Supporting Information

Sealing Rice Field Boundaries in Bangladesh: A Pilot Study Demonstrating Reductions in Water Use, Arsenic Loading to Field Soils, and Methane Emissions from Irrigation Water

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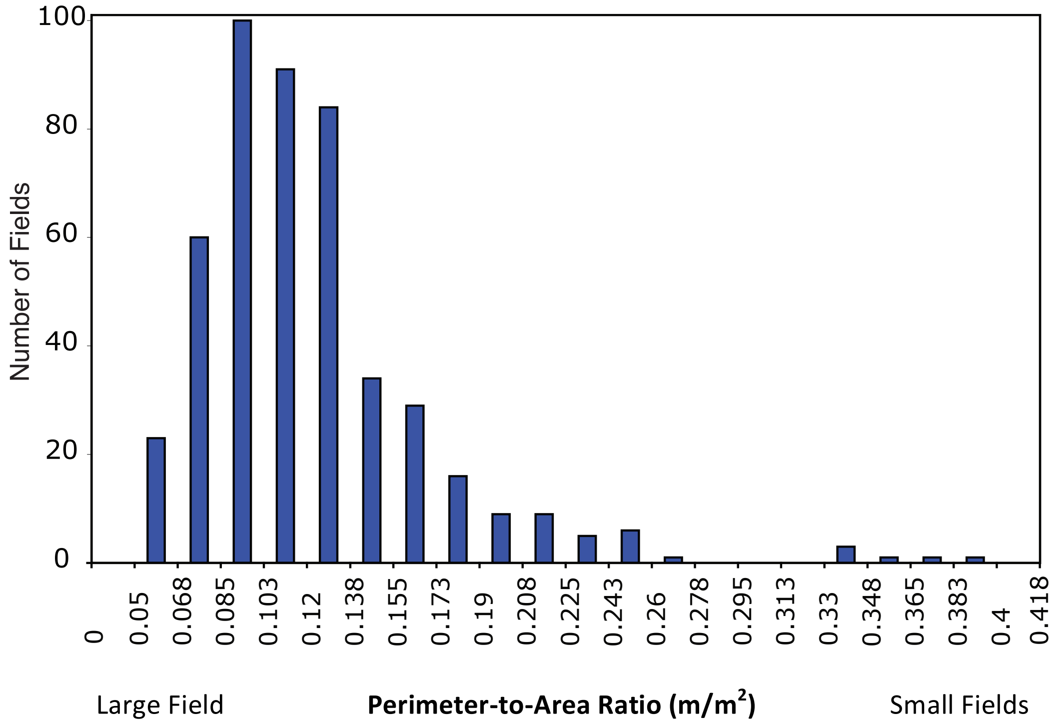
Summary:
19 pages
11 sections (noted below)
19 Figures
2 Tables

Sections:

1. Histogram of Field Perimeter-to-Area Ratios

Perimeter-to-area ratios of fields within a 1 km^2 area surrounding the experimental fields. Data collected from Google Earth image of site taken 12/24/2006. The average perimeter-to-area ratio is 0.12 m/m^2 and the median perimeter-to-area ratio is 0.11 m/m^2.

Figure S1



2. Pictures of Bund Sealing

Figure S2

Peeling surface of bund away and pulling up edge of plow pan. Faces of people in photograph are covered to protect privacy.

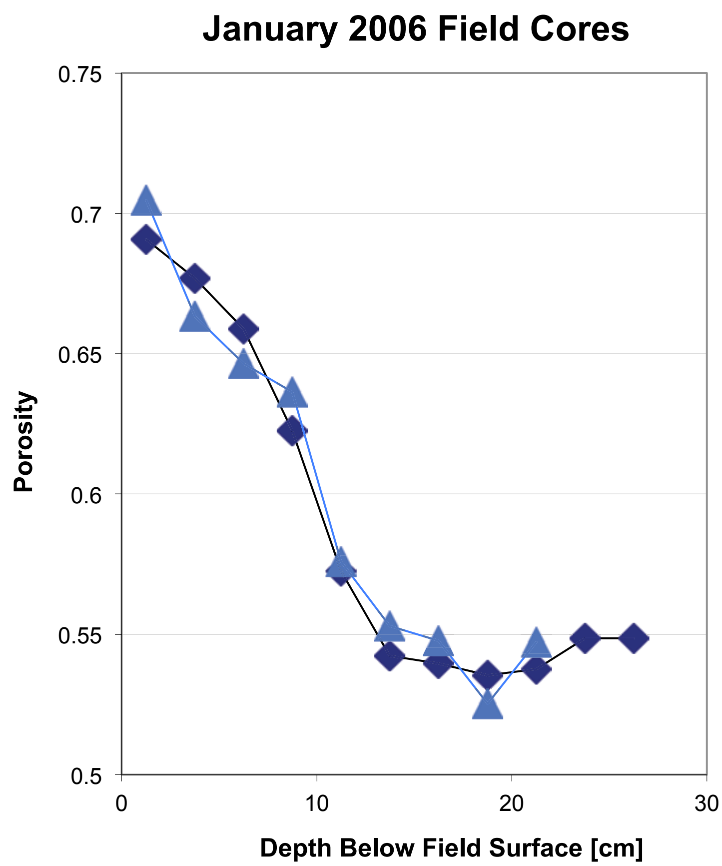
Figure S3

Anchoring plastic under raised edge of plow pan and rebuilding bund over plastic. Faces of people in photograph are covered to protect privacy.

