, lagged exposure variable including drinking water arsenic concentrations measured three, six, and nine months before toenail collection. Their findings suggest that the drinking water concentrations at three, six, and nine months contributed 69%, 14%, and 17%, respectively, to the arsenic detected in the toenail sample.

choice. We will carry out functional form tests and assess the robustness of our results to an alternative functional form for (16), a linear quadratic specification. The second issue concerns the conventional power and exclusion restrictions for an instrument. Specifically, the reduced-form covariation between a non-coresident family member's μ_{ln} and respondent productivity h_{ijl} is $(\mathrm{d}h_{ijl}/\mathrm{d}\mu_{ijl})\mathrm{var}(u_{ln})+ (\mathrm{d}h_{ijl}/\mathrm{d}r_{ijl})\mathrm{cov}(r_{ij}, \mu_{ln})$, from which it can be seen that both the variance of the common genetic component of arsenic methylation $\mathrm{var}(u_{ln})$ must be non-trivial and $\mathrm{cov}(r_{ijl}, \mu_{ln})$ must be negligible for μ_{ln} to be a valid instrument for A_{ijl}. That is, as noted, identification of δ requires not only that the household components of the error terms across households not located in the same village are uncorrelated but that the genetic polymorphisms that regulate the efficiency of arsenic metabolism are unrelated to those that affect the outcomes of interest h_{ijl}.[11]

In Appendix A, we show using human genome data that alleles associated with arsenic methylation in Bangladesh are not correlated with the appearance of alleles identified with cognition and physical strength. This evidence, however, cannot rule out the possibility that the relevant arsenic genes are correlated with yet-undiscovered genes predicting productivity outcomes. A unique advantage of using a genetic-based identification strategy for assessing the effects of arsenic is that genes regulating the methylation of arsenic that are impounded in our residual measure of arsenic retention should have no effect on outcomes in environments in which arsenic is absent if our key assumption is correct.

Recent prior studies of the direct relationship between polymorphisms of the MTHFR gene (rs1801133) and direct measures of cognitive performance in populations where arsenic contamination is absent show that it is not a correlate of either cognitive performance among prime age adults or with cognitive deterioration among the elderly (Schiepers *et al.*, 2011a,b) in Germany and Scotland, respectively.[12] Dalton Conley also carried out at our request a test of whether another gene identified as affecting arsenic methylation in Bangladesh (ss66088057) affected schooling attainment and height in the second- and third-generation respondents in the US Framingham sample. The within-sibling estimates he obtained are reported in Appendix Table A1, where it can be seen that the presence of the arsenic gene allele is not significantly related to either outcome variable in the U.S. population.

The absence of a relationship between genes affecting arsenic retention and human capital outcomes in uncontaminated populations is a necessary but not a sufficient condition for our identification strategy to be valid, since we are using a residual-based estimate of the genetic

11. One additional issue with this method is that the arsenic environment itself may epigenetically alter the expression of genotypes associated with arsenic metabolism. Epigenetics refers to external alterations to DNA that turn genes on or off (gene expression) but do not change the DNA sequence. In addition, there is evidence that epigenetic change, without a mutation to the DNA code itself, may cause long-term, heritable change in gene function. If the expression of genes that regulate arsenic metabolism are altered by exposure to arsenic, and if that gene expression is heritable, then parental exposure to arsenic may affect their offspring's efficiency at metabolizing arsenic in addition to the 'direct' effect of their heritable genotype. Although this type of epigenetic change has not been found for arsenic metabolism, it has implications for our study if it exists. First, using genotype as an instrument is still valid as long as there is any variation in arsenic metabolism attributable to genetic variation, although it will be less strong. Second, as epigenetic change may be long lasting, the beneficial effects of reducing arsenic intake may be muted by heritable epigenetic change—genetically "good" arsenic metabolizers and their offspring will not be so if their gene expression is epigenetically modified for the worse by a period of exposure to arsenic. Exposure to arsenic may consequently affect future generations even if they are no longer exposed. It is not possible to test for epigenetic change with our data. In principle, a sample with two state switches is required: a measure of an outcome (such as cognitive ability) prior to any arsenic exposure, a measure during exposure, and then a subsequent measure some time (or generation) after exposure has ceased.

12. This methylation gene is the most susceptible to the issue that its polylorphisms might directly affect cognitive functioning because it is associated with folate metabolism so it is important that it not be correlated with cognition in the absence of arsenic contamination.

component of arsenic methylation. There may be non-genetic family-based components of the residual, resulting from any mis-specification of (16) that could directly affect our outcome measures. We will exploit our long-term panel data to carry out a comprehensive test of whether our residual-based instrument has any power in predicting human capital investment in Bangladesh before arsenic became prevalent in the water consumed by Bangladesh households, as it should not if the residual-based instrument preponderantly reflects family-correlated genetic arsenic methylation capability.

4. DATA AND MEASUREMENT OF ARSENIC CONCENTRATIONS

4.1. *Survey design and sample size*

The main data set we use consists of information on 12,244 individuals residing in 2,480 households from the 2007–8 round of Bangladesh Nutrition Survey. The first survey was carried out in 1981–2 in fifteen rural villages from a sample meant to be representative of the rural population in Bangladesh (Ahmad and Hassan, 1982). These villages consisted of three in each administrative division that were selected from randomly chosen census circles of a Bangladesh fertility survey by a two-stage systematic sampling method. In addition, in order to study seasonal effects in nutrition in rural populations, two villages, one in Dhaka (Falshatia) district and the other in Mymensingh (Jorbaria) district, were selected based on their accessibility during monsoon season and their representativeness. The last village was drawn from a tribal region near the border with Myanmar. Security concerns led to dropping the tribal village from subsequent survey rounds. Fifty households per village were randomly selected, and individual-specific dietary intake and anthropometric data were collected from a randomly selected half of those households in each village.

The second round of the survey was conducted in 2000–3. There are two sub-samples. The first is based on the first-round individuals. All of the households in which any surviving member of the original 1981–2 households in the 14 villages resided were included regardless of location in Bangladesh, and information was collected on all individuals in those households regardless of whether they were in the original survey. Attrition of surviving individuals who still resided in Bangladesh at the time of the survey was less than 3%. Of the individuals aged 5 through 15 in 1982, 10% of the men and 88% of the women had left the original villages over the approximately 20-year period between rounds. The second component of the sample consists of 40 new, randomly–sampled households in each of the 14 1981–2 villages (560 households).

The sampling frame for the third-round survey in 2007–8 includes all of the surviving men and women from the 2000–3 survey (from both sub-samples), regardless of their location in Bangladesh. Thus, it includes all of the original men and women from the 1981–2 households, plus all of the additional households that entered the survey for the first time in 2000. In the 2007–8 round of the survey, the number of villages represented in the sample had grown because of migration from 14 in 1981–82 to 612. The attrition rate for this follow–up was higher, at 8%, due in part to increased migration outside of Bangladesh but still low by international standards. Because of the panel survey design, which tracked all individuals who were ever sampled regardless of location, kinship relationships among individuals residing in different households and villages are identified. The information on family links among spatially separated respondents, as noted, is key to the identification of the causal effects of arsenic ingestion and retention, given the genetic component of arsenic methylation.

The survey data provide more detailed information at the individual level than do most large-scale surveys. The data include individual-specific information on food intakes, observed by investigators over a 24-hour period. This information is required to carry out our estimation

strategy in which we eliminate diet as a source of retained arsenic variation. There are also a wide variety of individual-level productivity and health measures, including information on anthropometrics, morbidity, occupations, household activities, and labour force participation. In the last round of the survey we also collected measures of physical capabilities, measured by pinch strength, and cognition, measured by an abridged (13-question) version of the Raven's Colored Progressive Matrices exam, for every respondent meeting minimum age requirements.

4.2. *Measurement of respondent arsenic concentrations*

A key component of this study is the measurement of the arsenic concentrations of the respondents. We collected from each respondent aged eight years and above clippings from all ten toenails, providing a basis for a contemporaneous measure of arsenic ingestion for 7,356 individuals.[13] To extract information on arsenic concentration from toenails, trace metal analysis using inductively coupled plasma mass spectrometry (ICP–MS) must be used after preparation, including cleaning with solvents and digestion in acid.[14] Toenail clippings are the preferred biomarkers for measurements of arsenic ingestion in every case in which exposure lasts more than a few months, and is particularly preferred when a significant share of arsenic exposure occurs through food consumption (Kile et al., 2007). Kile et al. (2005) also demonstrate that arsenic concentrations in toenails vary with genetic polymorphisms known to affect methylation efficiency, using a sample of households from Bangladesh.

Because of the considerable expense of the laboratory analyses and preparation, we assayed only a subset of the toenails. To maximize the power of our identification strategy and to retain a gender balance in lineages, we confined the analyses to pairs of households containing related kin residing in different villages that have at least two same-sex respondents within each pair. Although it is useful for estimation precision to have this information for all respondents for which we have these biomarkers, identification, as noted, requires data on arsenic concentrations for closely related relatives living apart. Because of budget limitations, the number of over-eight respondents for whom we have arsenic concentration (*As*) measures is 4,265. Due to the sampling strategy, the subsample of respondents used for the laboratory analysis to obtain the retained *As* information slightly over-represents married women, due to their relatively greater mobility, and is somewhat older than the sample of respondents with unanalysed toenails. Neither average schooling levels nor landholdings, however, differ between the two subsamples. In all of our empirical analyses using this information, we will separately analyse males and females, when necessary, and control for age (and landholdings). Table A2 in the Appendix describes the subsample sizes and gender composition by round and subsample.

As part of the assessment of the laboratory methods, a sample of 25 respondents (graduate students residing in Rhode Island) also provided toenail clippings. These samples provide not only a basis for assessing the capabilities of the laboratory methods used to measure low levels of *As* concentrations but also a benchmark with which to compare the levels measured from the Bangladesh sample. The analyses indicate that the concentrations of arsenic in the Bangladesh respondents are quite high, vary considerably, but are spread across all economic groups. In the

13. In the 2007–8 round there were 9,998 individuals aged eight years and above. Approximately, 25% of the eligible sample either would not permit the cutting of their toenails or had insufficient toenail for cutting and analysis. Table A3 in the Appendix provides details on sample size by gender, by round and by the criteria used for the toenail analysis in the latest round sample.

14. Appendix B provides a detailed description of the methods that were used at the Environmental Chemistry Facility at Brown University in preparing the toenail samples and at the ICP–MS Laboratory at the Graduate School of Oceanography at the University of Rhode Island where the trace metal analysis was performed.

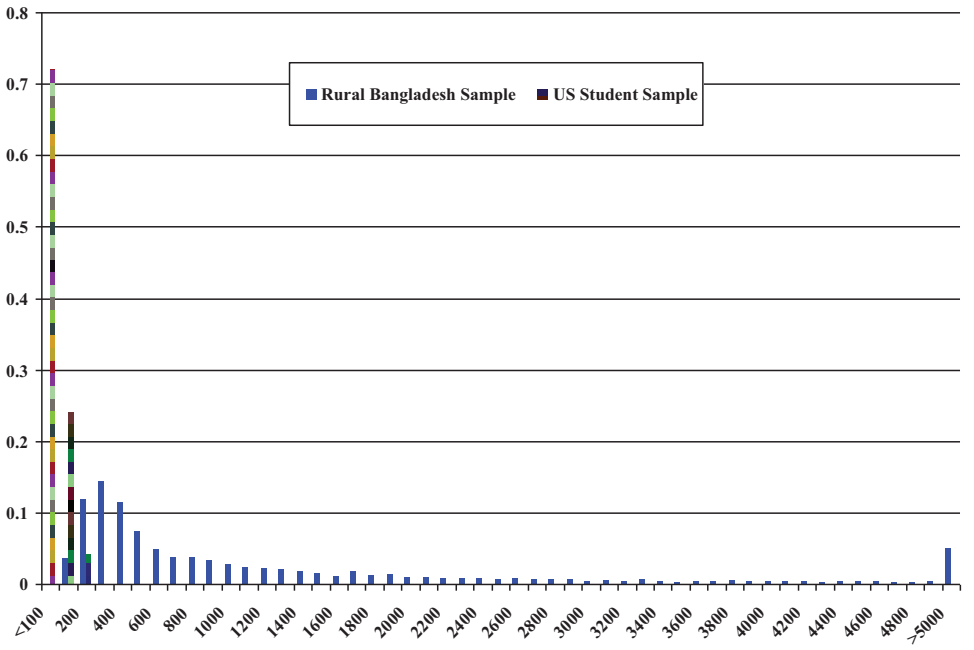

FIGURE 1
Distribution of As concentrations (ppb), by sample

U.S. graduate student sample, average *As* concentrations are 78.3 parts per billion (ppb), with a standard deviation of 46.6. In the sample of Bangladesh respondents the average concentration is 1,353 ppb, with a standard deviation of 1,894. Figure 1 provides the frequency distribution of the arsenic concentrations measured in the two samples, which show the substantial contamination of the Bangladesh respondents—90% of the Bangladesh sample have *As* concentrations greater than the highest value found in the U.S. sample, and over a third have concentrations exceeding 1,000 ppb. Figure 2 shows that arsenic contamination is not confined to the rural poor in Bangladesh—levels of *As* concentrations are actually slightly more elevated among households with larger owned landholdings.

4.3. *Analysis sample*

For the analysis of the effects of individual *As* concentrations on nutritional status, capabilities, and earnings, we use a sample of adult respondents aged 18–59 for whom we have toenail clippings and have immediate family members, also with *As* samples, who reside outside of their village. For this subsample, we have the *As* concentration measure for 52.3% of female and 44.5% of male respondents, the slight imbalance due to the oversampling of toenail samples for split family members and the higher spatial mobility of women. Respondents in the subsample reside in 465 villages. Based on the kinship relationships, we constructed 583 lineage groups—respondents living in different villages who are either a sibling or a parent–child pair.

