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Inversion of High-Arsenic Soil for Improved Rice Yield in Bangladesh

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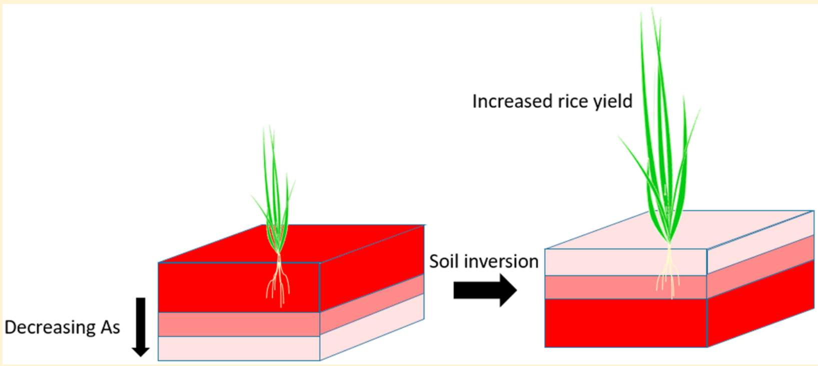
Supporting Information



ABSTRACT: Rice is the primary crop in Bangladesh, and rice yield is diminished due to the buildup of arsenic (As) in soil from irrigation with high-As groundwater. Implementing a soil inversion, where deeper low-As soil is exchanged with the surface high-As soil in contact with rice roots, may mitigate the negative impacts of As on yield. We compared soil As, soil nutrients, and rice yield in control plots with those in adjacent soil inversion plots. We also estimated the quantity of soil As deposited on a yearly basis via irrigation water, to explore the longevity of a soil inversion to reduce surface As. Soil As, organic carbon, nitrogen, and phosphorus concentrations decreased by about 40% in response to the inversion and remained lowered over four seasons of monitoring. Inversion plot yields increased above control plot yields by 15−30% after a one-season lag despite the recovering but still reduced nutrient levels. Farmers have started conducting soil inversions of their own volition, typically close to where irrigation water enters the field. However, the yield gain will be limited to a few decades at most due to deposition of As via well water, unless the field is irrigated with low-As river or pond water.

■ INTRODUCTION

Rice is the primary crop of Bangladesh in terms of production and caloric consumption, comprising 70% of calories consumed.[1,2] Rice is predominantly grown during the boro (dry winter) and aman (monsoon) seasons.[1,3] High volumes of groundwater are required to maintain the flooded conditions under which boro rice is grown, whereas aman rice is primarily rainfed, with occasional supplemental groundwater irrigation.[4]

About half of Bangladesh is affected by naturally elevated arsenic (As) levels in the shallow aquifers (BGS/DPHE, 2001) that irrigation water is drawn from for growing boro rice. When rice is irrigated with this water, the As can build up in rice field soil.[5−10] Among crops, rice is especially impacted by irrigation water As, since it is grown under flooded conditions, resulting in the use of higher volumes of As-contaminated irrigation water and in a chemically reduced soil environment that enhances As mobility. Soil As decreases rice yield, and the buildup of irrigation water As in soil is estimated to reduce boro rice yield by 7−26% across Bangladesh.[9,11,12] The build-up in soil adds to the often already high As content of grains grown in uncontaminated soil, but this is a separate issue not addressed in this particular study.

Various options have been considered to reduce the uptake of soil As by rice and the impacts of soil As on rice yield. These include providing cleaner irrigation water, growing As-resistant rice varieties, and growing rice under conditions that are less conducive to As uptake.[13,14] Even with these methods, rice yields will likely be negatively impacted by the high levels of legacy As contamination in many rice fields. Removal of the highest-As upper 10−15 cm of soil has been suggested to address this problem, since farmers commonly remove soil for

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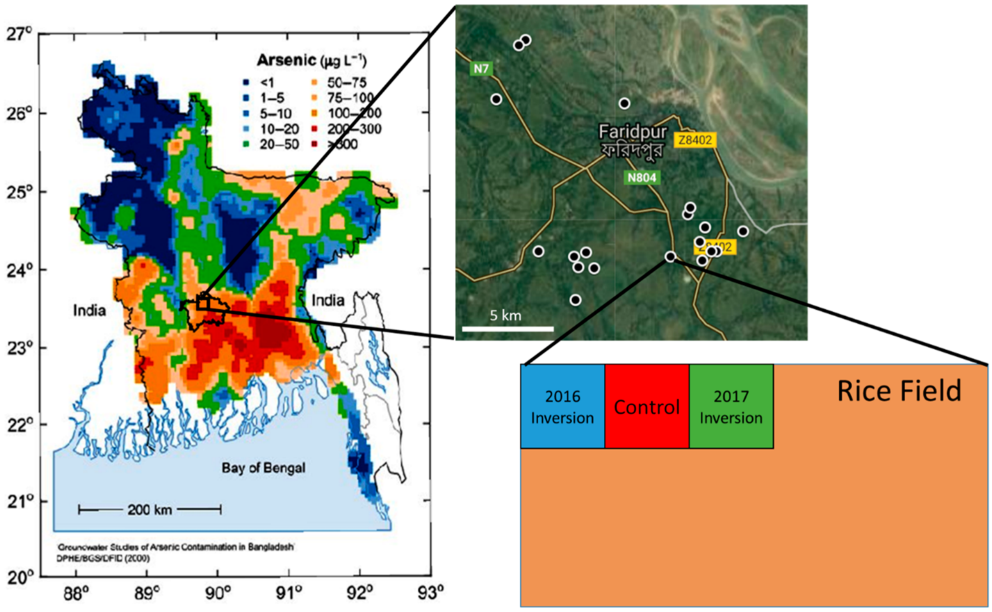

Figure 1. Layout and distribution of study sites in Faridpur, Bangladesh. Heat map of As in groundwater is from BGS and DPHE 2001.[33] Site map made with Google My Maps, Imagery © 2019 TerraMetrics.