3. Field Porosity

We determined the porosity of soil sitting above the plow pan using water content data from cores collected by Neumann et al.[1] in 2006 from two different locations in Field E. We assumed a specific gravity of 2.78 (the value used by Neumann et al.[2]) for the soil to transform water content into porosity. Resulting porosity values versus depth below the field surface are plotted below. We used the mid-point value of 0.6 when calculating the amount of irrigation water applied to fields.

Figure S4



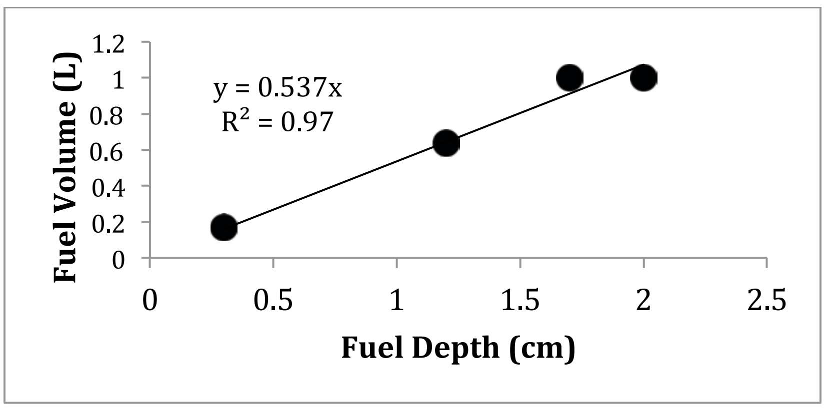
4. Methods: Implementation Analysis

Grain yields.
Data on grain yield in the six studied fields were collected by interviewing the farmers and asking them what their yield was during the study year and during the year previous to the study year.

Water—fuel connection.
Fuel costs were calculated based on irrigation water volumes applied the fields (as derived from field water level measurements) and from water consumption–fuel relationship established below.

Through a series of measurements we determined how much fuel the site's irrigation pump uses to pump a given volume of water out of the aquifer. First, a known volume of fuel was poured into the pump's engine and the resulting change in fuel depth was recorded. The relationship from this effort is shown below:

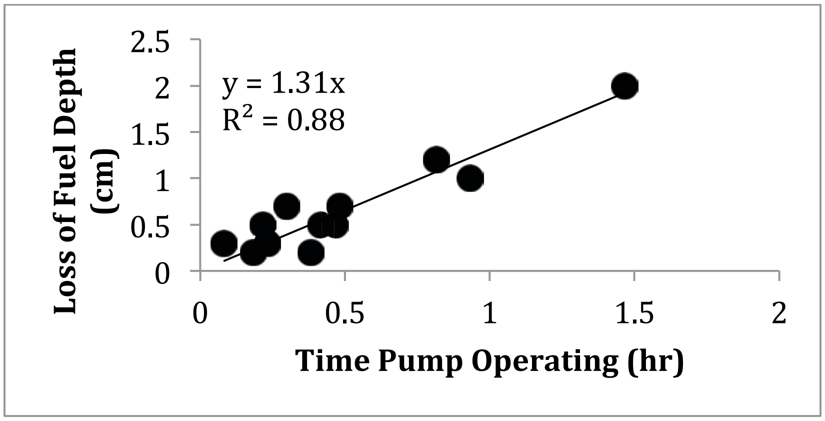
Figure S5



The standard error of the slope for this relationship is 0.02.

Second, the loss of fuel depth over time was tracked as the pump operated. These data are plotted below:

Figure S6



The standard error of the slope for this relationship is 0.08.

Third, 43 measurements of pump flow rate were taken by timing how long it took for the pump to fill a 91 L container. The average pump rate was determined to be 18.8 L/sec (standard error of the mean = 0.2 L/sec).

The volume of fuel consumed by the irrigation pump to pump a volume of irrigation water was determined from these three relationships (i.e., fuel volume to fuel depth, fuel depth to pump operation time, and pump flow rate):

[Vol Fuel (L)] = [1.04e-5 ±7.76e-7]*[Vol Water (L)].

The error associated with this relationship is the standard error of the slope for the fuel-volume–fuel-depth and fuel-depth–pump-time relationships, and standard error of the mean for the pump rate.

Financial calculations.