Because we require a lineage instrument for every respondent to estimate the effects of *As* using our identification strategy, the analysis sample is smaller than the sample of respondents with valid arsenic assays in the same age range 18–59. This is not only because we include respondents who have family members living apart but also because we require that there be

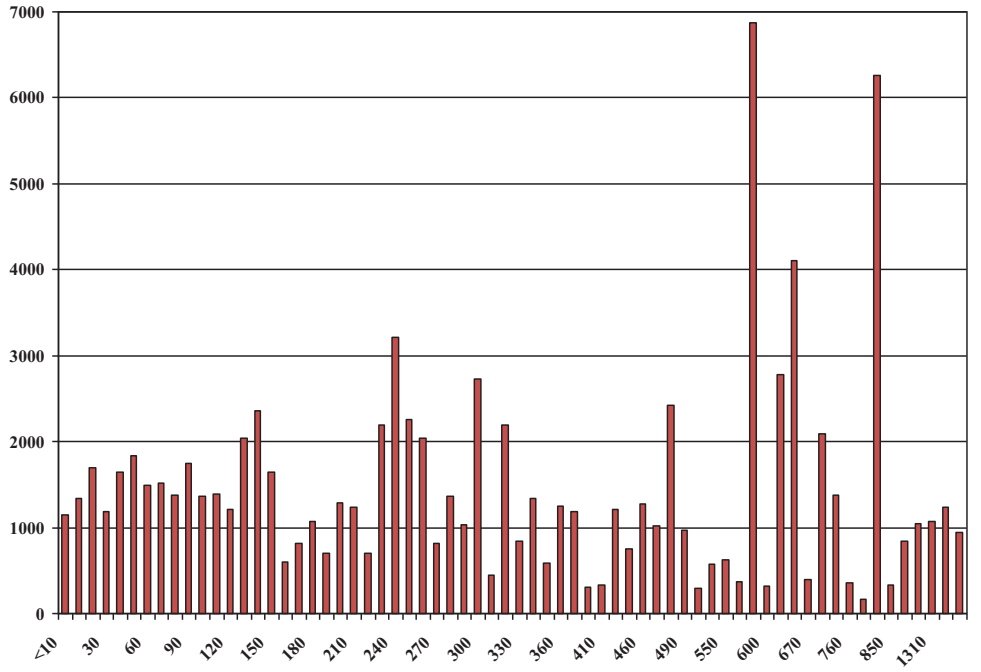

FIGURE 2
Mean As concentrations (ppb) by owned landholdings (square decimeters)

more than one household per village with the same lineage and there be two lineages represented in the same village. As a consequence, the sample size for analysis is 1,520 reduced from 2,369 (age-eligible and with an *As* assay). The total number of lineage groups for this analysis subsample is 307, with on average 11 persons in each lineage group. As shown in Appendix Table A3, the analysis subsample does not appear to be selective relative to the sample of all respondents for whom we have *As* concentration measures. Of the five outcome variables we look at, only age is statistically significantly different for both men and women, the men being older by 1.6 years on average and the women younger by one year in the analysis samples, and schooling is different for men across the subsample for whom we have instruments and the subsample for whom we do not (by 0.8 years).

A concern is that because of the asymmetry in mobility by gender, with women having higher rates of village out-migration than men, the lineage subsample of female respondents will have many more men than the sample of male respondents and lineage size may be greater for females than for males. This could be a problem if methylation gene expression differs by gender, although we know of no evidence of this. However, because the sampling of respondents for whom we obtained the toenail clippings prioritized respondents with same-sex non-co-resident kin, the lineage imbalance in size and sex ratios is actually substantially attenuated in the analysis subsample. Table 1 reports the number of lineages, the average number of respondents per lineage, and the fraction of males in the lineages for the analysis subsample by gender. As can be seen, the number of lineages and average lineage size are similar by gender (the difference is not statistically significant). However, while overall there is a balance of men and women within each lineage, as expected, men are represented more heavily in the lineages of women compared with those of men—for females, 56% of their lineage relatives are male, while for men the figure is 42%.

TABLE 1
Lineage characteristics for respondents aged 18–59 with relatives residing outside the village, by sub-sample

Sample/ characteristics	Number of lineages	Mean lineage size (SD)	Percentage of males in lineage
All	308	11.4 (10.8)	48.9
Females	260	11.1 (10.7)	42.1
Males	264	11.7 (10.9)	55.8
Females, same-sex lineage	140	6.24 (5.54)	0
Males, same-sex lineage	148	7.20 (5.87)	100

This difference, while statistically significant, is not substantial but in our analysis we will see if the lineage sex ratio matters directly and we will also assess to what extent it matters whether we use only male non-co-resident relatives or their female counterparts. We thus also constructed single-gender lineages for both men and women to assess whether there are differences in family links by gender. As seen in the table, this reduces the number of individuals in each lineage, by almost half, as well as the number of lineages.

Table 2 provides average individual-specific *As* concentrations, food intakes, and outcome measures by gender for the analysis subsample. As can be seen, the level of retained arsenic is approximately the same as the age-unrestricted sample, with women having concentration levels that are slightly higher than that of men, by 6.5%. This difference is not statistically significant at the 10% level. Women, however, also appear to consume less foods overall, and thus potentially less contaminants. And men smoke on average almost seven times more cigarettes per day than do women. In the table, we also see that women do less well on the Raven's test, are less strong, have less schooling, spend less time in the labour market and are less likely to operate a business, but these statistically significant differences are not necessarily attributable to the small gender differences in retained *As*.[15]

The data also indicate that retained individual *As* is significantly correlated even among separated family members. In a fixed-effects regression estimated on the subsample of respondents who had left the original 14 villages, the set of 14 dummy variable coefficients associated with the original villages was statistically significant at the 0.01 level. As one diagnostic for whether our instrument removes the village-level source of spatial correlation among separated kin, we will estimate the same regression using the estimated *As* residuals from the arsenic nutrition production function (16). Our procedure should eliminate village-level sources of spatial covariance as well as any kin-based persistence in food habits or preferences for water quality associated with choice of water source.

5. DIET, WATER SOURCE, AND ARSENIC CONCENTRATION

We first report estimates of (16), the relationship between retained arsenic and food intakes and water sources, using the individual-level information on food consumption, divided into seven food groups (grains, pulses, green vegetables, other vegetables, tubers, fruits, and meat, fish, and dairy); information on smoking (number of cigarettes per day); and information on the water source used for cooking, coded as a binary variable if a non-tubewell source was used. Over 26%

15. For example, women have less physical strength in all human populations (Pitt et al., 2012).

TABLE 2
Respondent characteristics (means and standard deviations): men and women aged 18–59

Variable	Men	Women
As concentration (ppb)	1,367	1,456
	(1,870)	(2,225)
Raven's CPM score (number of correct answers)	4.19	3.33
	(2.09)	(1.83)
Pinch test pressure (kg)	43.2	31.5
	(25.9)	(22.1)
Years of completed schooling	5.26	4.29
	(4.40)	(3.96)
BMI	19.5	19.8
	(2.73)	(3.10)
Illness in the last week	.189	.297
	(.392)	(.457)
Skill occupation	.515	.049
	(.500)	(.216)
Annual days worked in the labor market	297.5	15.7
	(104.8)	(59.2)
Operate a nonfarm business	.175	.010
	(.380)	(.100)
Grain consumption (grams per day)	519.8	448.0
	(244.6)	(177.1)
Green vegetable consumption (grams per day)	37.8	38.7
	(86.5)	(76.2)
Vegetable consumption (grams per day)	137.4	112.5
	(162.8)	(120.5)
Tuber consumption (grams per day)	87.7	76.9
	(88.4)	(76.4)
Fruit consumption (grams per day)	16.8	15.4
	(69.1)	(51.0)
Meat consumption (grams per day)	80.7	61.7
	(99.5)	(74.8)
Number of cigarettes smoked per day	7.38	1.08
	(10.7)	(1.21)
Cooking water source not a well	.232	.242
	(.422)	(.428)
N	742	778

Notes: Standard deviation in parentheses.

of households used water from non-tubewell sources for cooking. In contrast, more than 97% of households obtained drinking water from a tube well so that there is too little cross-household variation in this variable to obtain an estimate of the effects on arsenic retention of switching sources of drinking water.[16]

Avoiding tubewells as a source of cooking water appears to be associated with effort.[17] The distance to the water source for cooking is a statistically significant (0.03 level) 15% higher for users of non-tubewell sources and time spent fetching water in such households is a statistically significant 19.6% higher (0.037 level). Consistent with the fact that over 30% of households boil water that is not obtained from a tubewell, in households using non-tubewell water for

16. Intensive public health campaigns in Bangladesh over the past decades have informed almost all Bangladesh households that water from non-tubewell sources (which contain little arsenic but do contain organic material) must be boiled to reduce contaminants. Since most cooking involves boiling it is less costly to use non-tubewell water for cooking than for drinking, for which boiling would require added effort. However, irrigation predominantly uses tubewell water.

17. We cannot know whether such effort reflects attempts to reduce arsenic ingestion, though we find below that use of the alternative cooking water source does reduce retained *As*.

TABLE 3
Individual-Specific Production Function Estimates for (Log) As Concentrations, by Estimation Method and Gender for Respondents Aged 14–59

Variable/estimation method Sample	Village FE	Village FE-IV All	Village FE-IV Females	Village FE-IV Males
Log grain consumption	−0.0206	0.314	0.218	0.340
	(0.0303)	(0.0867)	(0.125)	(0.132)
Log green vegetable consumption	−0.0096	−0.0309	−0.0315	−0.0391
	(0.00561)	(0.0133)	(0.0177)	(0.0189)
Log vegetable consumption	−0.0118	−0.0197	0.00866	−0.0478
	(0.00720)	(0.0142)	(0.0191)	(0.218)
Log pulses	−0.0117	−0.0275	−0.0665	−0.0117
	(0.00716)	(0.0166)	(0.0228)	(0.0232)
Log tuber consumption	−0.0117	−0.0495	−0.0375	−0.132
	(0.0118)	(0.0250)	(0.0334)	(0.380)
Log fruit consumption	0.0053	−0.0085	−0.00948	0.00562
	(0.0828)	(0.0170)	(0.0233)	(0.0235)
Log meat consumption	−0.0220	−0.0357	−0.0328	−0.0598
	(0.00681)	(0.0139)	(0.0186)	(0.0201)
Log number of cigarettes	0.0142	0.0396	−0.0264	0.0267
	(0.0128)	(0.0193)	(0.136)	(0.0262)
Cooking water not from a well	−0.0907	−0.182	−0.204	−0.0965
	(0.0470)	(0.0989)	(0.137)	(0.144)
Male	0.180	0.145	–	–
	(0.0600)	(0.0578)		
Male × age	−0.0012	−0.0030	–	–
	(0.00188)	(0.00184)		
N	3,036	3,036	1,667	1,369
Endogeneity tests: *Wu-Hausman F* [*p*]	2.99 [0.0015]		1.63 [0.103]	2.22 [0.019]
Durbin $\chi^2(9)$ [*p*]	31.7 [0.0002]		19.5 [0.022]	26.0 [0.002]

Notes: Specification also includes the age and age squared of the respondent. Standard errors in parentheses. All of the rhs variables are endogenous except for age, age squared, male, and male × age. The identifying instruments are the schooling of the respondent, the value of the household's landholdings, the household head's age and schooling, and the latter two variables interacted with the full set of village dummy variables.

cooking, time spent fetching fuel is also a statistically significant 32.1% higher (0.001 level) than in households who use tubewell water for cooking.

As noted, the toenail-based *As* concentration measure represents arsenic retained in the body from arsenic ingestion over the past three months, while the food intakes are measured in a 24-h period. Both the outcome and input variables thus are short-term, but the food intake variables measure with error the food consumed over the period relevant to the concentration measure. Our instrumental-variables method should eliminate this source of bias, along with the biases due to the existence of unobservables that affect the choice of foods.

Columns one and two in Table 3 report OLS and IV estimates of the diet-arsenic production function, respectively, for respondents age 14–59.[18] Appendix Table A4 reports the first-stage estimates. As noted, all food variables and the quantity of cigarettes smoked are expressed in logs, as is the concentration of arsenic,[19] and the specification also includes village fixed effects to net out unobserved variation in well placement and water quality at the village level. While the signs of the OLS and IV coefficients are identical for all but grains (which are, however, the

18. Because of the age restriction the sample size is reduced from the 4,260 respondents aged eight and above with measured toenail *As* concentrations. In addition, we need to restrict the sample to villages having at least two households with members in the relevant age range. This results in only an additional 5% of households being excluded. The resulting sample size is 3,036.

19. The 50% of respondents (mostly women) do not smoke. We set the number of cigarettes to 0.01 for this group. The results are not sensitive to setting the zero-smoking level to as low as 0.0001.

largest single food item), the OLS coefficients for all endogenous variables are biased towards zero. The hypothesis that the set of OLS and IV coefficients are identical is also rejected, using either the Wu–Hausman test or the Dubbin test.

The estimates of the gender effect, using either estimation method, indicate that women at age 30, net of dietary intakes, retain 5.5% less arsenic in their bodies than do men. This result is consistent with the findings in the literature, as noted, that women methylate at higher rates than men, since the lower concentration of retained *As* is net of dietary differences in intakes. That in our sample on average women have more *As* concentrations than men thus appears to be because in part women consume diets that contain more arsenic. This gender difference does not appear to be due to the *effects* of individual food intakes being different across men and women. In the third and fourth columns of Table 3 the diet-arsenic production function IV estimates are reported by gender. Overall, the differences in the coefficients are not jointly statistically significantly different by gender. Among the individual coefficients, only the coefficient for tubers is statistically significantly different by gender (more negative for males) and there is only a statistically significant smoking effect for males. This latter difference, however, is due to the fact that almost no women in our sample smoke.

