Mapping the health harm of Bangladeshi brick kilns

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Abstract: Bangladesh suffers from poor air quality, with brick kilns as major contributors that remain difficult to regulate. We combine satellite remotely-sensed data, machine learning, and air-quality models to locate 9,228 clay brick kilns (2014–2023), individually estimating their technology, activity status, and health effects. Active kilns peaked in 2019 and have since declined by 3% annually. Kiln emissions cause approximately 3,380 (555–9,890) excess deaths yearly (30% lower than 2019), with 25% of deaths attributable to 9% of kilns, suggesting potential for targeted intervention. Current proximity-based regulations prove ineffective proxies for health impacts. Our resulting Pollution Source Prioritization System, now used by the government to allocate scarce enforcement resources, demonstrates how satellite data and air quality models can enhance environmental policy even where state capacity is weak.

Main Text:

Exposure to poor air quality is the most important environmental health risk worldwide (*1*, *2*), yet improving air quality remains a challenge, particularly in low-income countries. Although Bangladesh is among the most populous countries, and is believed to have the highest loss of life expectancy from air pollution (*3*), it currently lacks a national emissions inventory, and has limited resources for monitoring and enforcement of its pollution sources.

Brick kilns, in particular, have been identified as a major contributor to poor air quality in South Asia (*4*–*7*). In response, the Government of Bangladesh enacted the Brick Manufacturing and Brick Kiln Establishment (Control) Act of 2013 (hereafter, the "Brick Kilns Act"), that introduced laws of which the vast majority of the thousands of brick kilns in Bangladesh are in violation (*8*, *9*). However, brick kilns have proven difficult to regulate, especially as they have such extensive geographic coverage and yet can be ephemeral. Furthermore, there are limited capabilities for enforcing the Brick Kilns Act, allowing for only a small percentage of kilns to be shut down each year. Understanding which kilns are the most harmful to human health would be useful for prioritizing enforcement, but has been computationally expensive. Extant brick kiln regulations are often based on simple heuristics, such as proximity to schools and forests (*8*), which may not be good proxies for population exposure to pollutants from the brick kilns (and thereby their health harm). Furthermore, the effect of the brick kilns on human health, and the overall trends in kiln construction and demolition, have been unclear.

Here, we estimate the individual air quality-related health impacts of every brick kiln in Bangladesh active over a decade (2014–2023). We combine remote sensing for Earth observation satellite data and neural networks to identify the location and year-by-year characteristics (firing technology and activity status) of all brick kilns in Bangladesh, which we manually confirm for each kiln using historical satellite imagery. Then, we estimate the changes in pollutant concentrations and health impacts arising from the kilns, using technology-specific emission factors derived from a literature review, a combination of atmospheric models (GEOS-Chem (*10*) and InMAP (*11*, *12*)), and spatial demographic data to estimate population exposure and risk. We use our results to create a user-friendly "pollution source prioritization system" for guiding enforcement priorities to efficiently reduce the health harms of brick kilns, and we assess the extent to which our guidance differs from extant laws. The tool is easy to update, and is currently used by the Government of Bangladesh to plan enforcement activities.

Trends in active brick kilns from 2014–2023

The total number of brick kilns exhibited a peak in 2019 (see Figure 1a), resulting from both a sharp decline in new kiln construction and an increase in kilns shutting down (see Figure 1b). From 2014 until 2018, the total active kilns increased by 5% yr^{-1}, largely from high rates of kiln construction (+6% yr^{-1}) and relatively low rates of kilns being shut down (−1% yr^{-1}). From 2019 until 2023, the pattern was reversed. Total active kilns declined by −3% yr^{-1}, largely from shutting down kilns (−4% yr^{-1}) and low rates of kiln construction (+1% yr^{-1}). The change in trends of brick kilns roughly coincided with the 2019 amendment and increased enforcement of the Brick Kilns Act (originally enacted in 2013).