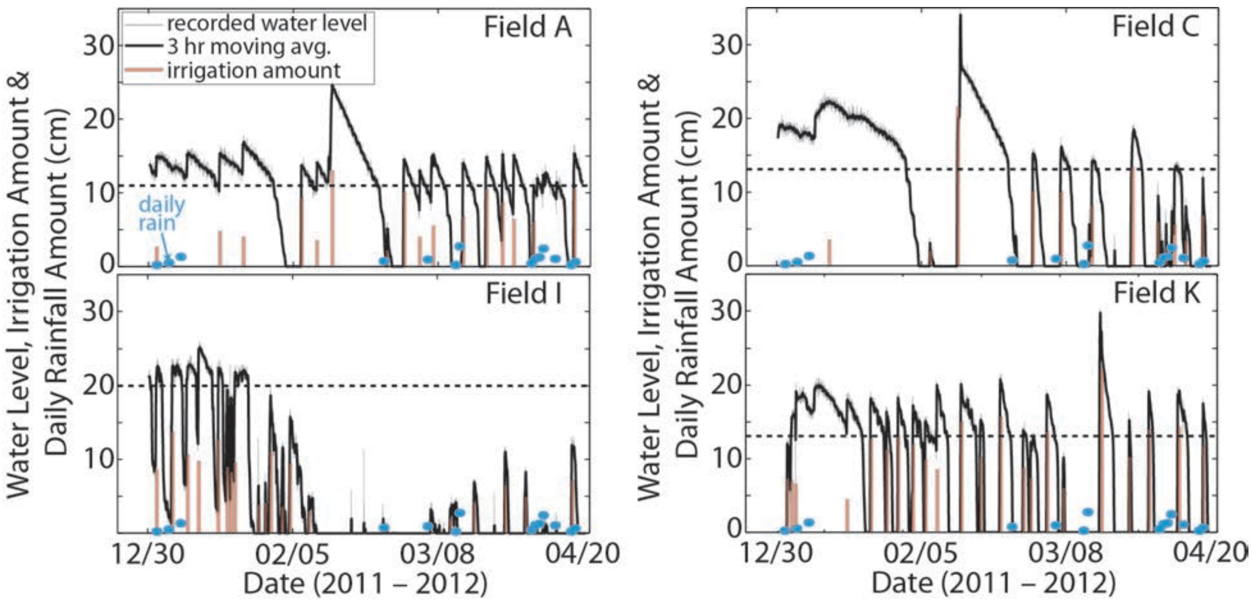
The financial calculations reflect what was spent on fuel and plastic to line the bunds during the field visit. It is possible that the prices paid for these items do not accurately reflect what a local farmer would pay.

Aquifer recharge model.

The impact that wide-spread implementation of bund sealing would have on site hydrology was assessed using a recharge model developed for the site by Harvey et al.[3] The model, a dynamic box model, is a set of coupled differential equations describing flux of water between different surface recharge sources (rice fields, ponds and rivers) and the aquifer over the course of a year. It was calibrated by fitting modeled and measured water levels. The model was taken as published,[3] and the amount of irrigation pumping was reduced by 40% to reflect the approximate amount of water saved in the bund sealing experiment for a perimeter-to-area ratio of 0.12 m/m^2, the average perimeter-to-area ratio at our site (see Results and Discussion in main manuscript). The field conductance value was then reduced (i.e., mimicking the reduction in conductance associated with sealing bunds) until the modeled rice field water levels in the reduced pumping scenario matched those modeled by Harvey et al.[3] The best fit was achieved with a 20% reduction in field conductance.

5. Water Level Data and Irrigation Amounts for Fields A, C, I and K

Figure S7



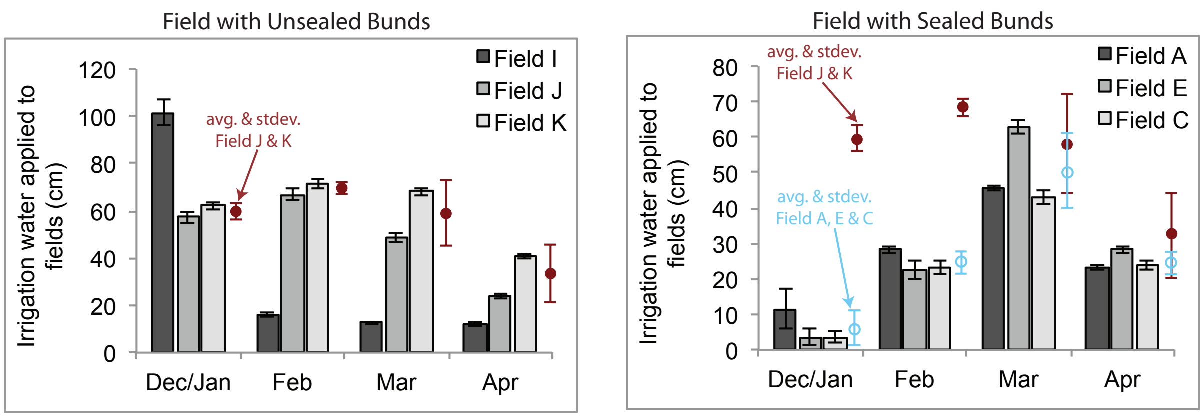
The bunds of Field A and Field C were sealed with plastic. Zero on the y-axis marks the location of the plow pan, and the black dotted line marks the top of the unconsolidated soil sitting on top of the plow pan. The blue circles indicate daily rainfall amounts.