The IV estimates for the full sample and each of the gender-specific samples indicate that the staple of rural Bangladesh diets, grains (principally rice, a food that uses large amounts of water for cooking), is causally associated with increased retained *As*, conditional on the water source used for cooking and other dietary intakes, and has the largest negative impact of all the consumed food groups.[20] The point estimate indicates that a one-standard deviation increase in grain consumption increases arsenic retention by 12.6%. Smoking also statistically significantly increases arsenic retention, a finding consistent with medical studies.[21] The point estimates indicate that the cessation of smoking would lower retained arsenic by 4%. The consumption of three food groups, however, significantly decreases retained arsenic in the contaminated water environment of Bangladesh—tubers, meat, and green vegetables. Recall that green vegetables, based on evidence obtained from the randomized distribution of folate supplements, given arsenic ingestion, lower arsenic retained in the body because of increased methylation.[22] And there is also recent evidence that tubers also reduce *As* based on population samples in Bangladesh (Pierce *et al.*, 2010), with consumption of roots and gourds being negatively associated with the appearance of skin lesions. Finally, the estimates indicate that there is a substantial payoff from shifting the source of cooking water from wells in terms of arsenic retention—switching from

20. Irrigation with arsenic-contaminated water particularly affects rice. This is partly because of the large amounts of water used to irrigate rice and partly because the form of arsenic present in a flooded field is the form that is most readily available to plant roots (Brammer and Ravenscroftet, 2009). Rice is also much more efficient at accumulating arsenic into the grains than other staple cereal crops, irrigated or not (Bhattacharya et al., 2012). In addition, rice readily absorbs arsenic when boiled in contaminated tubewell water. Huq *et al.* (2009) report that even if an uncooked rice sample did not contain any detectable amount of arsenic, the cooked rice (*bhat*) contained a substantial amount of the element arsenic when it was cooked with arsenic–contaminated water and Mahal *et al.* (2010) find that rice cooked in surface water contained less arsenic in Bangladesh.

21. Chen *et al.* (2007) and Lindberg *et al.* (2010) have demonstrated that smoking is associated with poorer methylation capacity. The effect of smoking may be related to competition between arsenic and some of the many chemicals found in cigarette smoke for common detoxification pathways (Hopenhayn-Rich *et al.*, 2006). Studies of Bangladesh sub-populations for whom measures of the products of the methylation process, arsenic metabolites, were obtained using spectrometry on biomarkers, have found that smoking interfered with arsenic methylation capacity but was not a direct source of arsenic (Kile et al., 2009).

22. On the other hand, green leafy vegetables in Bangladesh are strong accumulators of arsenic, much more so than fruity vegetables like tomato, gourd, or eggplant (Farid et al., 2003). Arum leaf, a popular and widespread green vegetable, has the highest arsenic load of any foodstuff in Bangladesh tested by (Huq et al., 2006).

wells to obtain water for cooking evidently decreases retained *As* by 18.2%, a result which is statistically significant at the 0.03 level, one-tailed test.

6. PREDICTING ARSENIC CONCENTRATIONS

As noted, we use the estimated residuals obtained by subtracting from the measured *As* of all respondents that part predicted by own consumption, household water choice and the village fixed effect using the estimates reported in Table 3 to form respondent-specific family lineage measures of arsenic retention that contain genetic but not behavioural components. These lineage "endowments" exclude any location effect and are then used as instruments to predict respondent arsenic retention based on the genetic linkages in arsenic methylation. Note that because we have eliminated any fixed effects associated with villages, we require that at least two different lineages reside in a village. As noted, this requirement, the requirement that there be at least one member of the lineage living apart from the respondent, and the added restriction to adults in the age range 18–59 results in a sample size of 1,520 individuals.

We first assess if our method of eliminating the environmental and behavioural components of measured *As* successfully eliminated the spatial correlation in retained arsenic levels. We regress the measured *As* of those respondents who had left the original 14 villages on their age, age squared, gender, and the value of their households' landholdings and the set of 14 village dummy variables corresponding to their village of origin. The origin-village fixed effects are highly jointly significant ($F(13, 505) = 46.33$) and explain 56% of the total variance in arsenic retention across the sample of leavers. Spatial and behavioural correlations in *As* are evidently high in our sample, perhaps due to selective migration. We then replace the dependent variable with the residual measure of *As*. Using the same sample and specification, the set of origin-village dummy variable coefficients is no longer jointly statistically significant ($F(13, 505) = 0.71$), and explains just 2.2% of the total variance in the residual measure.

Having successfully eliminated the environmental sources of the correlation in *As* among family members living apart using the residual method, the next question is whether and how the family-based residual measures explain the variation in actual arsenic retention across individuals. Genetic theory suggests that the functional form of the expected relationship between an individual's genetic ability to methylate arsenic and that of their family members is non-linear. In particular, the functional form of the first-stage equation is likely to be best described by a polynomial relationship if the inheritability of arsenic methylation efficiency is both polygenic and epistatic, as the genetic epistatic model with these attributes generates a non-linear relationship between the phenotypes of any one brother and the phenotypes of his siblings that can be approximated by polynomials.

One example of a polygenic and epistatic inheritability relationship is when there are three genes that determine particular characteristics, and the alleles of one gene must be of a certain type for there to be effects of the other two genes. The literature leaves no doubt concerning arsenic methylation's polygenic nature, with at least three genes, as discussed above, identified as sources of variation in arsenic methylation efficiency in humans. Epistatis, or gene–gene interaction, in complex metabolic mechanisms, such as the methylation of arsenic, is considered likely as they require many enzymes that typically function together, and the interactions inherent in these biochemical relationships play a key role in determining epistasis.[23]

23. Lehner (2011, p. 324) suggests that the simplest molecular mechanism that can cause epistasis between two genes is if their two protein products directly interact. The three arsenic methylation genes (AS3MT, MTHFR, and GSTO1) each regulate an enzyme required in the process and interact with other enzymes Vahter (2000). Argos (2011)

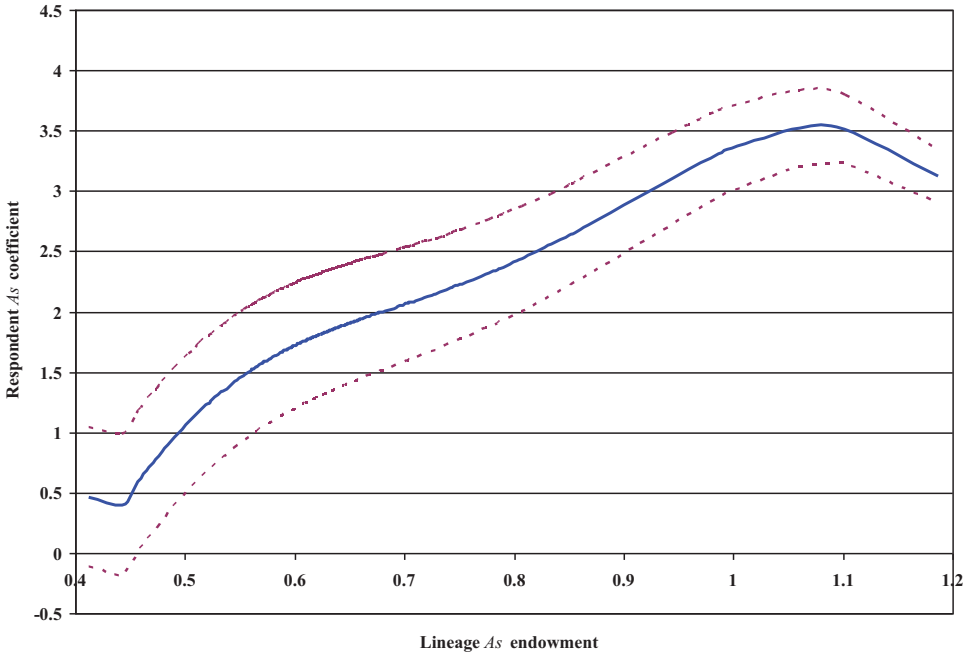

FIGURE 3
Locally weighted estimates of the effects of non-coresident lineage As endowments on respondent As concentrations, by lineage As endowment size

Figure 3 plots the locally weighted estimated coefficients from a regression of the endowment residual of a sample respondent on his or her average lineage residuals, by the level of those residuals, from our sample of respondents aged 18–59. As can be seen, the relationship suggests a quadratic form. To approximate this relationship, we thus use both the level and the square of the average lineage residuals as instruments for a respondents log *As* retention. The first two columns of Table 4 report the linear and quadratic specifications for the first-stage equation that we use in all of our subsequent IV estimates. The addition of the squared term adds explanatory power, and the two lineage variables are jointly significant at the 0.0025 level.[24] The set of additional variables are included because they will be used in all of the second stage equations. Of these, only the value of the household's landholdings is statistically significant, indicating that wealthier rural households, net of their genetic tendencies to methylate, have slightly higher levels of retained arsenic.

The first-stage estimates from subsample samples of women and men using the quadratic specification are reported in the third and fourth columns of Table 4. We cannot reject the hypothesis that the coefficients are the same for males and females. To assess if the modest gender imbalance in the lineages of men and women affects the results in the fifth and sixth columns of Table 4, we show the first-stage estimates by gender where we only use the same-sex members of lineages. As indicated in Table 1, by this restriction the number of lineages and

has found strong empirical evidence of gene–gene interactions for a set of 10 SNPs associated with arsenic methylation using data on 1,689 individuals from rural Bangladesh.

24. Pagan (1984) demonstrates that the OLS coefficient standard errors for residuals entered as regressions, as in our first-stage equation, are consistent. Thus, the tests of significance are valid.

TABLE 4
First–stage coefficient estimates, respondents aged 18–59: dependent variable = log As

Sample/variable	All		Females	Males	Females, same-sex lineages	Males, same-sex lineages
Mean log non-co-resident lineage (NCL) *As* residuals	1.82 (0.796)	−6.92 (4.51)	−9.87 (5.38)	−1.88 (4.37)	4.71 (3.52)	−22.2 (3.59)
Mean log non-co-resident lineage (NCL) *As* residuals squared		5.40 (2.52)	7.32 (3.01)	2.12 (2.44)	−1.47 (1.69)	16.46 (3.21)
Value of owned landholdings ($\times 10^{-7}$)	0.916 (0.458)	0.757 (0.372)	0.799 (0.454)	0.745 (0.344)	1.14 (0.659)	1.05 (0.449)
Male	0.0347 (0.0738)	0.0410 (0.0675)	–	–	–	–
N	1,520	1,520	778	742	709	546
F-test endowment instrument coefficients = 0 [*p*]	5.21 [0.023]	6.30 [0.002]	6.94 [0.001]	4.15 [0.016]	3.50 [0.031]	22.9 [0.000]
F-test (4, 620) gender coefficients = for all coefficients [*p*]	–	–	1.72 [0.128]		–	–

Notes: Specification also includes age and age squared of the respondent. Standard errors in parentheses clustered at the village and lineage level.

the average number of persons per lineage is substantially reduced. Nevertheless, the *As* lineage residuals still have a statistically significant relationship with retained arsenic.

7. RETAINED ARSENIC AND INDIVIDUAL PERFORMANCE

7.1. *Arsenic and cognitive performance*

The first column of Table 5 reports the random effects estimate of the relationship between performance on the Raven's Colored Progressive Matrices Test and the log of respondent's retained *As* for men and women aged 18–59 with information on arsenic retention. The estimate suggests that retained *As* and test performance is statistically significantly negatively correlated, indicating that a one standard deviation increase in arsenic retention lowers the test score by 7%. But is the relationship causal? One reason for the correlation is that we have imperfectly measured household income, which may jointly influence diet and thus arsenic retention as well as test performance, and we also have no information on the household's proximity to wells, or the amount of well contamination.[25]

In the second column of the table, we report household fixed effects estimates, which eliminate all variation in household-specific variables. The negative relationship between retained *As* and cognitive performance increases in absolute value by 36%. The Wu–Hausman test, however, indicates that we cannot reject the hypothesis that the OLS and household fixed effects estimates are identical. While this could be interpreted as rejection of the hypothesis that arsenic retention is endogenous, the test assumes that the fixed-effects estimator is consistent. But as noted, the household fixed effects estimator does not eliminate the influence of variation in individual productivity (skill) endowments, which may affect diet and thus arsenic ingestion. In the third and fourth columns, we display estimates using a household/family fixed effects estimator, based on subsamples including only household members who belong to the same lineage—father and children and mother and children, respectively. The estimator thus eliminates the variation in

25. The fact that the household's landholdings is positively associated with the test score suggests that there may be a nutritional or behavioural component to the relationship. For example, it is well known that schooling attainment has some effect on Raven's performance.

TABLE 5
Estimates of the effect of log As on cognitive performance: Raven's cpm score, by estimation procedure and sample for respondents aged 18-59

Estimation method	Random effects	HH FE	HH/family FE	HH/family FE
Subsample	–	–	Head/children	Wife/children
Log *As*	−0.195	−0.265	−0.550	−0.393
	(0.0389)	(0.0916)	(0.196)	(0.166)
Age	−0.104	−0.130	−0.159	−0.133
	(0.0209)	(0.0261)	(0.0550)	(0.0424)
Age squared	0.0704	0.108	0.139	0.108
	(0.0289)	(0.0361)	(0.0757)	(0.0610)
Landholdings value ($\times 10^{-7}$)	3.63	–	–	–
	(0.498)	–	–	–
Male	0.873	0.853	0.970	0.793
	(0.0646)	(0.0693)	(0.267)	(0.213)
N	2,852	2,852	1,437	1,693
Endogeneity test: *Wu-Hausman* $\chi^2(4)$ [*p*]	–	4.58	5.21	6.07
	–	[0.334]	[0.266]	[0.194]

Notes: Standard errors in parentheses clustered at the household level.

TABLE 5A
Estimates of the effect of log As on cognitive performance: Raven's cpm score, by estimation method and gender for respondents aged 18-59

	OLS		HH FE	
	Females	Males	Females	Males
Log *As*	−0.128	−0.289	−0.559	−0.652
	(0.0452)	(0.0563)	(0.526)	(0.402)
Age	−0.977	−0.0934	−0.156	−0.132
	(0.01278)	(0.033)	(0.119)	(0.114)
Age squared	0.0612	0.0567	0.145	0.105
	(0.0377)	(0.0447)	(0.164)	(0.156)
Landholdings value ($\times 10^{-7}$)	3.21	3.31	–	–
	(0.761)	(0.739)	–	–
N	1,498	1,354	1,498	1,354
F-test of gender equality [*p*]	1.58		0.99	
	[0.177]		[0.395]	

Standard errors in parentheses clustered at the household level.

endowments across family lineages. This means that while individual endowment heterogeneity is reduced, that component of arsenic retention variation due to exogenous genetic differences is also attenuated, so that more of the variation in *As* retention is driven by diet choice. Here, too the negative association between retained arsenic and the test scores increase but we cannot reject the hypothesis that, for comparable sub-samples, the OLS (not shown in the table) and household/family fixed effects estimates are identical. Again, this test result may simply mean that the principal source of bias is not eliminated using the household or family fixed effects estimator.