Different patterns are observed for the 2 major kiln types as determined by firing technology (see Figure 1a and Figure 1b). Traditional "fixed chimney" kilns (FCK) are more polluting than "zigzag" kilns (ZZK), and all operating fixed chimney kilns are in violation of the Brick Kilns Act. Total numbers of fixed chimney kilns steadily declined by −8% yr^{-1} from 2014 until 2018, and then by −11% yr^{-1} from 2019 until 2022. This can be explained by consistently lower rates of fixed chimney kiln construction compared to both shutting them down and converting them to zigzag kilns (see Figure 1b).

Zigzag kilns peaked during 2019 (~6,100 kilns), having increased by +11% $yr^{-1}$from 2014 until 2018, and since declined by −1% yr^{-1}. Their steep increase from 2014 until 2018 is explained by very high rates of kiln construction (+6% yr^{-1}), conversion of fixed chimney to zigzag kilns (+6% yr^{-1}), and low rates of being shut down (−1% yr^{-1}). From 2019 until 2023, zigzag kilns exhibited far lower rates of kiln construction (+0.4% yr^{-1}) and conversion from fixed chimney kilns (+2% yr^{-1}), and somewhat higher rates of being shut down (−3% yr^{-1}). As of mid-2023, there were 7,016 active kilns, the vast majority (80%) zigzag. Switching firing technologies from fixed chimney to zigzag kilns was responsible for 37% of the newly active zigzag kilns since 2014.

There are no brick kilns within Dhaka, the city with the highest population and thus a large demand for bricks. However, around 7% of all kilns are in subdistricts (*upazilas*) close to Dhaka (Dhamrai, Dohar, Gazipur Sadar, Kaliakair, Keraniganj, Nawabganj, Savar, and Sreenagar). These subdistricts see large changes in kiln construction and demolition (see Figure S1), where Gazipur Sadar, Keraniganj and Savar all see large net reductions in active kilns and Dhamrai sees a large increase in active kilns, possibly from spillover effects of increased enforcement of regulation in neighboring subdistricts. The districts close to the capital and in the east of Bangladesh tend to shut down a larger percentage of their kilns than districts in the west, despite having more kilns overall (see Figure S2).

Health impacts from brick kilns

We find that there are 3,380 (model range: 555–9,890) deaths from air pollution emitted from all brick kilns in Bangladesh active during the 2022–3 brick kiln season (1st November 2022 until 1st May 2023). While our estimates of total emissions and health impacts generally agree with other studies (see Supplementary Text), they are especially sensitive to the choice of emission factors and the relationship between pollutant concentrations and health (See Table S1).

The health harms attributable to individual brick kilns exhibit substantial variation (see Figure 2). The top percentile of most damaging kilns has over 27× the health harms as the 99th percentile. Only 9% of kilns cause ~25% of the health harms, and 25% of kilns cause ~50% of the health harms. Fixed chimney kilns are over-represented among the most damaging kilns, but many of the most damaging kilns are zigzag (see Figure 2b).

Brick kilns upwind of, and close to, the cities of Dhaka and Chittagong have larger health impacts per kiln than those elsewhere (see Figure S3). Subdistricts close to the city of Dhaka also generally have more kilns than in other areas, so they have an outsized impact on the total health harms of brick kilns (see Figure S3). Around 300 deaths yr^{-1} are attributable to kilns in just two subdistricts, Dhamrai and Savar, within Dhaka district.

Pollutant concentrations (see Figure 3) and health impacts (see Figure S4) from brick kilns have markedly declined in recent years. Since 2019, the health impacts of brick kilns in Bangladesh have reduced by 30% (see Table S1), and concentrations of $PM_{2.5}$ from brick kilns are lower almost everywhere (see Figure 3), including ~10 μgm^{-3} in some areas around Dhaka.

Current regulations

We find that fixed chimney kilns, which are illegal under the Brick Kilns Act, are more damaging than average, although there is wide variation (see Figure 4). Kilns upwind of the city of Dhaka, and especially kilns within the Dhaka and Gazipur districts, are far more damaging than average, including an upper tail of many of the most damaging kilns. The 2,003 kilns that were demolished over the decade were more damaging than average (see Figure 4), because they were more likely to be fixed chimney kilns or close to Dhaka.