6. Monthly Water Use and Field Dryness

Our study design compares water use in sealed and unsealed fields to assess the amount of water saved by sealing bunds. This approach implicitly assumes that the water management strategies of the farmers of the sealed and unsealed fields are similar. The monthly data presented below demonstrate that water management is largely similar among fields, though not identical.

Comparison of monthly water use in unsealed fields and sealed fields:

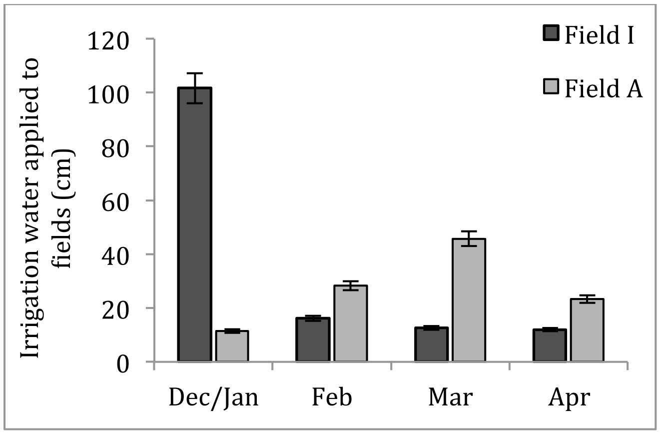
Figure S8



With the exception of Field I, monthly water use was similar between fields with unsealed bunds (i.e., Field J and K) and similar between fields with sealed bunds (i.e., Field A, E and C). In the sealed fields, water use slightly increased from January and February and then slightly decreased from February to March and more noticeably decreased from March to April. In the sealed fields, water use increased from January to February and February to March, and then decreased from March to April. Water use by sealed and unsealed fields (excluding Field I) was statistically different in January and February (ANOVA p-values less than 0.001 for both months), with the sealed fields using less water than the unsealed fields. The sealed and unsealed fields used similar amounts of water in March and April, though variability in water use increases in these two months. Below are plots of side-by-side comparison of monthly water use for the paired fields.

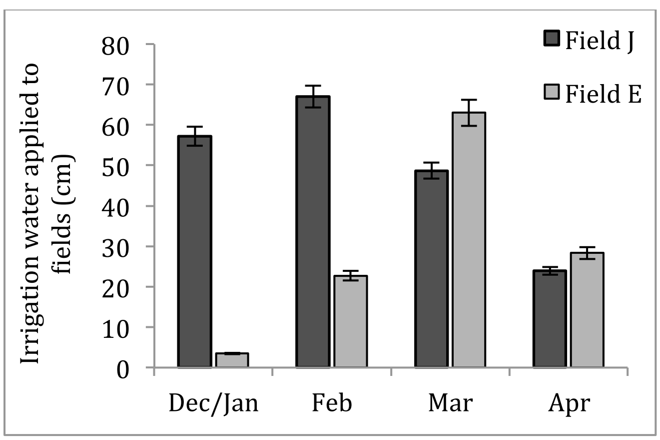
Largest Paired Fields (Smallest perimeter-to-area ratio)

Figure S9



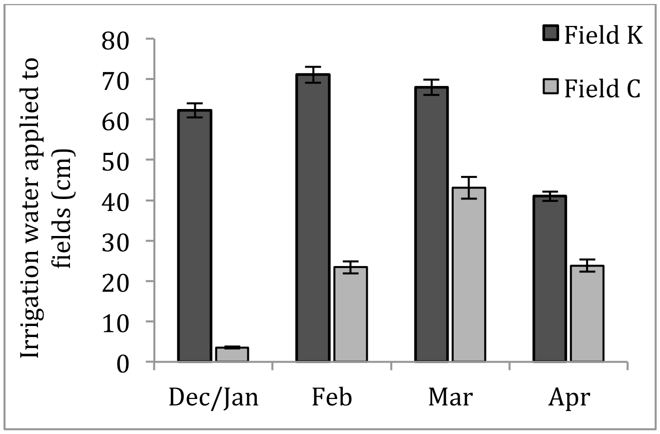
Medium-sized Paired Fields

Figure S10



Smallest Paired Fields (Largest perimeter-to-area ratio)