Table 5A reports the OLS and household fixed effects estimates by gender. The results are similar within each gender group to what we see for the combined sample, and we cannot reject the hypothesis for either estimation method that the results differ by gender.

In Table 6, we report OLS estimates and instrumental-variables estimates of the *As*-test score relationship using the sub-sample of 1,520 respondents for whom we have family-lineage based

TABLE 6
Estimates of the effect of log As on cognitive performance: Raven's cpm score, by estimation procedure and gender for respondents aged 18-59

Sample/variable	All		Females		Males	
	OLS	IV	OLS	IV	OLS	IV
Log *As*	−0.174	−0.962	−0.113	−0.765	−0.249	−1.37
	(0.0572)	(0.339)	(0.0622)	(0.307)	(0.0885)	(0.593)
Age	−0.123	−0.104	−0.119	−0.109	−0.129	−0.0921
	(0.030)	(0.0370)	(0.0359)	(0.437)	(0.0356)	(0.0404)
Age squared	0.0949	0.0704	0.0935	0.0827	0.0986	0.0492
	(0.0374)	(0.0495)	(0.0455)	(0.0579)	(0.0474)	(0.0550)
Value of owned landholdings ($x10^{-7}$)	3.30	4.04	3.28	3.98	3.28	4.18
	(0.662)	(0.795)	(0.901)	(1.098)	(0.767)	(0.946)
Male	0.889	0.911	–	–	–	–
	(0.101)	(0.133)				
N	1,520	1,520	778	778	742	742
Endogeneity test: *Wu-Hausman* $\chi^2(1)$ [*p*]	–	4.421		3.411		2.936
	–	[0.0355]		[0.0648]		[0.0866]
Weak identification test: *Cragg-Donald Wald F*	–	26.17		17.72		7.88
F-test excluded instrument coefficient = 0[*p*]	–	5.17		4.31		4.61
		[0.0240]		[0.0394]		[0.0330]
H: Gender coefficients = [*p*]	–	–	–	–	$F(4, 620) = 1.31$	$\chi^2(4) = 1.91$
					[0.263]	[0.752]

Notes: Specification also includes age and age squared of the respondent. Standard errors in parentheses clustered at the village and lineage level. The first stage equations are reported in Table 4.

instruments again clustering by both village and lineage.[26] Reassuringly, the OLS estimates in column 1 of the table are almost identical to the OLS estimates from the larger sample of all respondents in the same age group reported in the first column of Table 5, consistent with the subsample with lineage-based instruments being unselective. In the second column, we report two-stage least squares estimates using the first-stage specification reported in Table 4. The estimate of the *As* effect is now larger and remains statistically significant. The point estimate is substantial, indicating that a one standard deviation decrease in arsenic retention would increase performance on the test by one full correct answer, an increase of 24%.[27]

The Wu–Hausman test now indicates rejection of the hypothesis that *As* is exogenous, and the standard diagnostics indicate rejection of the hypothesis of weak instruments. In particular, the value of the Cragg–Donald F-statistic of 26.2 is well above the critical Stock and Yogo (2001) values for determining bias in the instrumented variables.[28] To assess whether this test has power, we also re-estimated the test score equation including the actual lineage average *As* in addition to the residual measures in the first stage specification (not shown). The Hansen C test indicated, as expected, rejection of the hypothesis that the family *As* "instrument" is excludable, while still indicating non-rejection for the residuals-based instruments.

In the last four columns of Table 6, we report the OLS and IV results by gender, using the lineage residuals for each gender. The results are qualitatively and quantitatively similar to those for the full sample and across men and women, with the IV estimates again larger in absolute value than the OLS estimates. The IV point-estimate of the effect of retained *As* on cognition is stronger for males than females, however we cannot reject the hypothesis for either the OLS or IV estimates that the set of coefficients in the cognition equation differ by gender. The instruments, however, are weaker for the two subgroups than for the full sample, particularly for the males and we can only reject exogeneity at 10% level.

To assess whether the imbalance of the sex ratios across the lineages of the male and female subsamples is affecting our results for the full sample, we first included the lineage sex ratio as an additional regressor. In this specification, (not reported) the coefficient on the lineage sex ratio variable was not statistically different from zero and its inclusion had no effects on the coefficients of the other variables. To assess if the gender of the relatives matters, we then estimated the effect of retained arsenic on the test score for women using, respectively, only their male and female non co-resident relatives. The estimate of the retained *As* effect on cognition, reported in Appendix Table A5, does not appear to be sensitive to which set is used, although, perhaps surprisingly, instrument power is weaker for females when we restrict the sample to non-co-resident female kin.

Given that we can find no differences in the first-stage estimates by gender and to ensure that our results do not depend on differences in the lineage characteristics of subgroups, we will use the same first-stage equation for all of our subsequent estimates based on the full sample, including those in which we stratify by gender and/or age, using limited information maximum likelihood (LIML).

26. The statistical results and conclusions are not sensitive to adding the lineage cluster to the village cluster. The IV standard errors are computed taking into account the use of the constructed instrument as noted.

27. The more negative IV estimate may be due to the elimination of attenuation bias due to the existence of measurement errors in the arsenic retention variable. The difference is also consistent with more skilled individuals consuming diets that tend to increase arsenic retention.

28. For example, the critical 5% F-value for two instruments when weak instruments are defined so that a 5% hypothesis test rejects no more than 15% of the time is 11.59. (Source: Table 1 from Stock et al. (2002).

TABLE 7
LIML Estimates of the effect of log As on physical performance (pinch test) for respondents aged 18–59, by gender: Kg of pressure

Gender	All	Male	Female
Log *As*	−1.60	−3.14	−1.05
	(0.812)	(1.59)	(1.88)
Age	0.662	0.611	0.923
	(0.246)	(0.224)	(0.389)
Age squared	−0.991	−0.854	−1.39
	(0.387)	(0.365)	(0.556)
Value of owned landholdings ($x10^{-7}$)	0.776	1.09	2.53
	(3.37)	(1.54)	(4.08)
Male	11.7	–	–
	(1.33)		
N	1,519	777	742
As gender coefficients = $\chi^2(1)$ [*p*]		0.51	
		[0.716]	

Notes: Specification also includes average ages and numbers of male and female household members and number of males aged 17–59. Standard errors in parentheses clustered at the village level.

7.2. *Arsenic and physical strength*

Table 7 reports OLS and LIML estimates of the relationship between retained arsenic and a measure of physical strength—performance on a standard pinch test. Each respondent was asked to pinch a dynamometer with each hand three times. We use the sum of the pressure exerted in all six tries (in kilograms of pressure). As for the cognition tests, the OLS estimate of the effect of retained *As* is substantially underestimated. The OLS estimate is not statistically different from zero, while the LIML estimate which accounts for endogeneity is statistically significant at the 0.05 level. The point estimate indicates that a one-standard deviation increase in retained arsenic reduces performance by over 6%. Also, as for cognition, while the point estimate of the effect is smaller in absolute value for women than for men, the differences by gender are not statistically significant.

7.3. *Retained arsenic and standard morbidity measures*

We use the same estimation methods to assess if an individual's retained arsenic affects health using conventional morbidity and anthropometric measures. Specifically, we look at the relationships between retained *As* and the probability of having any one of a standard set of morbidity symptoms in the week prior to the survey for the same sample. We also examine how body mass (BMI) and retained arsenic covary. The morbidity measure we use is based on a set of illness symptoms that respondents self-report. They include headaches, diarrheal symptoms, fever, and coughing. Over 25% of the sample respondents aged 18–59 reported having had at last one of these symptoms in the reference period. The medical literature suggests that all of these symptoms can be attributable to arsenic retention. However, they are also symptoms of many other illnesses that are prevalent in Bangladesh.

The first two columns of Table 8 report the probit and LIML probit estimates of the relationship between retained arsenic and the morbidity measure. Neither the probit nor the LIML probit estimate, which accounts for the endogeneity of retained arsenic, indicate that arsenic in the body is significantly related to these in standard morbidity symptoms. For BMI, while the OLS estimate of the association between BMI and *As* is negative and statistically significant, when the endogeneity of *As* is accounted for, the coefficient is no longer significant. The point estimates for BMI yielded by either estimation method are in any case very small, suggesting that a doubling

TABLE 8
Estimates of the effect of log As on morbidity and log body mass for respondents aged 18-59, by estimation method

Gender	Illness in the Last Week		Log BMI	
Estimation method	Probit	LIML Probit	OLS	LIML
Log *As*	−0.0353	0.0902	−0.0139	−0.0168
	(0.0324)	(0.0991)	(0.00644)	(0.0336)
Age	−0.0356	−0.0380	0.0161	0.0162
	(0.0185)	(0.0185)	(0.00247)	(0.00229)
Age squared	0.0675	0.0706	−0.0213	−0.0214
	(0.0235)	(0.0235)	(0.00482)	(0.00328)
Value of owned landholdings	−0.181	−0.287	0.291	0.294
($\times 10^{-7}$)	(0.393)	(0.404)	(0.0658)	(0.0708)
Male	−0.370	−0.370	−0.0147	−0.0146
	(0.0618)	(0.0612)	(0.00668)	(0.00676)
N	1,519	1,519	1,519	1,519
Endogeneity test: *Wald* $\chi^2(1)$ [*p*]	2.09 [0.148]		–	
Endogeneity test: *Wu-Hausman F* [*p*]	–		0.0087 [0.921]	

Notes: Specification also includes average ages and numbers of male and female household members and number of males aged 17–59. Standard errors in parentheses clustered at the village level.

of retained arsenic would decrease body mass by less than 1.7%. The reduced capabilities caused by arsenic do appear to be somewhat "hidden"—respondents with high levels of retained arsenic are neither experiencing any more illness symptoms nor are they smaller than respondents with low levels of retained arsenic.[29] One must be careful in interpreting these results—they do not necessarily imply that retained arsenic does not affect morbidity. In a poor population, like that in our sample, the commonality of arsenic retention symptoms and those of other prevalent illnesses make it difficult to detect the specific morbidity effects of arsenic retention. Being ill from bad sanitation or hygiene hides many symptoms of arsenic.

8. ARE THE PERFORMANCE RESULTS SPURIOUS?

8.1. *Sensitivity of results to mis-specification of the production function*

A major concern with using our residual-based instrument is that it contains determinants of the outcome variables, other than arsenic retention, due to the mis-specification of the arsenic retention production function. One source of mis-specification is the use of an inappropriate functional form. We chose to use a logarithmic specification for the production function, as it conforms to the well-established Cobb–Douglas form. We also carried out a Box Cox test, which allows us to compare linear ($\lambda = 1$), our double log ($\lambda = 0$) and multiplicative inverse ($\lambda = -1$) functional forms. The estimate of λ was -0.212 (sd $= 0.0140$) and the likelihood-ratio statistics for the hypotheses of linear, double log and inverse multiplicative forms were 7,269.7, 245.5, and 2,773.8, respectively. These statistics reject all three functional forms but also clearly indicate that the log–log form that we chose is clearly the best approximation among the three nested parametric alternatives.

Given only weak statistical support for our specification against all non-nested alternatives, we then examined the sensitivity of our estimates to an alternative functional form for the production function. We could reject the linear specification in favour of a quadratic specification using our

29. Skin lesions (keratosis) and discoloration (melanosis) are visible physical symptoms of retained arsenic, but these in many cases take years to show up, and are only imperfectly correlated with the amounts of retained *As*. They were not included among the symptoms listed in the survey instrument.

IV method and we chose to use this specification as a comparator.[30] The estimates using this functional form were similar to those from the log-log form reported in Table 3—the coefficient signs are identical and, exactly as in Table 3, all food coefficients except vegetables and fruits were statistically significant. Moreover, the correlation between the residuals from the log–log and linear-quadratic estimates was 0.98, and the correlation between the constructed lineage variables from the two specifications was 0.89. In the first-stage, our log–log based lineage instruments were more strongly associated with log *As* than those based on the linear quadratic specification.[31] And the second-stage results using the residuals from linear quadratic specification as instruments are almost identical in terms of statistical significance and magnitudes to those reported in Tables 5 and 6.

8.2. *Methylation genes, omitted characteristics, and cognitive outcomes*

Another explanation for why use of our residual-based instruments, which rely on the genetic correlation in methylation within family lineages, implies that there are significant effects of arsenic retention on cognitive and physical performance is that methylation genes are negatively correlated with genes determining inherent cognitive ability and strength, which are also inheritable. As noted, estimates of the association between arsenic methylation genes, genes associated with cognition and physical strength, and direct measures of cognition in non-arsenic-contaminated populations indicate that this source of error is unlikely. However, as noted, our residual may also contain yet unidentified genetic factors related to both cognition and methylation or other common family factors associated with arsenic ingestion that affect behaviour due to any mis-specification of the arsenic production function (15), including both the use of an inappropriate functional form and omitted inputs. A more global test for spuriousness would be to estimate the effect of our instrumented arsenic variable on measures of cognition for the same individual prior to ingesting arsenic and after. While our data indicate that in 2007–8 all of our respondents are exposed to arsenic-contaminated water, we can still carry out placebo tests by examining the consequences of cognitive impairment for human capital investment, occupational choice, and entrepreneurship before the arsenic contamination of consumed water by exploiting differences across cohorts in our panel survey, the first round of which was collected when arsenic-contaminated water sources were substantially less important.

8.2.1. Arsenic and schooling attainment by cohort. To assess whether our results are spurious we first examine schooling attainment by cohort. We should expect that those individuals with lower cognitive performance, whatever its origin, will obtain less schooling and thus those respondents with higher predicted *As* concentrations should have lower schooling attainment.[32] However, because the shift to arsenic-laden well water started in the late 1970's, older respondents should not have been affected by arsenic poisoning when they made their schooling decisions. And, as indicated by the U.S. Framingham results, having a lower ability to methylate should therefore have had no effect on schooling attainment. Thus, we have a cohort test of spuriousness—if we find older cohort's completed schooling is as related to current arsenic retention as that of

30. The $\chi^2(7)$ statistics for the sets of linear and quadratic food coefficients were 14.5 and 17.0, respectively, both significant at the 0.04 level.

31. The F-statistics for the log–log and quadratic based lineage measure coefficients in the first stage were 6.16 [$p=0.0025$] and 4.69 [$p=0.011$], respectively. Estimates using the alternative functional forms for the arsenic production function are available from the authors.