Table 1. Irrigation Water Added and As Deposited for 10 Selected Irrigation Well Command Areas

site	year pump installed	pump depth (ft)	as concentration measured by ICP-MS (μg/L)	pump rate (m^3/h)	hours pumped during boro 2017 growing season	paddy area irrigated (m^2)	irrigation water applied (cm)	as added to soil (mg/kg) per year[a]
choradampur	1995	100	199	54.0 ± 0.1	523	52 000	54.4 ± 0.1	0.416 ± 0.001
choradampur 2	2002	120	185	36 ± 1	201	16 640	43.1 ± 1	0.308 ± 0.008
chornosipur 1 and 3	1985	240	150	35.0 ± 0.0	895	37 440	83.7 ± 0	0.484 ± 0.000
doyarampur	1988	205	277	42.6 ± 0.3	570	60 320	40.3 ± 0.3	0.429 ± 0.003
Ikri 1 and 2	1996	250	210	52.4 ± 0.6	830	93 600	46.5 ± 0.6	0.375 ± 0.004
Middle Tambulkhana	1989	370	220	186 ± 8	871	166 400	97.1 ± 4	0.82 ± 0.04
Purbopara	1976	250	162	49 ± 1	822	62 400	64.9 ± 2	0.404 ± 0.01
Sachia	1990	275	208	170 ± 10	747	124 800	101 ± 7	0.81 ± 0.06
West Ikri	1995	195	260	39.3 ± 0.5	596	35 360	66.2 ± 0.9	0.663 ± 0.009
West Sachia	1996	150	101	56 ± 3	923	33 280	156 ± 8	0.61 ± 0.03

[a]Assuming the As is uniformly added to the top 20 cm of soil.

use in brick-making, building houses, and raising infrastructure above monsoon flooding.[13] However, the impacts of soil removal on soil As and rice yield have not been documented.

This study paper follows a prior research study in the same region, where we exchanged soil between high- and low-As areas of farmers' fields and compared those soil exchange plots with adjacent control plots to document the impact of soil As on rice yield.[15] Building on the idea of soil removal to improve rice yield, we conducted a series of soil inversions. Since As concentration in paddy soil decreases with depth, we exchanged the deeper low-As soil with the surface high-As soil, putting the low-As soil in contact with the rice roots. We then compare As concentrations, nutrient concentrations, and rice yields in 5 × 5 m control plots to those in the soil inversion plots. A soil inversion is more versatile than soil removal, since there is no elevation difference between the inversion area and the surrounding paddy that would disrupt irrigation water management. It additionally does not require disposal of As-contaminated soil. To investigate the longevity of the inversion's impact on soil As, we measured the volumes of irrigation water applied based on daily farmer record and measured As concentrations in irrigation water to estimate deposition rates of As in paddy soil.

■ MATERIALS AND METHODS

Experimental Site and Design. The study was conducted in fields irrigated by high-As wells in Faridpur district, Bangladesh (Figure 1). The wells ranged from 17 to 46 years in age and drew water from 25 to 120 m in depth with As concentrations of 100−300 μg/L (Table 1, Supporting Information (SI) Table S1).

Up to two rice crops—boro and aman—are grown at our study sites each year. The boro rice is transplanted, and the aman rice is transplanted or broadcast sown. The predominant rice varieties that farmers grew at our study plots during the 2016, 2017, and 2018 boro seasons were BRRI dhan 28 (BR 28) and BRRI dhan 29 (BR 29). These are also the predominant rice varieties grown across Bangladesh, and were estimated in 2005 to be grown in nearly 60% of the total boro rice cropped area in the country.[16] During the boro seasons, farmers chose to grow other rice varieties in a few study plots, which they reported as BR 50, Banglamoti,

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Basmoti, and hybrid. The predominant rice variety that farmers grew at our study plots during the 2016 and 2017 aman seasons was BRRI dhan 39 (BR 39). During the aman seasons, farmers chose to grow other rice varieties in a few study plots, which they reported as BR 51, Sisumoti, Chini Atop, and Hijol Deegha.

In January 2016 before the fields were transplanted with boro rice, soil inversions were conducted on twenty-one 5 × 5 m plots. To conduct the inversion, soil was excavated in three layers: a top 20 cm layer, followed by two 10 cm layers. The layers were then replaced in the excavated area in reverse order, such that the lowest-As soil was at the top, where the rice plant roots are primarily located.[17,18] Each soil inversion plot was paired with an adjacent 5 × 5 m control plot where no changes were made and the same variety as in the adjacent inversion plot was grown.

Another 20 soil inversions were conducted in January 2017. For the 2017 soil inversions, we conducted two inversions adjacent to each control plot and, at the recommendation of some farmers who had experience supplementing paddy soil after soil removal, we added 2.5 kg of cow manure and 1.2 kg of mustard seed oil cake to one of the two inversion plots at each study site. The amounts were based on discussions with several rice farmers, and were in addition to fertilizer that farmers were already adding uniformly across the rice fields where the study plots were located.