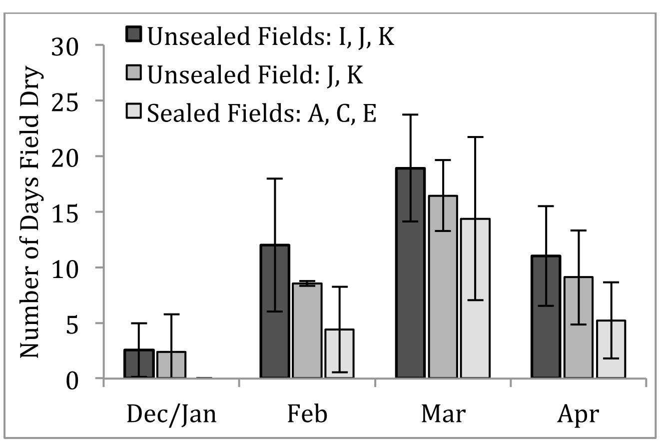
Figure S11



With respect to the paired fields, it appears that bund sealing resulted in a water savings for two months in the pair with the middle perimeter-to-area ratio (Fields E and J) and all four months in the pair with the largest perimeter-to-area ratio (Fields C and K). The impact of bund sealing is expected to have the biggest impact on water use for the field with larger perimeter-to-area ratios. It is difficult to draw conclusions about the field pair with the smallest perimeter-to-area ratio (Field I and A) due to the abnormal watering pattern for Field I.

Another metric for comparing field management practices is the number of days the fields sat dry during the irrigation season. The plot below shows the average number of days the water level in the unsealed field and the sealed fields was at or below the plow pan during the irrigation season. Error bars represent the plus and minus one standard deviation. The general trend in both field types is an increase in dryness from January to February and February to March, and then a slight decrease in dryness from March to April. There is a high level of variability in the data, and there is no statistically significant difference in field dryness between the sealed and unsealed fields (ANOVA p-value > 0.05).

Figure S12



7. Pictures of Bund Plastic Deterioration

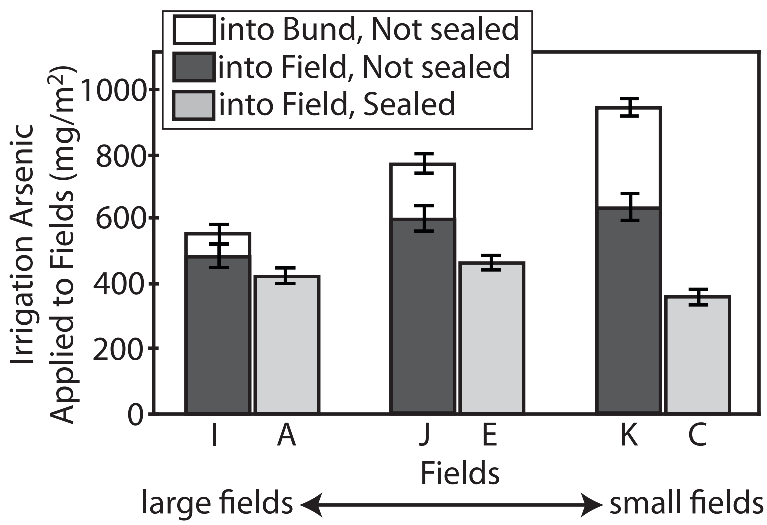
Figure S13

Figure S14

8. Arsenic Loading into Bunds and Field Soils for Sealed and Unsealed Fields

Decreased use of arsenic-rich irrigation water reduces the application of arsenic to field soils. However, because a portion of the applied irrigation arsenic is lost down field bunds,[1] the reduction in arsenic loading to field soils due to bund sealing does not directly correspond with the amount of water saved. Sealed fields use less water but all of the irrigation arsenic enters field soils. Unsealed fields use more water but a portion of the irrigation is sequestered into field bunds rather that field soils. The Figure below shows the estimated amount of irrigation arsenic sequestered into bunds and field soils of unsealed fields, and the amount of irrigation arsenic sequester into field soils for sealed fields. We assume that for sealed fields, all of the applied arsenic in irrigation water enters the surface soils.