32. Choice of schooling should depend on comparative advantage in skill versus brawn. Our estimates indicate that retained *As* lowers cognitive performance substantially more than it decreases physical strength.

TABLE 9
LIML Estimates of the effect of log As on cognitive performance by age group: Raven's cpm score

Age group	18–34	35–59
Log *As*	−0.633	−0.755
	(0.170)	(0.282)
Age	0.0133	−0.260
	(0.166)	(0.137)
Age squared	−0.191	0.238
	(0.318)	(0.150)
Value of owned landholdings ($\times 10^{-7}$)	4.87	3.17
	(1.11)	(0.848)
Male	1.00	0.820
	(0.125)	(0.130)
N	878	641
As gender coefficients = across age groups $\chi^2(1)$ [*p*]	0.22 [0.640]	2.86 [0.100]
As coefficients = across age groups $\chi^2(1)$ [*p*]	0.19 [0.665]	

Notes: Specification also includes average ages and numbers of male and female household members and number of males aged 17-59. Standard errors in parentheses clustered at the village level.

younger cohorts, this would suggest that the *As* residual is correlated with fixed family attributes that affect the ability to learn.

We first assess if the current cognitive performance of the old and young are equally affected by their current arsenic retention. We re-estimated the Raven's test equation, using LIML, for the age group 18–34, who were likely consuming arsenic-tainted water throughout their entire lives, and the cohort aged 35–59, most of whom were not likely consuming arsenic-contaminated water from wells as children. Table 9 reports the estimates for both age groups. As can be seen, the estimates of the *As* effects on *contemporaneous* cognitive performance are no lower for the older cohorts. We cannot reject the hypothesis that the estimates are identical by age group—current arsenic retention evidently affects current cognitive performance for both old and young—and equally by gender within age groups.

When we examine schooling, however, the results are strikingly different. The relationships between current *As* retention and completed schooling by cohort and gender, unlike for the test score results, appear to reflect the historical conversion to tubewells as sources of water. Table 10 reports LIML estimates of the relationship between arsenic retention and number of years of schooling for two age groups—those aged 24–34, who have all completed their schooling and were likely consuming large amounts of arsenic during their school decision years, and those aged 45–64, who were not likely affected by arsenic while of school age—and by gender.

As can be seen, for both men and women the negative relationship between current *As* retention and completed schooling is substantially stronger for the younger cohort. For women, the estimates are not statistically significant for either cohort, and are much smaller than those of men.[33] Among the men, current arsenic retention and schooling attainment are strongly and statistically significantly negatively correlated for the young cohort, while as expected for the

33. The smaller effect of arsenic retention among women in the older cohort compared to men in the same cohort is consistent with the existence of barriers to women's schooling in the years preceding the late 1980's, as evidenced by the facts that the schooling levels and enrollment rates of women in the 1980's were substantially lower than those for men and that since the 1980's, women's schooling has risen at a considerably faster rate for women than for men (Pitt et al., 2012). That the effect of arsenic retention on the schooling of younger women is relatively small is a puzzle, given our findings on the effects of arsenic retention on cognitive performance for both women and men. Many programs were put in place in Bangladesh since the 1980's that specifically encourage female schooling, which may have led to the schooling of women being less sensitive to costs and returns. In Pitt et al. (2012), we found that health endowments had little effect on schooling choices for women but did for men in the last two rounds of our survey.

TABLE 10
LIML Estimates of the effect of log As on schooling attainment (years), by gender and age cohort

Gender	Male		Female	
Age group	24–34	45–64	24–34	45–64
Log *As*	−3.44	−0.609	−1.23	−0.244
	(1.47)	(0.521)	(1.22)	(0.428)
Age	−1.08	1.39	−1.53	−0.0186
	(1.70)	(1.12)	(1.10)	(0.0157)
Age squared	1.91	−1.33	1.36	−0.0247
	(2.96)	(1.05)	(1.04)	(0.0216)
Value of owned landholdings (x10^{-7})	33.0	6.22	10.5	2.07
	(7.40)	(4.89)	(4.45)	(2.42)
N	260	205	243	188
As coefficients = across age groups within gender $\chi^2(1)$ [*p*]	3.37 [0.066]		0.60 [0.440]	
All control-variable coefficients = 0 across age groups $\chi^2(14)$ [*p*]		38.0 [0.001]		
All control-variable coefficients = across age groups $\chi^2(7)$ [*p*]		7.81 [0.349]		
As coefficients = by gender within age group $\chi^2(1)$ [*p*]	6.86 [0.009]	0.30 [0.583]	–	–

Notes: Specification also includes control variables: average ages and numbers of male and female household members, landholdings, and number of males aged 17–59. Standard errors in parentheses clustered at the village level.

older cohort of men, whose contemporaneous relationship between *As* retention and cognition is identical to that of the young, current arsenic retention and schooling attainment are unrelated. The point estimates indicate that the elasticities of schooling at the relevant mean schooling levels of the two cohorts with respect to arsenic retention are −0.69 for men in the younger cohort, and a statistically insignificant −0.18 for the older cohort. The difference in point estimates by cohort is statistically significant ($\chi^2(1)=3.37[p=0.066]$).

One concern with this test based on birth cohorts is that there might have been other changes in the rural Bangladesh economy than the shift in the availability of arsenic-laden water from wells that could have differentially affected the determinants of the old and young cohorts' schooling choices. However, as reported in the table, there are no statistically significant differences in the effects of the seven control variables on schooling across the two cohorts ($\chi^2(7)=7.81[p=0.349]$), and this is not due to these variables having no effect on schooling for the cohorts ($\chi^2(14)=38.0[p=0.001]$). Evidently, only the effect of the contemporaneous arsenic measure on schooling attainment differs across the cohorts.

To assess if the results for men are also sensitive to the choice of age group, and given that the historical switch to tubewell-sourced water was likely gradual, we also used local-IV to estimate the relationship between current arsenic retention and schooling attainment by age across the cohorts aged 24-59. The lowess-smoothed local estimates by age for the men, along with the relevant 95% confidence bands, are shown in Figure 4, which, as expected, display a monotonic decrease in the negative relationship with current predicted arsenic retention as the year of birth retreats in time. In contrast, the lowess-smoothed plot of local-IV estimates of contemporaneous *As* effects on cognition across the age groups is flat and statistically significantly negative for all ages, as displayed in Figure 5.

8.2.2. Arsenic, occupational choice, and entrepreneurship by time period and cohort. We next compare the effects of retained arsenic on occupational choice and entrepreneurship across time-periods using the subsample of young men aged 18–35 in the 2007–8 and 1981–2 rounds of the data for whom we have both own 2007–8 arsenic retention information and arsenic measures for their non-village family members. We focus on this age group because we expect that the selection of career paths occurs early in the life-cycle and, as indicated by the schooling

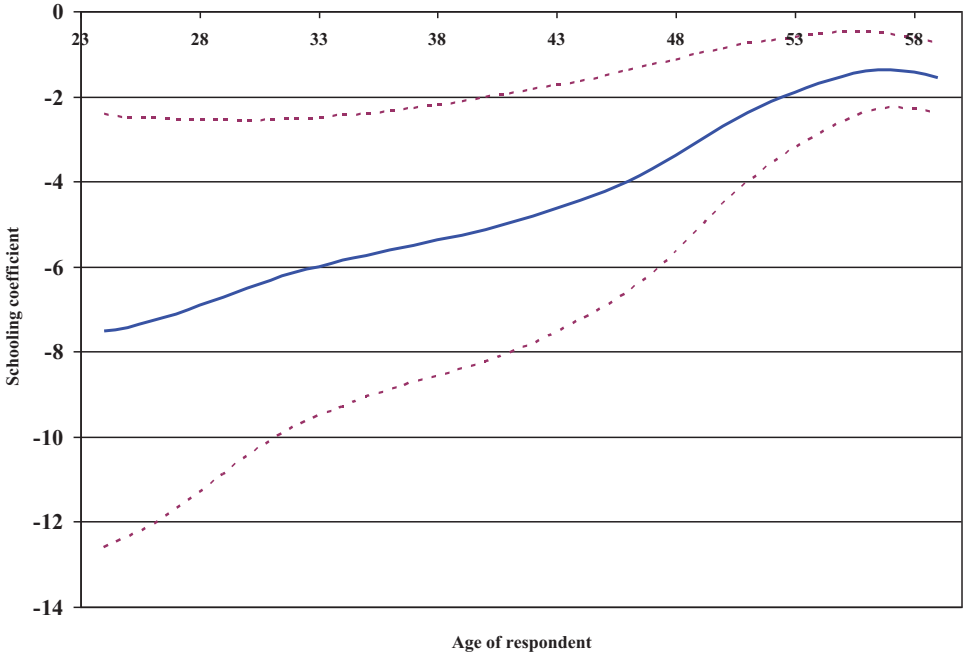

FIGURE 4
Locally weighted IV estimates of the effects of *As* on years of schooling completed for men, by age (cohort)

attainment findings, older respondents were unaffected by arsenic in their water sources while young. To characterize occupation, we used the information on the primary occupation reported by respondents in both survey rounds and classified the respondents as being in a skill occupation according to whether it seemed reasonable skill and/or decision-making were important in the occupational category.[34] Of the 65 categories for workers, we categorized skill workers as those in the professions (teacher, doctor, government administrator) or in business management including farmers (but excluding a farm worker) and shopkeepers. For entrepreneurship, we used survey information on the nonfarm enterprises of individuals and categorized any respondent who reported having received nonfarm business income in the year prior to the survey as an entrepreneur. With these definitions, 26.1% of men aged 18–35 in 1971–2 and 49.2% of the men in the same age group in 2007–8 were in skill occupations and 4.6% in 1971–2 and 19.2% in 2007–8 of males aged 18–35 were operating, or were at least a residual claimant of, a non-farm business.[35]

The first column of Table 11 reports the LIML probit estimates of the determinants of being in a skill occupation for the 18–35 age group in the 1981–2 survey round. The estimation procedure taking into account the endogeneity of retained arsenic indicates that increases in the amounts of arsenic stored in the body, as measured in 2007–8, has no statistically significant relationship with occupational choice made in 1981–2. Because the number of respondents in that age group present

34. The occupational codes used in the 2008 round are identical to those used in the 1996 Matlab Health and Socioeconomic Survey.

35. We do not examine the determinants of occupation choice or entrepreneurship for women, as only 6.6% of women spent any time in the labor force in the year before the survey and only 1.2% of women reported having a non-farm business.

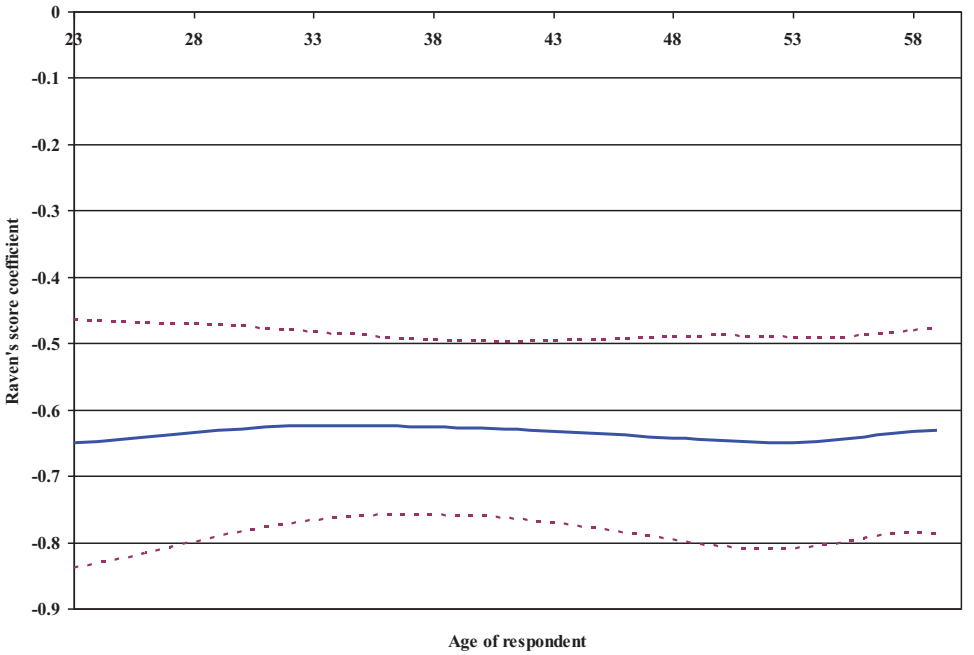

FIGURE 5
Locally weighted IV estimates of the effects of As on Raven's cpm score, by age (cohort)

at the time of the first round was small, we also looked at the occupation of the corresponding age cohort in 2007–8 (males aged 43–60) who were also 18–35 in 1981–82 but not surveyed then.[36] Consistent with the schooling attainment results, the initial occupational choice of the cohort should also not have been affected by the inability to methylate arsenic. And, as seen in the second column of Table 10, there is also no relationship between the contemporaneous measure of arsenic retention and occupation for this enlarged sub-sample in the same age cohort.

In contrast to the effects in the earlier period (for the older cohort), the LIML probit estimate of the effect of contemporaneous arsenic retention on the current occupational choice of the young men in 2007–8 indicates that arsenic retention reduces significantly the probability of being in skill occupations, a result consistent with the evident impairment of cognitive functioning and subsequent reduction of schooling for current young men. The point estimate is relatively large, indicating that cutting by half the average levels of arsenic in this sub-population would increase the proportion in skilled occupations by 12.2 percentage points, or by 24%.

We find similar results for entrepreneurship in the last three columns of the table—retained arsenic only significantly reduces the entry of young men into entrepreneurship in 2007–8. The LIML probit point estimate for the young men in 2007 suggests that cutting retained arsenic levels by the same 50% would increase the proportion running nonfarm businesses by over 5 percentage points, an increase of 26%. And, as we found for schooling, the coefficients on the determinants of occupational choice and business ownership other than arsenic retention are not statistically different across the cohorts: the χ^2 statistics indicate rejection of the hypothesis that the retained

36. Because in the 2001–2 round of the survey an additional random sample of respondents were added, this cohort sub-sample is larger than that present in the 1981–2 round.