We measured soil As concentrations and nutrient concentrations in the soil inversion and control plots during the 2016−2017 boro and aman seasons. We measured rice yield in the soil inversion and control plots during the 2016−2018 boro seasons and the 2016−2017 aman seasons.

Soil As Measurements. Soil cores of 20 cm depth were collected monthly during the boro 2016 growing season (three total cores per plot). During the aman 2016 growing season, cores were collected monthly from the transplanted plots (three total cores per plot) and during months 1−4 for two of the broadcast sown plots and months 1−3 and 5 for the third plot (four total cores per plot). During the boro 2017 and aman 2017 growing seasons, soil cores were collected monthly for most plots (three total cores per plot) but twice-monthly for the 2016 and 2017 soil inversion and control plots at Aliabad, Ikri, and Middle Tambulkhana.

The 20 cm cores were separated into 5 cm deep subsample increments to provide depth profiles of soil As. The soil subsamples were dried in an oven at 40 °C and homogenized by mortar and pestle for As analysis with XRF. Total soil As concentrations were measured using an Innov-X Delta Premium field X-ray fluorescence (XRF) spectrometer in the manufacturer's "soil" mode for a total counting time of 35−150 s. Soil standards 2709 and 2711 from the National Institute of Standards and Technology (NIST) were analyzed at the beginning and end of each day and periodically during longer sample runs. The measured average and standard deviation for standard 2711 of 108 ± 7 (n = 19) matched the reference value of 105 ± 8 mg/kg. The measured average and standard deviation for standard 2709 of 16.7 ± 1.6 (n = 20) matched the reference value of 17.7 ± 0.8 mg/kg. All soil As concentrations were above the detection limit of the XRF analyzer.

Soil Nutrient Measurements. Three sets of 20 cm deep soil cores were taken from each plot during the boro 2016, aman 2016, boro 2017, and aman 2017 seasons at the same times as the cores for soil As measurement were collected. The cores were dried in an oven at 40 °C and sent to the BRAC soil laboratory in Gazipur, Bangladesh, for measurement of N (total Kjeldahl nitrogen), organic carbon (Walkley-Black method), P (modified Olsen method), K (ammonium acetate extraction), S (calcium hydrogen phosphate extraction), and Zn (diethylenetriaminepentaacetic acid extraction).

Rice Yield Measurements. Rice yields were measured for a 3 × 3 m area in the center of each 5 × 5 m plot. The rice was threshed immediately after harvest, its weight and moisture content were recorded, and yield values were adjusted to 14% moisture content by drying a subsample of the rice. In the 2016−2017 boro and aman seasons, we obtained an estimate of the error on yield by dividing each 3 × 3 m plot along the diagonal and making a separate measurement of the yield for each half of the 3 × 3 plot. In some study plots farmers chose to switch away from rice, to plant no crops, or to abandon their rice during some seasons, resulting in differences in which plots we obtained yield measurements for from season to season. For the 2016 soil inversions, we obtained yield measurements for 19 pairs of inversion and control plots during the boro 2016 season, 16 pairs during the aman 2016 season, 12 pairs during the boro 2017 season, 11 pairs during the aman 2017 season, and 12 pairs during the boro 2018 season. For the 2017 soil inversions, we obtained yield measurements for 20 pairs during the boro 2017 season, 18 pairs during the aman 2017 season, and 18 pairs during the boro 2018 season.

Irrigation Water Measurements. The As content of groundwater pumped by all irrigation wells was first determined with the ITS Econo-Quick kit, which tends to overestimate water As by about a factor of 2.[19] For a subset of 10 wells that irrigate the study sites, well water As concentrations were also measured using inductively coupled plasma mass spectrometry (ICP−MS). Irrigation water was collected in 20 mL polyethylene scintillation vials with a PolySeal-lined cap (Wheaton no. 986706). Samples were acidified to 1% high-purity HCl (Fisher Scientific Optima) at least 1 week before analysis with a Thermo-Finnigan Element2 high-resolution inductively coupled plasma mass spectrometer.[20] This procedure has been shown to ensure redissolution of any arsenic associated with precipitated iron oxides.[21] An in-house consistency standard of artificial groundwater containing 430 μg/L As and reference materials NIST1640a (8.2 ± 0.3 μg/L As) and NIST1643f (58.6 ± 0.5 μg/L As) were included with every run to verify accuracy and precision of the method to within <5% of expected values.

For the same 10 wells, irrigation water flow rate was estimated by timing with a stop watch the number of seconds it took for water from the pump to fill a 120 L container. Two such measurements were made to provide an error estimate on the flow rate. Throughout the boro 2017 season, the manager of each well recorded each day whether the well was used and, if so, the time at which the pump was turned on and turned off. Well managers also reported the total area of rice fields irrigated by each well.

RESULTS

Effect of the Soil Inversion on Soil As Concentrations. Within the upper 20 cm of soil, where the rice plant roots are primarily located, the boro 2016 soil inversions decreased soil As by an average of 12.1 ± 2.3 mg/kg (40%) compared to the adjacent control plots during the growing season immediately after the inversion (Figure 2). Similarly, the boro 2017 soil f2

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inversions decreased soil As by an average of 18.0 ± 3.0 mg/kg (39%) compared to the control plots (Figure 2).