Figure S15

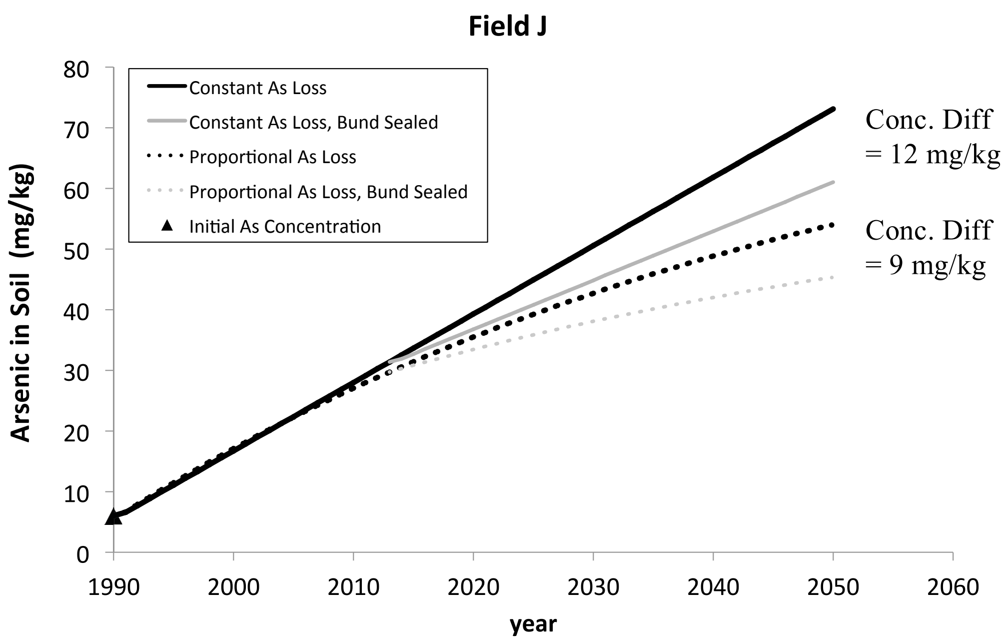


9. Estimated Rice Field Arsenic Concentrations With and Without Bund Sealing

Field arsenic concentrations cannot be simply determined as the sum of all arsenic put into fields during the irrigation season; Dittmar et al.[4] and Roberts et al.[5] demonstrated that in our study area, arsenic is lost from fields during the monsoon season. Dittmar et al.[4] conducted a three-year long arsenic mass-balance for Field I and estimated, based on measured soil arsenic concentrations and assumed arsenic inputs from irrigation (440 mg/m^2), that 240 mg/m^2 of arsenic accumulated in the field soils and thus 200 mg/m^2 of arsenic was lost from the soils. Dittmar et al.[4] further estimated that 105-210 mg/m2 of arsenic was lost during the monsoon season, suggesting that 0 to 95 mg/m2 of arsenic was lost during the irrigation season. Neumann et al.[1] later showed that loss during the irrigation season could be attributed to bunds flow and arsenic sequestration into bund soil. With these mass-balance numbers, Dittmar et al.[4] estimated future field arsenic concentrations (for Field I) for two different scenarios: loss of arsenic (during both the irrigation season and monsoon season) is constant (i.e., does not depend on field arsenic concentrations) and loss of arsenic is proportional to field arsenic concentrations. We followed this approach to explore the impact that bund sealing could have on field arsenic concentrations. However, our approach inherently incorporates arsenic loss during the irrigation season given our focus on bund sealing. Therefore, our modeled losses include only those occurring during monsoon flooding. Like Dittmar et al.,[4] we assumed that before irrigation began, the soil had an arsenic concentration of 6 mg/kg. We then assumed that each year, the unsealed fields in our experiment (Fields J and C – we do not consider Field I due to its irregular watering pattern) received the same arsenic loading as they received during our experiment (Table 2, main manuscript). We distributed this arsenic within a 40 cm depth increment, using an average bulk density of 1.11 g/cm^3. This is the average depth-weighted bulk density measured by Dittmar et al.[4] for soils in the top 40 cm of Field I (0.89 g/cm^3 for 0-10cm depths, 1.18 g/cm^3 for 10-25cm depths, and 1.20 g/cm^3 for 25-40cm depths). For the loss of arsenic during the monsoon season, we applied either a constant loss of arsenic (100 to 200 mg/m^2, the monsoon loss estimate from Dittmar et al.[4]) or a proportional loss of arsenic [1.6% to 3.2% of arsenic from top 40 cm, pairing the monsoonal loss rate (100 to 200 mg/m^2) with the average arsenic concentration in the top 40 cm measured by Dittmar et al.[4] (624 mg/m^2)]. For both scenarios, in the year 2013, we hypothetically seal the bunds of the fields and decreased arsenic loading based on the reductions determined from our experiment (Table 2, main manuscript). The results of the calculations are below for the two experimental fields. Our calculated concentrations differ from Dittmar et al.'s[4] because our modeled arsenic input during the irrigations season was based on irrigation amounts derived from our water level data, which were higher than the irrigation amount assumed by Dittmar et al.