TABLE 11

LIML Probit estimates of the effect of log As on occupational choice and entrepreneurship by time-period and cohort: males aged 18-35 in 1982 and in 2007 and males aged 43-60 in 2007 (18-35 in 1982)

Outcome	Skilled Occupation			Operate a Nonfarm Business		
Survey year	1982	2007	2007	1982	2007	2007
Cohort	18–35	43–60	18–35	18–35	43–60	18–35
Log *As*	0.144	0.270	−0.624	−0.0748	0.128	−0.863
	(0.306)	(0.284)	(0.297)	(0.299)	(0.533)	(0.229)
Age	0.475	1.50	−0.0417	0.833	0.595	0.204
	(0.406)	(0.615)	(0.160)	(0.367)	(0.692)	(0.198)
Age squared	−0.0105	−1.47	0.0919	−0.0153	−0.641	−0.331
	(0.00784)	(0.586)	(0.296)	(0.00677)	(0.668)	(0.345)
Owned landholdings	0.0526	−9.39	5.50	–*	−14.7	0.0229
(acres × 10^{-2})	(0.170)	(6.66)	(3.00)		(8.70)	(0.0158)
N	72	164	409	72	164	409
As coefficients = across cohorts $\chi^2(1)$ [*p*]	8.46 [0.004]			154.3 [0.000]		
All control-variable coefficients = 0 across cohorts $\chi^2(10)$ [*p*]	19.0 [0.041]			21.9 [0.016]		
All control-variable coefficients = across cohorts $\chi^2(5)$ [*p*]	6.09 [0.298]			7.07 [0.215]		
Endogeneity test: *Wald* $\chi^2(1)$ [*p*]	0.01 [0.918]	1.27 [0.261]	1.85 [0.174]	0.28 [0.599]	0.10 [0.756]	3.49 [0.0617]

Notes: Specification also includes average ages and numbers of male and female household members and number of males aged 17–59. Standard errors in parentheses clustered at the village level. *Owning land predicts perfectly having a nonfarm business.

arsenic coefficients are the same across the cohorts for both the occupation and business variables ($p=0.004$ and 0.000) while not rejecting the hypothesis that the five jointly significant control variable effects are identical ($p=0.298$ and 0.215).

9. INCOME, HOUSEHOLD PRODUCTION, AND EFFORT EFFECTS OF *AS* RETENTION IN A MULTIPLE-MEMBER HOUSEHOLD

The results for human capital and occupation at the individual level cannot straightforwardly be used to also assess losses in economic productivity and earnings in rural Bangladesh. First, in rural Bangladesh few women participate in the formal labour market, yet they contribute importantly to household production in addition to child-rearing. Second, a large fraction of earning men, as is typical in many low-income countries, are self-employed and jointly produce with male relatives. Thus, it is difficult to directly measure earnings associated with individual capabilities or skills. In addition, in Bangladesh activities associated with consumed water quality are typically carried out by non-earning women.[37]

With information on the exogenous variation in arsenic retention among earners in a household it is possible, however, to identify whether and how arsenic retention affects earnings productivity h_A. This is because the effect of variation in earners' (denoted by m) A_{mj} on total household consumption C_j is $N_{mj}w_j\Omega h_{Am}$, given (4) and where N_{mj} is the number of earners in household

37. In our 2008 data, 98% of household members who spend any time fetching water, gathering fuel (wood or dung), and/or cooking are women, almost 80% of whom are wives of the head. Of the women who participated in these activities, less than 3% also participated in the labor market inclusive of household earning activities such as farming, fishing or non-farm enterprises. Of all women aged 24–59, 94.9% report "housewife" as their primary occupation.

j, and we find no effect of arsenic retention on male labour supply.[38] The major advantage of using the household consumption expenditure approach is that we can obtain estimates of earnings losses using all sample households that contain any men of labour-force age regardless of whether they earn wages or are self-employed. We thus avoid selectivity bias that would afflict estimates of earnings effects using only the subsample of wage earners, who represent less than half of prime-age males in the labour force in Bangladesh.[39]

The household expenditure equation that we estimate is given by

$$\log E_j = \beta_1 A_{mj} + \beta_2 A_{mj} N_{mj} + \beta_3 A_{fj} + \beta_4 A_{fj} N_{fj} + \mathbf{Z}_j \boldsymbol{\beta}_5 + \varepsilon_j, \tag{17}$$

where $A_{m(f)j}$ = log average arsenic retention of prime-age men (women), $N_{m(f)j}$ = number of prime-age men (women), and $\mathbf{Z}_j$ is a vector of control variable such as the total number, age and sex composition of household members. Given the division of labour in Bangladesh households, we would expect that $\beta_3, \beta_4 = 0$, as women do not participate in the labour force, while $\beta_2 = w_j \Omega h_{Am} < 0$, which is the earnings loss for one male earner from an increase in retained arsenic.

Equation (17) cannot be estimated using OLS, as we have seen that levels of arsenic depend on the composition of expenditures so that A_{mj} and A_{fj} will be correlated with the error term. If every household member belonged to a distinct lineage group and we had information on the arsenic levels of their non-co-resident kin, estimation of (17) for a multi-member household using IV would be straightforward extension of the approach we have taken for an individual's measured productivity. However, this is not the case. First, a subset of the members of the household is members of the same lineage. Our lineage-based instrument can be used to predict retained arsenic for all household members within the same lineage—the instrument is the common component of their ability to methylate arsenic. We thus have to assume that the effect of variation in retained arsenic within gender and age groups is the same for all household members of the same lineage. This does not seem to be a strong restriction, as we can divide up household members into categories by age and gender.

What is necessary for identification is that there are some households that only have members within the same lineage and gender/age group and not members of the same lineage in other age/gender groups. For example, if all households had a prime-age male head, his brother and a sister ($N_{mj} = 2$, $N_{fj} = 1$), we could not separately identify all of the β's because we would only have a common prediction for retained arsenic for all of the members in each household. This exclusivity condition, however, is easily met in the data: few prime-age sisters or daughters of heads co-reside. This enables identification of β_1 and β_2. Conversely, when we have lineage instruments for wives, because wives do not co-reside with their father or brothers, and as long as there are some households where wives do not have prime age adult sons, β_3 and β_4 are identified. We do not, of course, restrict the sample to these subsets of households. The restriction is that the effects of retained arsenic on aggregate household expenditures are the same by gender and age-group regardless of household composition.

A second limitation of our lineage-based instruments is that we only have lineage instruments for members of households who were in the prior rounds of the survey. We thus do not have

38. We estimated the effect of retained arsenic on the number of days worked per year for the prime—age males in the year preceding the 2007–8 survey. The estimates (available from the authors by request) indicate that the quantity of work carried out by men with higher levels of retained arsenic is no less than that of workers with lower concentration levels of arsenic.

39. Of course, for identification we use lineage-based instruments that necessitate that some family members leave their origin villages. Given that, as we have shown, almost all daughters leave their origin village to marry, in the context of Bangladesh this is not nearly as strong a restriction as the requirement that a man work for a wage or salary.

lineage instruments for all members of households. For example, in a household containing two married brothers who are of earning age ($N_{mj}=2, N_{fj}=2$), we might have a lineage instrument for the two brothers, because they had sisters in an earlier round who left their household and village to marry, but not their wives, who come from households outside of the original set of surveyed households. For such households we can estimate β_1 and β_2, under the assumption that the effect of retained arsenic on earnings is the same for each brother. We cannot, however, estimate β_3 and β_4, so we need to exclude the wives' arsenic levels from the equation. The absence of lineage instruments for all household members thus requires an additional orthogonality restriction—that there is not assortative mating with respect to methylation genes. The exclusion of spouse arsenic levels will then not impart bias in the estimates of β_1 and β_2 (or β_3 and β_4 if the spouse is male)—the instruments for the brothers' retained arsenic, based on the retained arsenic endowments of their non coresident kin, will be uncorrelated with the wive's retained arsenic.

How plausible is it that there is not marital sorting by the ability to methylate? We expect that marital sorting will be attentive to the arsenic contamination of water sources, to the extent these are identified, so area-specific arsenic contamination is likely to have conditioned marriage sorting in Bangladesh in recent years. But in the absence of strong signals of individual arsenic retention for persons in a given environment, it does not seem likely there will be sorting on the relevant genes. And our estimates suggest that obvious outward signs of retained arsenic—stature and conventionally measured morbidity—are not useful for identifying individual-specific arsenic retention.

We can carry out a test of marital sorting by arsenic methylation ability, making use of the survey information on age at marriage and exploiting again the historical shift in water sources and thus arsenic contamination in consumed water. Those couples who married when arsenic-contaminated water were not a health problem, prior to the 1980's, clearly did not sort on propensities to methylate arsenic. If such sorting did occur, it would have been after the problem was well known. We would then expect that the current relationship between the retained arsenic of husbands and wives would be stronger among couples who married in recent years compared with couples who married before the 1980's. The first column of Table 12 reports fixed-effects village estimates from a regression of the husband's log level of retained arsenic on that of his wife from a combined sample of couples who either married before 1981 or after 1990. Not surprisingly, given the couples likely consume and cook from a common water source and consume similar food, the coefficient is large and statistically significant. However, when we add an interaction term allowing the relationship to be different for marriages before 1981 compared with marriages after 1990, as reported in the second column of the table, we see that the association in arsenic levels within the couples has not changed across the marriage cohorts defined by the presence of arsenic contamination in tubewell water at the time of marriage.

TABLE 12
Within-village relationship between husbands and wives log As, by period when married: all marriages occurring before 1981 and after 1990

Variable	(1)	(2)
Log husband's *As*	0.407	0.402
	(0.0710)	(0.0668)
Log Husband's *As* × married before 1981	–	0.0149
		(0.0466)
Married before 1981	–	−0.00716
		(0.358)
N	1,114	1,114

Notes: Standard errors in parentheses clustered at the village level. Village fixed effects included in the specification. Pre-1981 correlation = 0.840; post-1990 correlation = 0.776.

TABLE 13
Household characteristics

Variable	Mean
Total annual household expenditures (*Tk*)	54,290
	(45,015)
Cooking water source not a well	0.233
	(0.432)
Value of landholdings ($Tk \times 10^{-4}$)	37.2
	(78.4)
Number of males	1.72
	(1.10)
Number of females	1.52
	(0.836)
Number of males 18-59	0.672
	(0.755)
Number of females 18-59	0.692
	(0.739)
Average age of household males	17.8
	(6.09)
Average age of household females	15.6
	(7.82)
N	1,101

Notes: Standard deviation in parentheses.

9.1. *Arsenic retention and male earnings*

We estimate (17) for households that have at least one prime-age adult, aged 18–59, of either gender. There are 1,101 households meeting this criterion. Of these, 64% meet the exclusivity criterion and contribute to identification of the β's—there are men or women in the relevant age group with different lineages.[40] Table 13 presents descriptive statistics from the sample of 1,101 households for the set of variables used in the specification. Total household expenditures are the sum of household expenditures on food in the month prior to the survey (including the value of own-produced food valued at market prices) multiplied by 12 plus total non-food expenditures for the year, based on detailed questions for 149 foods and 61 non-food items, including durable goods, school fees, housing costs.

The first column of Table 14 presents the OLS estimates of the expenditure equation (17) and the second column the LIML estimates. The (marginally) statistically preferred LIML estimates conform to the patterns implied by the division of labour in Bangladesh households. The test statistics indicate that only the retained arsenic of prime age males matters for total household expenditure—the β_1 and β_2 coefficient are jointly significant at 0.02 level, while the coefficients β_1 and β_2 associated with prime-age women are not statistically significantly different from zero. The β_2 coefficient is negative, consistent with h_A being negative and in accord with the findings with respect to cognitive and physical performance. Given that our finding that time worked is insensitive to changes in retained arsenic, the β_2 point estimate, which is estimated precisely, indicates that reducing arsenic levels to those in the U.S. would increase male market productivity (annual earnings) in rural Bangladesh by 9%. For a household with two male earners, the household expenditure increase would be double that, to 18%.[41]

40. Of these, 236 households have both prime-age men and women of with different lineages; 92 contain only prime-age women and 131 only prime-age men.

41. 74% of households have only one prime-age male. Only 9% of households have more than two men in this age group. We tested and could not reject the multiplicative functional form imposed in (16) by estimating a more general specification allowing the β_2 coefficients to differ by number of males.

TABLE 14
Estimates of the effect of log As contamination within the household on log total annual household expenditures, by estimation method

Estimation method	OLS	LIML
Mean log *As* of men aged 18–59 (m*As*)	−0.00100	0.00113
	(0.00600)	(0.00664)
Mean log *As* of men aged 18–59 × number of men aged 18–59 (m*As* × mp)	−0.0239	−0.0941
	(0.0139)	(0.0355)
Mean log *As* of women aged 18–59 (f*As*)	0.00333	0.00109
	(0.00771)	(0.00779)
Mean log *As* of women aged 18–59 × number of women aged 18–59 (f*As* × fp)	−0.00689	−0.00108
	(0.0133)	(0.0216)
Number of men aged 18–59 (mp)	0.209	0.673
	(0.0939)	(0.243)
Number of women aged 18–59 (fp)	0.0305	−0.00393
	(0.0905)	(0.131)
Value of owned landholdings ($\times 10^{-7}$)	1.89	1.91
	(0.196)	(0.196)
ρ m*As* and expenditure residuals	–	0.222
		(0.152)
ρ (m*As* × mp) and expenditure residuals	–	0.262
		(0.161)
ρ f*As* and expenditure residuals	–	0.173
		(0.143)
ρ (f*As* × fp) and expenditure residuals	–	0.169
		(0.147)
N	1,101	1,101
Test: error correlations = 0 (endogeneity of *As*) $\chi^2(4)$ [*p*]	–	7.15 [0.128]
Test m*As* = 0, m*As* × mp = 0 $\chi^2(2)$ [*p*]	–	7.46 [0.024]
Test f*As* = 0, f*As* × fp = 0 $\chi^2(2)$ [*p*]	–	0.02 [0.990]
Test f*As* × fp < m*As* × mp $\chi^2(1)$ [*p*]	–	4.98 [0.013]

Notes: Specification also includes average ages and numbers of male and female household members. Standard errors in parentheses clustered at the village level.