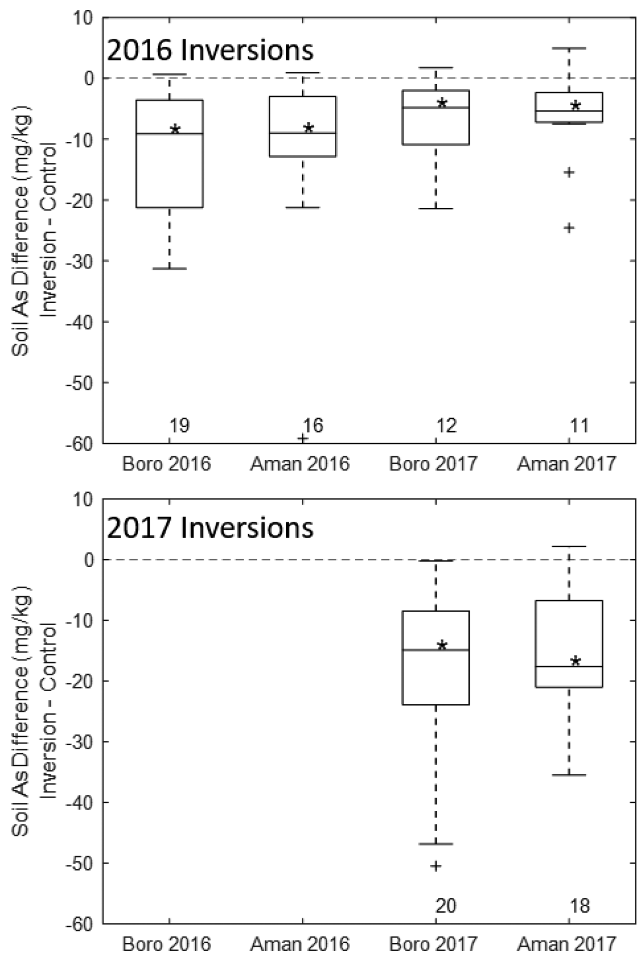

Figure 2. Soil As differences between soil inversion and control plots. Differences in soil As between inversion and adjacent control plots over the top 20 cm as measured by XRF on samples collected monthly during the growing season for soil inversions conducted in 2016 (top) and 2017 (bottom). Data are shown for all plots where yield was measured in each growing season, and the numbers below each box indicate the number of pairs of plots that box represents. The tops and bottoms of each box are the 25th and 75th percentiles. The line in the middle of the box shows the sample median. Outliers are values that are more than 1.5 times the interquartile range beyond the edge of the box. Asterisks denote that the mean significantly differs from zero at $p = 0.05$ according to a one-sample t test.

The effect of the soil inversion on soil As remained significant for plots observed during the aman 2016, boro 2017, and aman 2017 growing seasons following the 2016 inversions (Figure 2). However, the magnitude of the difference decreased over time following the inversions. The soil As difference between inversion and control plots for the boro 2016 inversions decreased from 12.1 ± 2.3 mg/kg during the boro 2016 growing season to 6.4 ± 2.1 mg/kg during the aman 2017 growing season (Figure 2). A similar trend is observed in the data for the subset of 10 plots where As was measured in all growing seasons (SI Figure S1). Soil As did not differ between the 2017 inversions with added cow manure and mustard seed oil cake and the inversions without these soil amendments. The data were therefore combined in the box plot.

Based on the depth profiles, the soil As decrease was concentrated in the top 15 cm of inverted soil, with similar soil As concentrations observed between inversion and control plots over the 15−20 cm depth interval at the base of the upper layer of inverted soil (Figure 3).

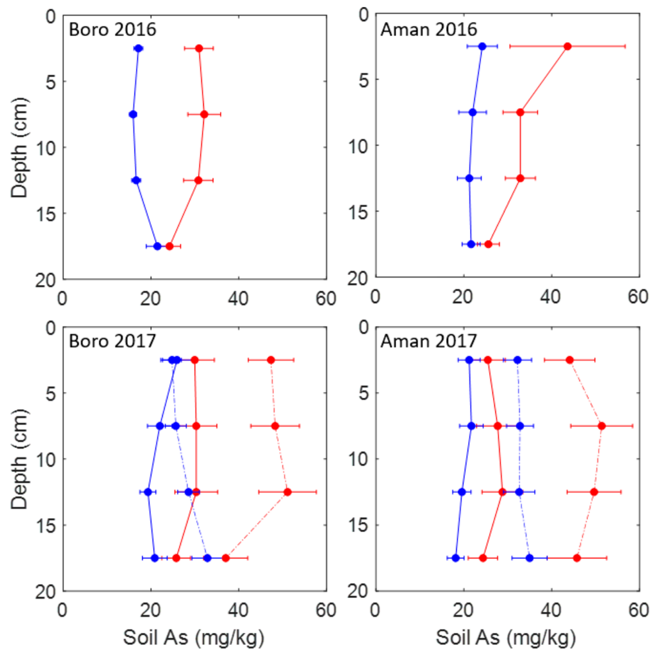

Figure 3. Soil As depth profiles in soil inversion and control plots. Arsenic profiles measured over the top 20 cm of soil for the inversion (blue) and control (red) plots for 2016 inversions (solid lines) and 2017 inversions (dashed lines) during boro 2016, aman 2016, boro 2017, and aman 2017. These figures represent the average across study plots and across monthly samples taken three to six times from each plot during the growing season. Error bars represent standard deviation divided by the square root of the number of samples.