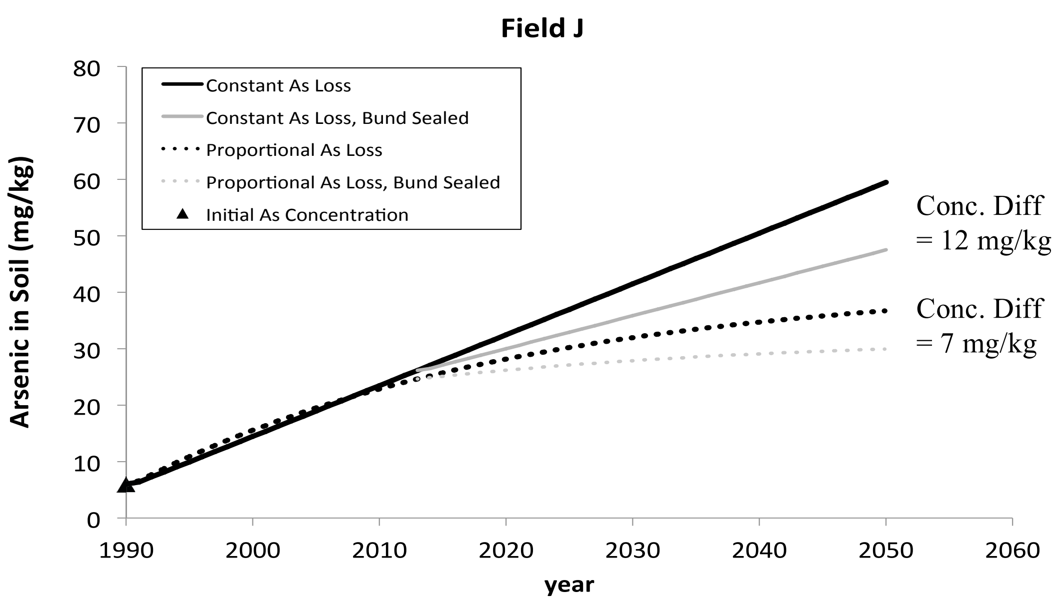
Field with middle perimeter-to-area ratio in experiment and monsoon arsenic loss of 100 mg/m^2:

Figure S16



Field with middle perimeter-to-area ratio in experiment and monsoon arsenic loss of 200 mg/m^2:

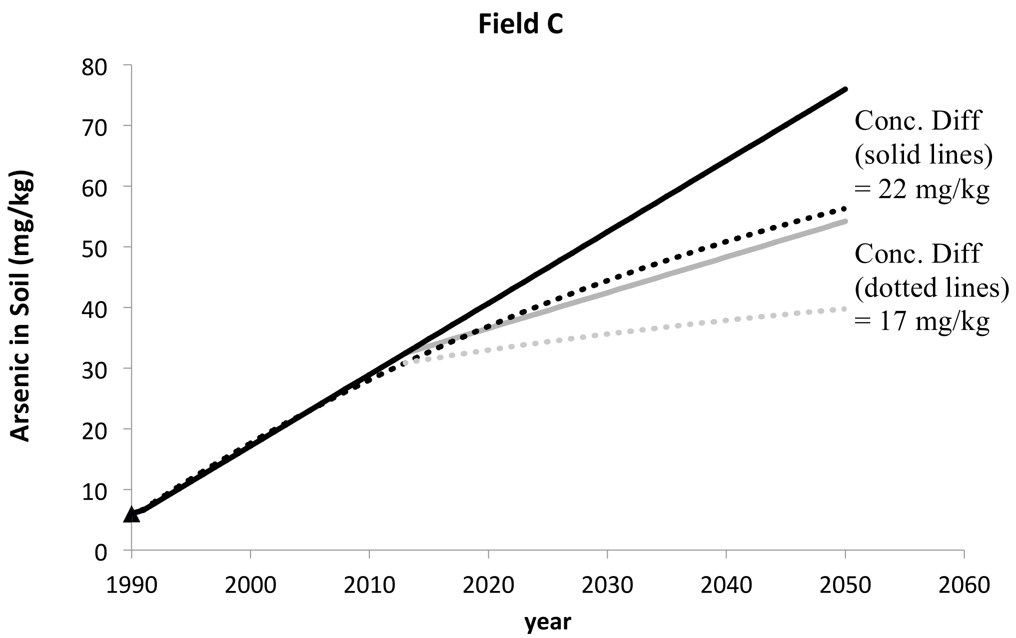
Figure S17



Modeled arsenic concentration difference for Field J (Figures S16 and S17) due to bund sealing ranged from 7 mg/kg to 12 mg/kg.

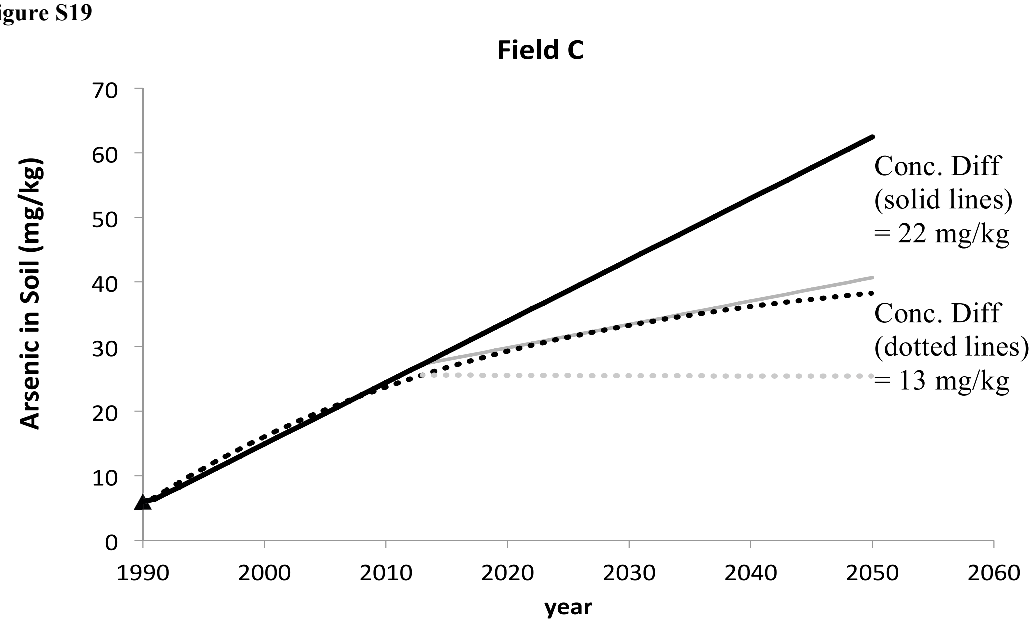
Field with largest perimeter-to-area ratio in experiment and monsoon arsenic loss of 100 mg/m^2 (legend same as for Field J):