9.2. *Arsenic and household productivity*

The estimate of β_2 indicates that men with higher retained arsenic have significantly lower market productivity. Because women do not earn, the estimates of (16) are uninformative about productivity effects for women in household production and thus the estimate of β_2 may not fully account for the harm arsenic does to household welfare, which also depends importantly on home-produced goods. As noted, one important home-produced good is clean water, and this task is almost exclusively taken on by women. In this section, we estimate the determinants of the household choice of whether or not to choose a non-tubewell source of cooking water using the same sample of households we used to obtain the estimates of the determinants of household expenditures. The equation we estimate is

$$W_j = \gamma_1 A_{mj} + \gamma_2 A_{mj} N_{mj} + \gamma_3 A_{fj} + \gamma_4 A_{fj} N_{fj} + \mathbf{Z}_j \gamma_5 + \varsigma_j, \tag{18}$$

where W_j takes on the value of 1 if the household does not use tubewell water for cooking.

Recall that non-tubewell sources of water are more costly, requiring more time than tubewell sources for water consumption, but that use of such sources significantly reduce retained arsenic (Table 3). Given these findings, it follows that if higher arsenic retention among women is associated with increased use of non-tubewell sources of water this would imply that retained arsenic among women reduced productivity in producing home goods; *i.e.*, $\gamma_4 > 0$, given that only women fetch and treat water.

TABLE 15
Estimates of the effect of log As contamination within the household on whether the household chooses non tubewell water, by estimation method

	Probit	LIML Probit
Mean Log *As* of men aged 18−59 (m*As*)	−0.0230	0.0030
	(0.81)	(0.11)
Mean log *As* of men aged 18−59 × number of men aged 18−59 (m*As* × mp)	0.136	0.399
	(1.30)	(4.87)
Mean log *As* of women aged 18−59 (f*As*)	0.0777	0.0883
	(2.99)	(3.24)
Mean log *As* of women aged 18−59 × number of women aged 18−59 (f*As* × fp)	0.238	0.362
	(2.80)	(4.50)
Number of men aged 18−59 (mp)	−0.987	−2.73
	(1.51)	(5.44)
Number of women aged 18−59 (fp)	−1.93	−2.68
	(3.22)	(5.18)
Value of owned landholdings ($\times 10^{-7}$)	−0.319	−0.12
	(0.50)	(1.81)
ρ m*As* and cooking water residuals	–	−0.654
		(5.63)
ρ (m*As* × mp) and cooking water residuals	–	−0.713
		(6.38)
ρ f*As* and cooking water residuals	–	−0.634
		(5.31)
ρ (f*As* × fp) and cooking water residuals	–	−0.679
		(5.85)
N	1,349	1,101
Test: error correlations = 0 (endogeneity of *As*) $\chi^2(4)$ [*p*]	–	16.9 [0.002]
Test: m*As* = 0, m*As* × mp = 0 $\chi^2(2)$ [*p*]	–	34.8 [0.000]
Test: f*As* = 0, f*As* × fp = 0 $\chi^2(2)$ [*p*]	–	52.1 [0.000]
Test: f*As* × fp < m*As* × mp $\chi^2(1)$ [*p*]	–	0.08 [0.389]

Notes: Specification also includes average ages and numbers of male and female household members. Absolute values of *t*-ratios in parentheses clustered at the village level.

Because, as we have found, use of non-tubewell water reduces retained arsenic, the estimates of the $\gamma's$ in equation (18) are likely to be negatively biased. Comparison of the OLS and LIML estimates in Table 15 confirm this. The LIML estimates, which make use of the lineage instruments for the estimation of household consumption expenditures, indicate that both γ_2 and γ_4 are positive and statistically significant. The LIML point estimates for γ_2 and γ_4 are three times and 1.5 times larger, respectively, than their OLS counterparts, with the OLS γ_2 estimate is not statistically significant. And indeed the correlations of each of the retained arsenic variables are significantly negatively correlated with the residuals ς_j.

The LIML γ_4 estimate indicates that arsenic contamination significantly reduces productivity in household-goods production. However, the estimate also implies that reductions in arsenic in the source of water, because they would decrease water purification effort, would increase household overall income or consumption by less than the 9%. Thus 9% is an upper bound estimate for the household income gain from the elimination of arsenic in the water sources used by rural households in Bangladesh.

10. CONCLUSION

In this article, we have used recent evidence from the molecular genetics literature on the genetic basis of arsenic metabolism and unique information on family links among respondents living in different environments from a large panel survey to uncover some of the hidden costs of arsenic poisoning in Bangladesh. Based on toenail clipping biomarkers, we found that the levels of

retained arsenic in the rural Bangladesh population are nearly 20 times those measured in subjects residing in the U.S., vary considerably across individuals but are no more elevated in high- than in low–wealth sub-populations. Using these data and information on individual consumption, we implemented our identification methodology by first obtaining estimates of the causal effects of the consumption of seven food groups, choice of water source and smoking on arsenic retention. These estimates show that diet matters for arsenic retention, with the consumption of grains, the staple of the Bangladesh diet, significantly increasing, but tubers, in accord with the epidemiology literature, reducing measured arsenic concentrations. We also find that using non-tubewell water sources for cooking reduces retained arsenic concentrations by 18%.

We then examined the relationship between retained arsenic and measures of individual cognitive and physical capabilities, schooling attainment, health, occupational choice, entrepreneurship, and income using as instruments measures of arsenic retention net of the influence of diet, water–source choices, and village fixed effects of separated family members. We found that performance on a test assessing cognition was significantly lower the higher are levels of retained arsenic and that the significant negative effects on cognition are manifested in lower schooling attainment especially for young males. Young men with higher concentrations of retained arsenic were also significantly less likely to have a skilled occupation or to become entrepreneurs. We showed that these results for schooling, occupation and entrepreneurship were not in evidence for older cohorts, who were contemporaneously just as impaired by arsenic ingestion as the young. This difference by age cohort is consistent with such outcomes being determined when arsenic was not prevalent in Bangladesh water sources and provides evidence of the internal validity of the residual-based estimation strategy based on genetic pre-dispositions for arsenic methylation. We also could find no relationship between arsenic retention and BMI and conventional morbidity symptoms reported in our survey data, consistent with the productivity effects of arsenic contamination being hidden in a population with relatively high levels of morbidity from other causes.

Using information on household expenditures, we also obtained estimates of the effects of variation in retained arsenic among prime-age males regardless of their status as wage or self-employed workers. The estimates indicated that lowering the amount of retained arsenic among Bangladesh prime-age males to levels observed in uncontaminated countries would increase total household expenditures by 9% for each prime age male. We also found that retained arsenic reduces the productivity of women in home production.

What do our estimates imply for policies that may reduce the economic burden of arsenic-contaminated wells? First, while we have found that diet matters for arsenic retention, the beneficial effects of dietary changes are relatively small—for example, doubling tuber consumption would only reduce retained arsenic by 5%. Second, while we obtained estimates that implied that if everyone switched from tubewells as their source of cooking water, retained arsenic would decline by 18%, that would only represent less than 20% of the gap between average retained arsenic levels in the rural Bangladesh population and that in non-contaminated populations, and would only increase incomes by less than 2%.

The convenient provision of non-contaminated water that would eliminate the problem of arsenic contamination, through a one-time investment in the provision of piped water or simple treatments of contaminated water, is obviously costly in a rural population. Our estimates suggest, however, that the economic benefits are not trivial, even ignoring all of the potential health costs in later life (*e.g.* cancers). The annual benefits include a rise in earnings for every male worker of $54 per year. If the value of time of women is half of that of men, and the loss in productivity is similar, recalling that we found evidence of a significant loss in non-market productivity for women that would imply an additional benefit of $27 per year. Added to this would be a reduction in women's time spent fetching water, which our data suggest is on average 20 min per day. Valued

at half of the male wage, the freeing up of women's time from having convenient, clean water available would add an additional benefit of $13 per year. The present discounted value of the per-household gain of $94 over twenty years ranges from $1,400 to $1,000 for discount rates of from 3% up to 8%. The added consumption through productivity improvements, of course, assumes that there would be no economic growth. As income grows, the hidden cost of not improving clean water availability also grows. And the loss in human capital from the reductions in cognition and human capital investment suggest that growth rates may also be reduced.

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Supplementary Data

Supplementary data are available at *Review of Economic Studies* online. And the replication packages are available https://dx.doi.org/10.5281/zenodo.4275954.

Appendix A

A. Estimates from genomic data

In this appendix, we report results from using genomic data to test directly whether there is a genetic link between genes reliably associated in the genetics literature with both cognitive ability and strength and those demonstrated to be associated with arsenic methylation. The basic genetic variations examined are single nucleotide polymorphisms (SNPs), which are DNA sequence variations that occur when a single nucleotide (A (adenine), C (cytosine), T (thymine), or G (guanine)) in the genome sequence is altered. For example, a SNP might change the DNA sequence AAGCCTA to AAGCTTA. In this case there are two alleles: C and T. Almost all common SNPs have only two alleles. For a variation to be considered a SNP, it must occur in at least 1% of the population. SNPs, which make up about 90% of all human genetic variation, occurs every 100 to 300 bases along the 3-billion-base human genome.[42] For a pair of SNPs, the combinations of alleles define haplotypes.

Two SNPs are said to be in linkage disequilibrium (LD) when alleles at two or more loci (places on the DNA sequence, such as a SNP) appear together more often than would be expected by chance. LD in humans primarily manifests itself in correlation between pairs of SNPs on the same chromosome and typically extends only for relatively short distances, on the order of tens or hundreds of kilo base pairs (kbs). LD between two SNPs can be quantified as the correlation between alleles across population chromosomes.

One standard measure of this correlation is the square of the correlation coefficient, which may be expressed as functions of the allele frequencies of the two SNPs. Consider the haplotypes for two SNPs 1 and 2 with two alleles each. Denote a variable X_A to be 1 if the allele for the first SNP is A and 0 if the allele is a, and a variable X_B to be 1 if the allele at the second locus is B and 0 if the allele is b. A haplotype is the pair defined by the realizations (X_A,X_B). The linkage disequilibrium coefficient D_{AB} is

$$D_{AB} = P(AB) - P(A)P(B), \tag{A.1}$$

where P(A) and P(B) are the frequencies of A and B, respectively, and P(AB) is the frequency of haplotype AB. The linkage disequilibrium correlation coefficient between X_A and X_B variables is:

$$r_{AB} = D_{AB}/P_A(1-P_A)P_B(1-P_B). \tag{A.2}$$

Shifman *et al.* (2003) have examined the relationship between r-squared and base-pair distance across the human genome. Mean r-squareds are close to 0.1 for SNPs even 160 kilo base pairs (kbp) (out of 300 billion base pairs) away and fall to near zero at a distance of 500 kbp.[43]

42. Two of every three SNPs involve the replacement of cytosine (C) with thymine (T). Over 50 million SNPs are listed in the dbSNP repository (http://www.ncbi.nlm.nih.gov/projects/SNP/).

43. Linkage disequilibrium is gradually broken down by recombination and gene-conversion. Recombination is the crossing-over of chromosomes during the process of sexual reproduction in which DNA is exchanged between a pair of

Appendix

TABLE A1a
SNPs related to arsenic methylation

SNP	Gene	Chromosome	Gene Function	Relation to other health conditions
rs11191439 rs7085104	AS3MT	10	Arsenite methyltransferase, a critical enzyme for arsenite biotransformation, is encoded by the AS3MT gene	none
rs1801133 rs1801131	MTHFR (methylenetetrahydrofolate reductase)	1	Provides instructions for making the enzyme methylenetetrahydrofolate reductase. This enzyme is important for a chemical reaction involving forms of folate (folic acid) which has been linked to both arsenic metabolism and toxicity.	Neural tube defects (NTD), spina bifida, and homocystinuria, all relatively rare inherited disorders.
rs4925 rs11509438	GSTO1	10	Encodes glutathione S-transferase omega-1 enzyme. This enzyme reduces susceptibility to environmental toxins such as arsenic and some drugs.	Mutations linked with an increase in a number of cancers, likely due to an increased susceptibility to environmental toxins and carcinogens.

TABLE A1
Within-sibling regression estimates from the US Framingham sample: educational attainment and height and the presence of the SNP allele (GSTO rs4925 wild type) found to be associated with urinary arsenic excretion in Bangladesh

Variable	Schooling (years)	Height (inches)
Presence of GSTO rs4925 allele	−0.0823	0.0905
	(0.0697)	(0.126)
Intercept	15.1	67.2
	(0.0674)	(0.122)
N	1,878	1,889

Notes: Standard errors in parentheses clustered at the family level. Estimates carried out by Dalton Conley at our request.

As discussed, a number of SNPs have been related to variations in the ability to methylate arsenic both from knowledge of the biochemical processes involved in arsenic methylation, and from associations in the data. Appendix Table A1a describes five SNPs related to arsenic methylation, and the name and metabolic function of the genes on which they are located. A review of the literature suggested a set of SNPs for intelligence (five SNPs), body mass and height (eight SNPs), and muscle development and strength (five SNPs) used in the LD analysis. The Supplementary Appendix briefly describes these 18 SNPs and the criteria we used to select them based on a review of the literature.

chromosomes. Two genes that were previously unlinked, being on separate chromosomes, can become linked because of recombination. Gene–conversion is the non-reciprocal transfer of genetic information that alters the sequence of the recipient DNA. It is one of the ways a gene may be mutated. In rare cases, LD may extend for longer distances, for example, when the effective population size is small or in populations that have undergone recent admixture, neither of which characterize the Bangladeshi population.