Effect of the Soil Inversion on Soil Nutrient Concentrations. The inversions also considerably decreased the concentrations of some nutrients in the upper 20 cm of soil. The boro 2016 soil inversions decreased organic carbon, nitrogen, and phosphorus to about 60% of their concentrations in the adjacent control plots (Figure 4). Organic carbon decreased from an average of 1.21% to 0.69%, nitrogen from 0.10% to 0.06%, and phosphorus from 64.0 μg/g to 40.1 μg/g. The inversion also produced a small but significant 8% decline in zinc. The boro 2017 inversion similarly decreased the concentrations of these nutrients in the topsoil (Figure 4). The inversions did not significantly affect soil potassium or sulfur concentrations.

Similar to soil As, soil nutrient concentrations in the inversion plots began to rebound at later times. By the aman 2017 growing season, organic carbon, nitrogen, and phosphorus in the 2016 inversion plots had recovered to about 70% of their original concentrations (Figure 4). No difference in soil nutrients was observed between the 2017 inversions with added cow manure and mustard seed oil cake and the inversions without these soil amendments, so the data were combined in the box plot. Back-of-the-envelope calculations based on reported concentrations of N and P in manure and mustard seed oil cake[22,23] suggest that the amendments would at most increase P by 4 μg/g and N by

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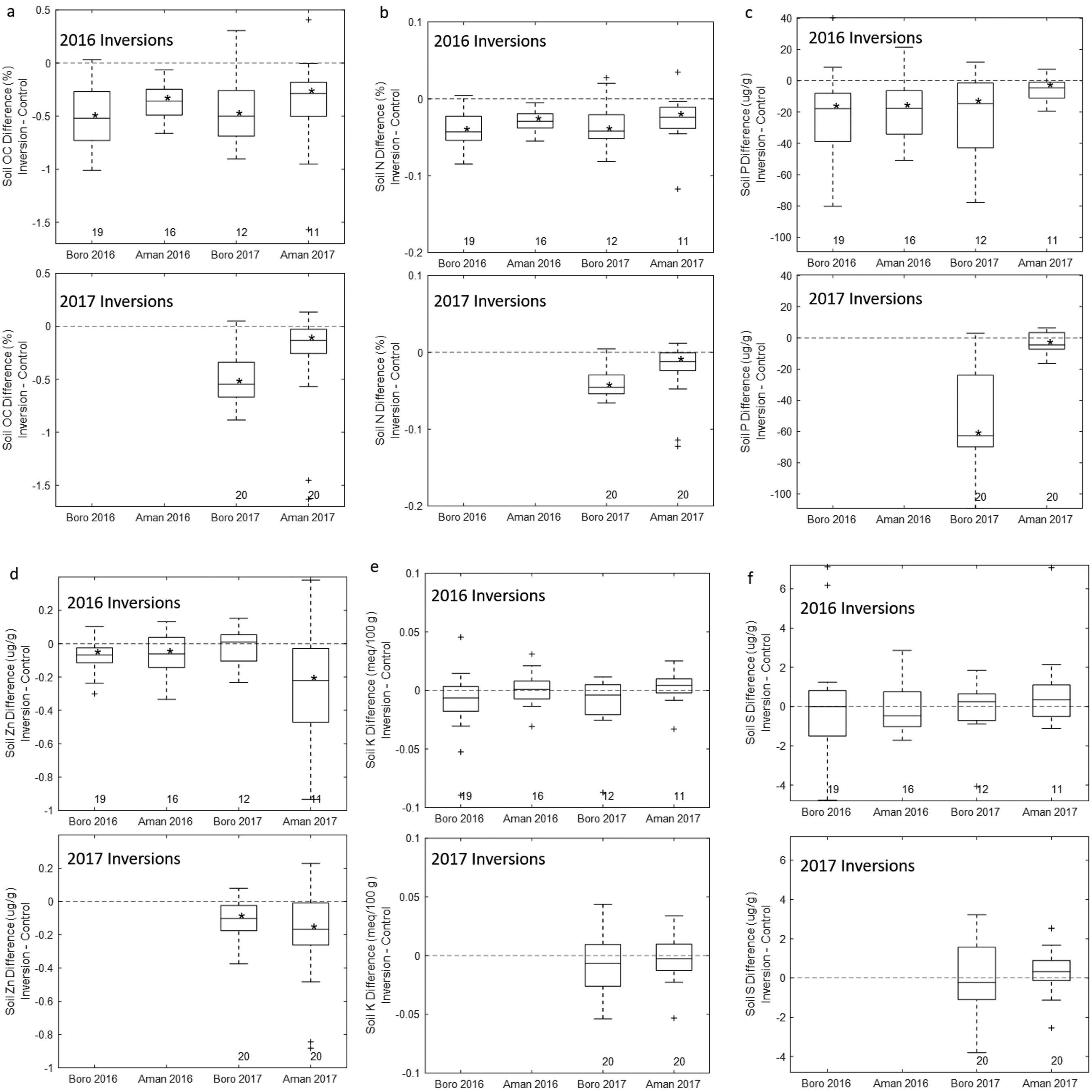

Figure 4. Soil nutrient differences between soil inversion and control plots. Differences in organic carbon, nitrogen, phosphorus, zinc, potassium, and sulfur between inversion and adjacent control plots over the top 20 cm as measured on samples collected monthly during the growing season for soil inversions conducted in 2016 (top) and 2017 (bottom). Data are shown for all plots where yield was measured in each growing season, and the numbers below each box indicate the number of pairs of plots that box represents. The tops and bottoms of each box are the 25th and 75th percentiles. The line in the middle of the box shows the sample median. Outliers are values that are more than 1.5 times the interquartile range beyond the edge of the box. Asterisks denote that the mean significantly differs from zero at $p = 0.05$ according to a one-sample t test.