Figure S18



Field with largest perimeter-to-area ratio in experiment and monsoon arsenic loss of 200 mg/m^2 (legend same as for Field J):

Figure S19



Modeled arsenic concentration difference for Field C due to bund sealing (Figures S18 and S19) ranged from 13 mg/kg to 22 mg/kg.

10. Grain Yields

Below are yields, as reported by the field farmers, for five of the six experimental fields from the studied growing season (2011–2012) and the previous growing season (2010-2011). Both sealed and unsealed fields saw a decrease in yield during the studied season. It does not appear that bund sealing negatively impacts yields. All of the fields with yield data, except Field E, reported a 15 to 17% decrease in yields. Field E is anomalous with a 28% decrease in yield.

Table S1

Field	P/A	Last Year (kg)	This Year (kg)	Change (%)
A (sealed)	0.073	1182	1000	-15
C (sealed)	0.127	327	273	-17
E (sealed)	0.103	455	327	-28
I (NOT sealed)	0.076	1182	1000	-15
K (NOT sealed)	0.137	655	545	-17

11. Financial Calculations

Table S2

Field	Status	Diesel Used (mL/m^2) [a]	Diesel Saved (mL/m^2)	Diesel Costs (Tk/m^2) [b]	Diesel Costs Saved (Tk/m^2)	Plastic Cost (Tk/m^2)
A	Sealed	11 ±1	3 ±2	0.57 ±0.05	0.17 ±0.09	0.57
I	Not sealed	15 ±1		0.74 ±0.07		
E	Sealed	12 ±1	8 ±2	0.61 ±0.06	0.41 ±0.10	0.80
J	Not Sealed	20 ±2		1.02 ±0.09		
C	Sealed	10 ±1	15 ±2	0.48 ±0.05	0.77 ±0.11	1.00
K	Not Sealed	25 ±2		1.26 ±0.10		

[a] [fuel volume (L)] = [$1.04x10^{-5}$±$7.76x10^{-7}$ * volume of water (L)], see SI section 4 for method and main manuscript Table 1 for volume of water.
[b] cost of diesel fuel during field visit (December 2011) = 50 Tk/L

References

(1) Neumann, R. B.; St Vincent, A. P.; Roberts, L. C.; Badruzzaman, A. B. M.; Ali, M. A.; Harvey, C. F. Rice field geochemistry and hydrology: An explanation for why groundwater irrigated fields in Bangladesh are net sinks of arsenic from groundwater. *Environ. Sci. Technol.* **2011**, *45*, 2072–2078.

(2) Neumann, R. B.; Polizzotto, M. L.; Badruzzaman, A. B. M.; Ali, M. A.; Zhang, Z.; Harvey, C. F. The hydrology of a groundwater-irrigated rice field in Bangladesh: Seasonal and daily mechanisms of infiltration. *Water Resour. Res.* **2009**, *45*, W09412, doi:10.1029/2008WR007542.

(3) Harvey, C. F.; Ashfaque, K. N.; Yu, W.; Badruzzaman, A. B. M.; Ali, M. A.; Oates, P. M.; Michael, H. A.; Neumann, R. B.; Beckie, R.; Islam, S.; Ahmed, M. F. Groundwater dynamics and arsenic contamination in Bangladesh. *Chem. Geol.* **2006**, *228*, 112–136.

(4) Dittmar, J.; Voegelin, A.; Roberts, L. C.; Hug, S. J.; Saha, G. C.; Ali, M. A.; Badruzzaman, A. B. M.; Kretzschmar, R. Arsenic accumulation in a paddy field in Bangladesh: Seasonal dynamics and trends over a three-year monitoring period. *Environ. Sci. Technol.* **2010**, *44*, 2925–2931.

(5) Roberts, L. C.; Hug, S. J.; Dittmar, J.; Voegelin, A.; Kretzschmar, R.; Wehrli, B.; Cirpka, O. A.; Saha, G. C.; Ali, M. A.; Badruzzaman, A. B. M. Arsenic mobilization from paddy soils during monsoon flooding. *Nature Geosci.* **2010**, *3*, 53–59.