TABLE A2
Sample sizes and gender composition, by survey round and selection criteria

	Number of respondents				
Survey round	1981/82	2002/3	2007/8		
Restriction	–	–	–	Age = 8+ Years	Age = 8+ Chosen for *As* assay
Males	2,155	5,087	6,242	5,143	2,169
Females	1,952	4,751	6,002	4,855	2,096
All	4,107	9,838	12,244	9,998	4,265

TABLE A3
Respondent characteristics across instrument and non-instrument sub-samples, by gender

	Men			Women		
Variable Sample	Mean (SD) Non instr.	Mean (SD) Instr.	Difference (SE) Total	Mean (SD) Non instr.	Mean (SD) Instr.	Difference (SE) Total
Ravens score	4.00	4.19	−0.193	3.40	3.33	0.0630
	(2.04)	(2.09)	(0.130)	(1.94)	(1.83)	(0.109)
Pinch test	42.5	43.2	−0.713	31.6	31.5	−0.218
	(6.53)	(25.9)	(1.34)	(5.24)	(5.37)	(1.02)
BMI	19.6	19.5	0.106	19.6	19.8	−0.175
	(2.77)	(2.65)	(0.169)	(3.07)	(3.10)	(0.179)
Illness	0.204	0.189	0.0152	0.296	0.297	−0.0010
(week)	(0.404)	(0.392)	(0.0248)	(0.457)	(0.457)	(0.0264)
Schooling	4.73	5.27	−0.797*	3.92	4.29	−0.373
	(4.38)	(4.40)	(0.275)	(3.79)	(3.96)	(0.225)
Age	35.4	33.8	1.61∗	32.1	33.2	−1.05*
	(11.1)	(10.8)	(0.710)	(11.3)	(11.5)	(0.662)
Land value	46.0	47.4	−1.47	44.5	44.2	0.282
	(90.6)	(88.4)	(5.59)	(87.3)	(86.9)	(5.03)
N	387	741	1,128	486	777	1,261

Notes: *Significant at the 0.05 level. The non-instrument sub-sample include all respondents aged 18-59 for whom we have an estimate of the *As* residual but for whom we do not have a member of that person's lineage residing in another village or there is no other household with the same lineage residing in the same village. The instrument sub-sample of respondents meet both requirements. Both subsamples have no missing values for any of the variables listed in the table.

The data set we use is HapMap Release 22, which uses single nucleotide polymorphisms (SNP) information from HapMap phase II that consists of genotypes for more than 3.1 million single SNPs assayed from 30 lineage trios (father–mother–child) of Utah residents with ancestry from Northern and Western Europe.[44] This sub-population sample of SNPs are considered relevant for South Asian populations because South Asian Indian populations are both geographically and genetically intermediate between European and East Asian populations (González-Neira et al., 2006; Xing et al., 2008).

The r-squareds were estimated by maximum likelihood using the EM algorithm. Appendix Table A1b presents *z*-statistics for pair-wise tests of linkage disequilibrium obtained by computing the r-squared for each of five arsenic SNPs with each of the set of SNPs associated with intelligence, body mass and height, and muscle development and strength. Thus, these are tests of whether genetic variation in the ability to methylate arsenic, as determined by a set of SNPs, is correlated with genetic variation affecting important aspects of cognitive and physical functioning, as determined by a

44. There are three other HapMap populations: Yoruba from Ibadan, Nigeria; Japanese from Tokyo, Japan; and Han Chinese from Beijing, China.

TABLE A4

Village fixed-effects estimates of the first-stage equations for the arsenic food production function: all respondents aged 14–59 with assayed toenails

Variable/consumption item	log grains	log green vegetables	log vegetables	log tubers	log fruits	log meat	log number of cigarettes	Cooking non-well
Age	0.0185	0.0231	0.0343	0.0243	0.0178	0.0305	0.0547	0.00213
	(0.00329)	(0.0175)	(0.0140)	(0.00849)	(0.0116)	(0.0150)	(0.0102)	(0.00170)
Age squared	−0.0242	−0.0296	−0.0446	−0.0268	−0.0243	−0.0433	−.0841	−0.00330
	(0.00479)	(0.0254)	(0.0204)	(0.0123)	(0.0169)	(0.0218)	(0.0148)	(0.00247)
Male	0.155	0.0125	0.218	0.282	0.0672	0.120	−0.199	0.0243
	(0.0345)	(0.183)	(0.146)	(0.0889)	(0.122)	(0.157)	(0.106)	(0.0178)
Male × age	0.00296	−0.000578	0.00160	−0.00175	0.00005	0.00657	0.0389	0.000681
	(0.00101)	(0.00535)	(0.00429)	(0.00260)	(0.00356)	(0.00459)	(0.00312)	(0.000520)
Head's age	−0.107	−0.852	0.330	0.0399	0.0330	−0.0617	−0.00660	−0.188
	(0.055)	(0.293)	(0.235)	(0.142)	(0.195)	(0.25)	(0.171)	(0.0285)
Head's schooling	0.599	−1.03	−0.322	−0.926	5.13(1.49)	3.92(1.92)	4.33(1.30)	0.0194
	(0.421)	(0.2.23)	((1.79)	(1.08)				(0.217)
Value of landholdings	0.0689	−1.00	−0.832	1.02(0.500)	−0.540	3.88(0.885)	0.0868	0.159
($\times 10^{-7}$)	(0.194)	(1.03)	(0.826)		(0.686)		(0.601)	(0.100)
Own schooling	0.000444	0.0129	0.0110	0.0256	0.0155	0.0130	−0.0416	−0.00108
	(0.00249)	(0.0131)	(0.0105)	(0.00641)	(0.00878)	(0.0113)	(0.00770)	(0.00128)
N	3,036	3,036	3,036	3,036	3,036	3,036	3,036	3,036
R^2-within	0.572	0.458	0.573	0.534	0.562	0.501	0.513	0.691
F (541, 1884) excluded variables [*p*]	3.52 [0.000]	2.94 [0.000]	4.60 [0.000]	3.77 [0.000]	4.46 [0.000]	3.94 [0.000]	1.12 [0.053]	7.74 [0.000]

Notes: Standard errors in parentheses. All specifications also include the set of village dummy variables interacted with the head's age and schooling.

TABLE A5
IV Estimates of the effect of log As on cognitive performance: Raven's cpm score, by lineage gender for female respondents aged 18–59

Variable/lineage type	Only females in lineage	Only males in lineage
Log *As*	0.379	−0.268
	(0.243)	(0.0919)
Land value ($\times 10^{-3}$)	3.37	2.65
	(0.959)	(0.975)
N	709	514
Weak identification test: *Cragg–Donald Wald F*	17.05	68.8
F-test of excluded instruments [*p*]	3.70 [0.027]	45.9 [0.000]

Notes: Specification also includes age and age squared of the respondent. Standard errors in parentheses clustered at the village and lineage level.

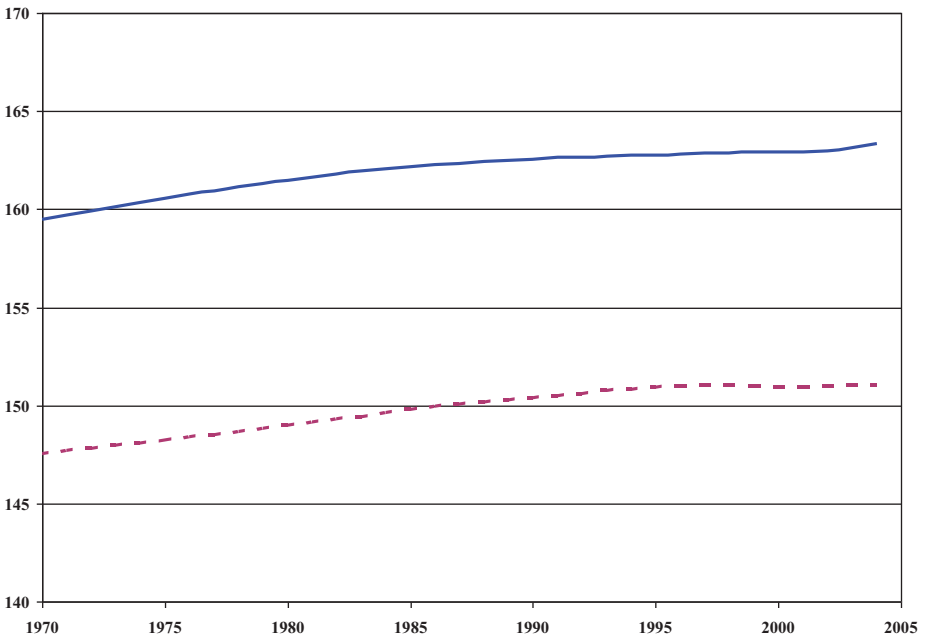

FIGURE A1
Height (cm) by year attained age 22 and gender, 1970–2004 for respondents aged 22–59 in 2007–8 (lowess-smoothed)

different set of SNPs.[45] The last column of Appendix Table A1b presents critical-rejection *p*-values using the Holm–Sidak Bonferroni-type adjustment for multiple comparisons. The *p*-values are 0.54, 0.23, and 0.80 for intelligence, body mass and height, and muscle development and physical strength, respectively. For the full set of SNPs, the *p*-value is 0.49.

45. The chromosome and base–pair locations of all the SNPs are presented in Appendix Table A1c. The only SNPs that share a chromosome with any of the arsenic SNPs are rs821616 (intelligence) and rs211683 (body mass). Both are located on chromosome 1 as are two of the arsenic SNPsS (rs1801133 and rs1801131 on the MTHFR gene), but both are more than 500 kbp away. The r-squareds that we estimate for these sets of SNPs are consistent with the location data.

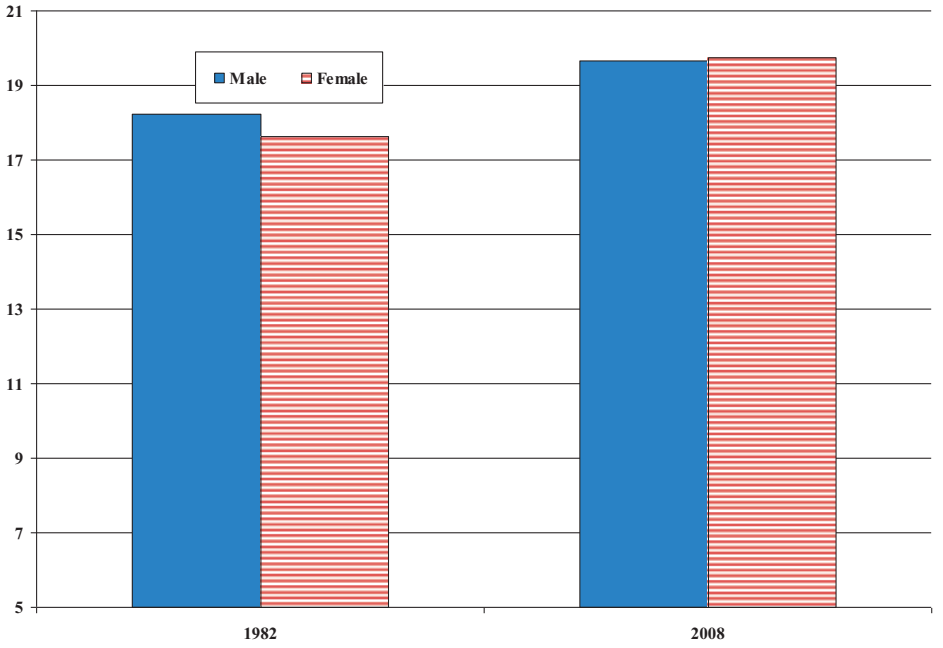

FIGURE A2
BMI in 1981–2 and 2007–8, by gender

Appendix B

A. Analytical methods for determination of As in toenail solutions

Toenail samples were cleaned and digested by Robert Correra using the Environmental Chemistry Facility at Brown University under the direction of David Murray. The nail clippings were prepared for *As* analysis by ICPMS using a cleaning procedure modified from one used at the Trace Element Analysis Laboratory at Dartmouth College (http://www.dartmouth.edu/~toxmetal/assets/pdf/teamethods.pdf). Toenail clippings from an individual, targeting a combined weight between 10 and 50 mg, were placed in a 7 ml polyethylene vial (Fisher #03–337–20) after removing any visible dirt. Two millilitres of Optima grade acetone were added to each sample and vials were placed in a rack in an ultrasonic bath for 20 min. The acetone was removed with a vacuum siphon and 2 ml 1% solution of Triton X-100 was added. Vials were sonicated again for 20 min, 5 ml of deionized (DI) water was added, and the supernatant was removed with a vacuum siphon. Samples were rinsed 4 more times with 5 ml DI water, decanting the water after shaking clippings and water. Rinsed samples were dried in a convection oven at 60° C for 12 h.

The cleaned nail sample was weighed (0.1 mg accuracy), placed in pre-weighted and labelled 15 ml polypropylene centrifuge tube (VWR #21008–103), and 1.0 ml Optima grade Nitric Acid was added. Racks containing batches of 100 tubes were placed in an 80° C water bath for 120 min. After cooling for 30 min, 0.2 ml of optima grade hydrogen peroxide was added, and tubes were placed in the 80° C bath for 30 min. After cooling, 6 ml of DI water was added to each tube and the final weight was recorded. Batches of 100 tubes include 91 toenail samples, 2 samples each of National Research Council Canada reference material DORM–3 and DOLT–4, one set of 0.5, 1, and 2 ppm *As* standards, and 2 blanks.

Solutions were analysed for *As* concentration using a Thermo X–Series II quadrupole inductively coupled plasma mass spectrometer (ICP–MS) equipped with collision cell technology (CCT) at the Graduate School of Oceanography, University of Rhode Island, under the supervision of Professor Kathleen Kelley. The CCT was flushed with a He–H gas mix to break up the 40Ar35Cl interference on 75As. Daily assessment of the efficiency of the collision cell, monitoring mass 75 in an ultra-pure 2% HCl solution, showed that the CCT reduced the interference to $<0.02\%$ 40Ar35Cl/35Cl. In practical terms, this translated to count rates of <1 count per second attributed to Cl in the unknown solutions, effectively removing the interference. All samples were run using identical analysis and data reduction protocols, similar to procedures described by (Kelley et al., 2003). A procedural blank was subtracted from all raw data, and count rates were corrected for instrumental drift using an external drift correcting solution analysed every 5 samples, which was matrix–matched to the unknown samples and spiked with 15 ppb As. Concentrations of As in unknown solutions were determined by calibrating

against four single–element As solution standards spanning a range from 0.5 to 100 ppb. Calibration curves were linear, with $r > 0.9990$ for all analytical runs. Arsenic concentrations in unknown solutions were then corrected for the dilution of each starting sample weight, to yield the concentration of *As* in the raw toenail material. Each unknown solution was analysed twice in every analytical session, and within-session reproducibility was $<10\%$ rsd for these replicate analyses (on average, within 5% rsd). Some samples contained enough material to perform replicate dissolutions of the starting material ($n = 184$), and these replicate dissolutions are in excellent agreement, on average within 15% rsd. Lower precision for replicate dissolutions of the raw material is not surprising, likely resulting from heterogeneities within the toenails, which were dissolved as whole clippings without attempting to homogenize the material in advance.

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