0.002%, differences that would not be large enough to detect, even if the nutrients had not been taken up by the rice plants.

Effect of the Soil Inversion on Rice Yield. The 2016 and 2017 soil inversions improved rice yield with a one-season lag between inversion implementation and impact on yield (Figure 5). At the boro 2016 harvest, inversion plot yields ranged widely and were statistically indistinguishable from control plot yields, but at the aman 2016 harvest, the rice yield in the inversion plots was less variable and greater by 0.70 ± 0.15 t/ha (28% ± 6%) compared to the adjacent control plots. Yields in the inversion plots remained significantly higher (by 15–20%) than those in the control plots at the boro 2017, aman 2017, and boro 2018 harvests. Similarly, at the boro 2017 harvest, the yields in the newly implemented 2017 inversion plots ranged widely and were indistinguishable from those in the control plots. At the aman 2017 harvest, inversion plot yields were higher by 0.47 ± 0.08 t/ha (18 ± 3%) and at the boro 2018 harvest inversion plot yields were higher by 1.10 ± 0.24 (26 ± 6%) than those in the control plots. Yield did not differ between the 2017 inversions with added cow manure

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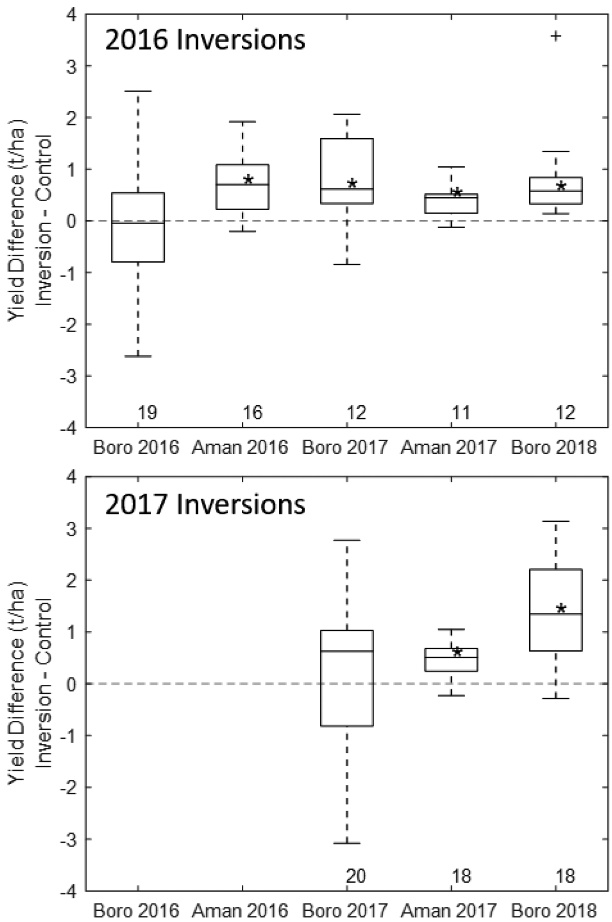

Figure 5. Yield differences between soil inversion and control plots. Differences in yield between inversion and adjacent control plots for soil inversions conducted in 2016 and 2017. Data are shown for all plots where yield was measured in each growing season, and the numbers below each box indicate the number of pairs of plots that box represents. The tops and bottoms of each box are the 25th and 75th percentiles. The line in the middle of the box shows the sample median. Outliers are values that are more than 1.5 times the interquartile range beyond the edge of the box. Asterisks denote that the mean significantly differs from zero at $p = 0.05$ according to a one-sample t test.

and mustard seed oil cake and the inversions without these soil amendments. The data were therefore combined in the box plot.

Multiple Linear Regression on Rice Yield as a Function of Soil As and Nutrients. We expected that lowered soil As concentrations in response to the soil inversion would correlate with higher rice yields, whereas lowered nutrient concentrations would correlate with lower rice yields. However, in a stepwise linear regression of rice yield difference between each inversion plot and its adjacent control plot as a function of soil As difference, nutrient differences, the year the inversion was conducted, and the growing season, no variable was a significant predictor of the rice yield difference at the p = 0.05 level. Furthermore, there were no visually identifiable relationships between rice yield and soil As, organic carbon, nitrogen, or phosphorus (SI Figure S2) or between the differences (inversion−control) for these parameters (Figure 6). Thus the differences in As and soil nutrients that we measured were unable to explain the one season lag followed by improvement in rice yield resulting from the soil inversion.

Irrigation Water Addition and Soil As Deposition. The amount of irrigation water added to rice field soil during the boro 2017 growing season at the monitored irrigation wells ranged from 0.4 to 1.6 m, with an average of 0.8 ± 0.1 m (Table 1). This estimate is close to the values of 0.8−1.5 m per season estimated with limited reference to data in Bhuiyan,[24] close to the 1 m per year commonly cited without reference to a primary source,[25,26] and at low end of the range measured for three unsealed paddy fields where water levels were monitored with pressure transducers.[27]

From the volume of irrigation water applied and the water As concentration, rates of As deposition can be estimated. Assuming a 1.3 kg/dm^3 soil density, even distribution of As across all rice fields irrigated by a well, and deposition of all irrigation water As within the top 20 cm of soil, an estimated 0.3−0.8 mg/kg As is added during a single growing season to the rice fields irrigated by these 10 wells.

■ DISCUSSION

Impact of the Soil Inversion on Rice Yield. The 2016 and 2017 soil inversions decreased soil As concentrations and, after a one season lag, increased rice yield, but yield differences between inversion and control plots were not correlated with the soil As differences between those pairs of plots. Prior studies conducted on rice in Bangladesh have demonstrated a linear relationship between soil As concentrations and rice yield.[9,11] However, in our prior study in this area, we did not observe a direct correlation between rice yield and soil As, but rather a correlation between soil As and yield *differences* between pairs of plots that had no systematic differences in parameters other than As.[11]

The lack of a directly observed correlation between soil As and rice yield in our prior study indicates that other environmental variables can easily obscure the relationship between rice yield and soil As. In contrast with our prior study, where nutrients did not systematically differ between soil replacement and control plots, in this study we observed differences between soil inversion and control plots with respect to multiple soil nutrients. We did not observe a correlation between nutrient differences and yield differences. However, since we measured nutrients in soil and not in the plant tissue, it is possible that the differences in soil nutrients were not sufficiently indicative of the differences in nutrients available to the rice plants, resulting in the observed lack of correlation.

In addition to differences in the variables we measured, there were likely also differences in variables we did not measure, such as soil structure or microbial community, which could impact rice yield. For example, the farmers reported that the soil in the inversion plots was much softer than the soil in the adjacent control plots and was difficult to plow during the first season after the inversion. These unmeasured variables may have contributed to obscuring the relationship between soil As and yield and to the one-season lag in rice yield improvement following the 2016 and 2017 soil inversions.

Another possible explanation for the lack of correlation between soil As difference and rice yield difference between inversion and control plots is that in addition to directly affecting rice yield, soil As may indirectly affect rice yield through its impacts on other soil characteristics. For example, lowering soil As concentrations may create an environment more conducive to soil pests such as nematodes,[28] which are present in our study area and negatively affect yield. Further

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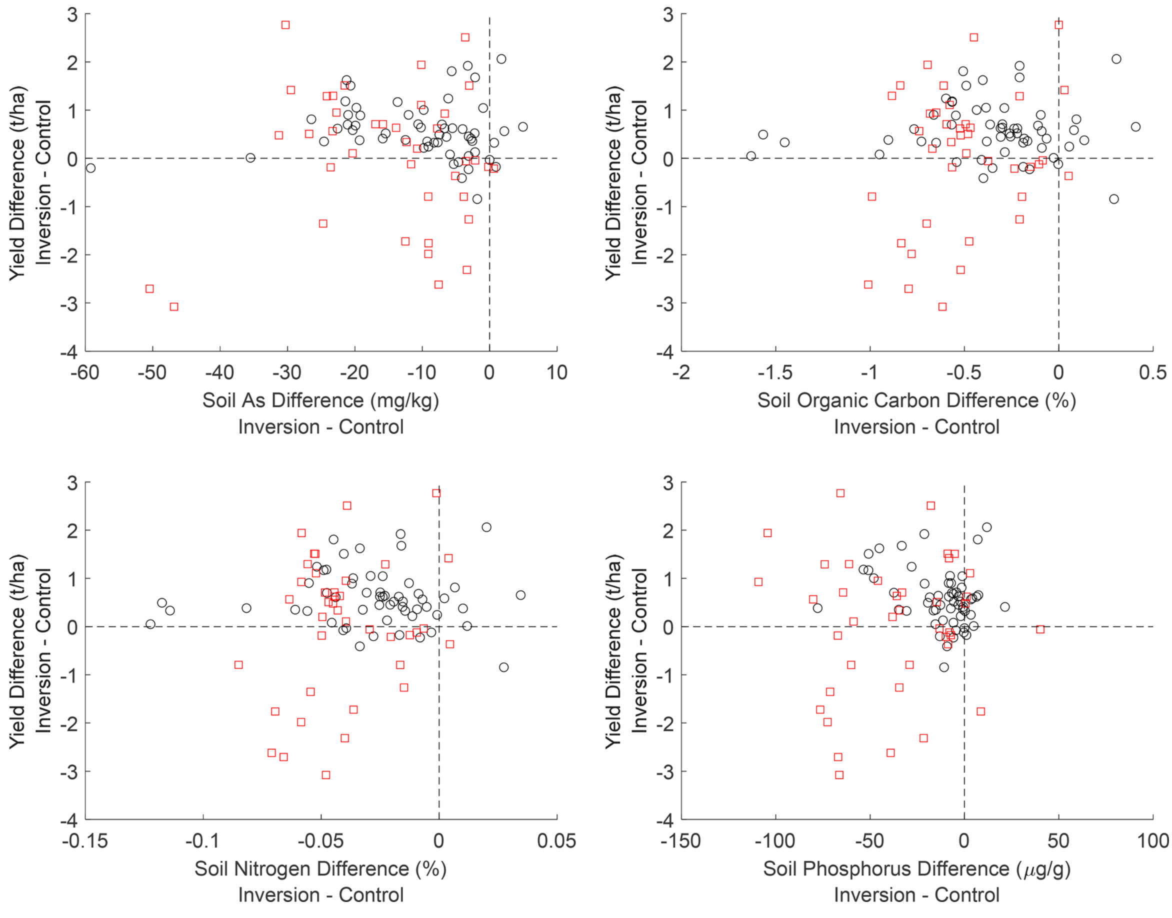

Figure 6. Yield difference between inversion and control plots as a function of soil As and nutrient differences. Yield difference in the first season after the soil inversion (red) and subsequent seasons after the soil inversion (black) as a function of soil As difference (mg/kg), soil organic carbon difference (%), soil nitrogen difference (%), and phosphorus difference (μg/g). Data are shown for all plots where yield was measured in each growing season.

research is needed to better understand the causes and timing of the yield improvement following a soil inversion.

Even though the mechanism for the yield improvement has not been definitively identified, farmers outside of our study cohort have become interested in implementing soil inversions in high-As areas where they are dissatisfied with their rice yield. By May of 2018, 17 farmers had requested help measuring their soil As concentrations as part of deciding whether to conduct a soil inversion, and three farmers chose to implement a soil inversion in a portion of their rice paddy, over areas ranging from 12 to 20 m^2. Farmers and their family members can conduct a soil inversion over areas of this size without hiring outside labor, making a soil inversion an appealing low-cost intervention with the potential to improve rice yield.

Longevity of the Soil Inversion Impact on Soil As. Even if the positive impacts of the soil inversion are related to factors other than soil As, it is valuable to understand the buildup of soil As in the inversion plots over time, since increasing soil As concentrations have negative yield effects. In our study plots over the two years of monitoring after the inversions, the soil As difference between control and inversion plots rapidly diminished. This may be because the soil inversions were conducted over a relatively small 5 × 5 m area, which may permit lateral mixing from surrounding high As soil over time. However, in our prior study conducted on 5 × 5 m plots in rice fields in the area, we did not observe evidence of substantial lateral mixing between plots over two years of monitoring.[11] Another possibility is that, since the high As layer of soil remains present below the low As layer, there may be vertical mixing or diffusion via soil water of buried As from the deeper layer to the layer above.[29] Previous studies have shown that little of the As accumulating in paddy soil contributes to recharge of shallow aquifers because of most of the recharge occurs through the bunds that separate different field.[27] It seems unlikely that burying high As soil somewhat deeper through a soil inversion would alter this situation although it cannot be ruled out. A soil removal, rather than inversion, conducted over a larger area would minimize (in the case of lateral mixing) or eliminate (in the case of vertical mixing or diffusion) these effects.

The buildup of As added to the soil via irrigation water is also likely to impact the longevity of a soil inversion. In contrast with the rebound of soil As in the inversion plots described above, As deposition from irrigation water should affect both inversion and control plots similarly and thus should not affect the As difference between the two. We estimated that 0.3 to 0.8 mg/kg soil As is deposited on average in the top 20 cm of soil around our high-As wells each year. We reached this estimate based on measuring As in irrigation water, since changes of this magnitude are too small to be distinguished based on our soil As measurements (SI Figure S3). Given that the soil inversions decreased As in the top 20 cm by about 12 mg/kg (2016 inversions) and 18 mg/kg (2017 inversions) on average, these As deposition rates suggest that

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boro rice irrigation alone could erase the impacts of a soil inversion or removal as quickly as one to two decades or, in areas with a greater lowering of As from soil removal or lower rates of soil As buildup, as slowly five to six decades. Unlike removing soil, a soil inversion can be conducted only once at a given location because of the presence of contaminated soil at depth.

The estimate of the duration of the impact of an inversion does not take into account the varying spatial distribution of As or loss of As to monsoon flooding.[30] Incorporating the varying spatial distribution of As shortens the time estimate for the rebound, since soil As removal would most likely be targeted at the most contaminated rice fields, and these are often the fields closest to an irrigation well where soil As builds up the fastest.[9,31] Thus, localized rates of soil As buildup in intervention areas are likely to be faster than rates of soil As buildup averaged over the full irrigated area.

Incorporating loss of As to monsoon flooding lengthens the time estimate, since 13−46% of soil As may be lost during monsoon flooding rather than remaining in the paddy soil.[10,32] Collectively, then, these two factors partially balance each other out, and the exact rate of As buildup will depend on the specifics of each intervention. However, the fact that soil As does eventually build up again suggests that interventions to lower soil As are best used in conjunction with interventions to reduce the future buildup of soil As. The growing number of soil inversion conducted by farmers of their own volition will not markedly affect the yield from an entire field but, combined with soil As measurements, the experience might convince a farmer to look for an alternative source of low-As irrigation water such as a nearby stream or pond.

■ ASSOCIATED CONTENT

Supporting Information

The Supporting Information is available free of charge on the ACS Publications website at DOI: 10.1021/acs.est.8b06064.

Table with data on the wells irrigating the study sites. Figures with soil As and yield differences for the subset of 10 plots where soil As and yield were measured in all four growing seasons, yield as a function of soil As and nutrients for all study plots, and soil As for the subset of 11 plots where soil As was measured in all four growing seasons (PDF)

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