Many kilns violate the Brick Kilns Act because of their proximity to schools, wetlands (excluding rivers), railways, hospitals, forests, and ecologically critical areas. We find that the proximity-based laws fail to capture the most damaging kilns and are poor proxies for health harm (see Figure 4). The average health harm per brick kiln of kilns in violation of proximity-based laws are not substantially different to the average health harm for all brick kilns; for kilns close to ecologically critical areas, the kilns are on average less damaging. The 201 kilns that violate more than 2 proximity-based laws (see Figure 4) are not substantially more damaging than the average kiln, and far less damaging than the 1,374 fixed chimney kilns, suggesting that the proximity-based violations are not that useful as proxies for improving public health compared to regulation based on firing technology.

If Bangladesh prioritised enforcement towards shutting down the most damaging 20% of kilns, this would avoid approximately 1,460 excess deaths yr^{-1}. By contrast, shutting down all 1,374 fixed chimney kilns (20% of all kilns) would avoid 1,200 deaths yr^{-1}, and switching their technologies to zigzag kilns will avoid around 716 deaths yr^{-1}. Shutting down the 502 kilns in subdistricts close to Dhaka (7% of total) would avoid ~435 deaths yr^{-1}, which is 67% of the benefits of the most efficient strategy (which shuts down the most damaging 7% of kilns to avoid ~650 deaths yr^{-1}). Enforcing both strategies (shutting down kilns close to Dhaka and shutting down fixed chimney kilns) would involve shutting down 28% of total kilns to avoid 1,600 deaths yr^{-1}, which is close to the most efficient strategy, achieving 95% of the avoided deaths for the same number of kilns.

Instead of shutting down kilns, Bangladesh could prioritize improving their energy efficiency through low-cost policy interventions, such as in a recent, notable randomized controlled trial for zigzag kilns (*25*). Using the same emissions as this study (where zigzag kiln $PM_{2.5}$ emissions roughly correspond to our high emissions scenario), we estimate that a national roll-out of this intervention across Bangladesh (with the observed uptake) would avoid 142–344 deaths per year (see Table S1).

Pollution source prioritization system

In collaboration with the Department of Environment of the Government of Bangladesh, we incorporated our results into a "Pollution Source Prioritization System" (PSPS), a web-based information system designed to aid government decisions for allocating scarce resources for enforcing environmental regulations (see Figure 5 for a screenshot). The PSPS has been deployed for around two-thirds of Bangladeshi districts, whose increased use of the system compared to control districts was statistically significant (see Figure S15 and Table S2 for usage statistics). From February 2024 until April 2025, officials in districts where the PSPS was deployed spent 142 minutes per month querying the PSPS on average (control districts: 46 minutes per month) and logged into the PSPS more than once every 2 months. Officials based in the national or divisional headquarters logged into the PSPS more than once per month on average, and queried the PSPS for a total of 437 minutes per month.

Conclusions

Low- and middle-income countries suffer disproportionately from air pollution (*13*), yet they have fewer resources to address it effectively, including regional and sub-sectoral emission inventories (*14*), air quality monitoring networks (*15, 16*), and enforcement capacity. Our study demonstrates how satellite Earth observation data (*17, 18*), machine learning (*19*), and reduced-complexity models (*12, 20*) can overcome these barriers to enable effective environmental governance.

We present a comprehensive assessment of the individual health impacts from all brick kilns across an entire country over the past decade. Previous work (*8*, *17*, *21*) has mapped brick kiln locations in South Asia for a snapshot in time, but not detailed characteristics (firing technology or activity status) over long periods, despite evidence that kiln technologies have improved drastically in recent years (*22*, *23*). Prior health impact studies of brick kilns have covered only specific regions of Bangladesh (*4, 24*), or used rough estimates without air quality models (*6*). No prior studies have estimated the air quality-related health impacts of each individual kiln, which is essential for targeting enforcement to achieve maximum public health benefit. Our approach reveals that just 9% of Bangladesh's kilns cause 25% of the health harms, enabling highly targeted interventions that current proximity-based regulations fail to capture.

The immediate real-world impact is demonstrated through our pollution source prioritization system, now actively used by the Government of Bangladesh for regulatory planning. This represents a successful transition from research to policy implementation, complementing recent bottom-up approaches working directly with kiln owners (*25*).

Our methodology is readily scalable and repeatable across South Asia, where our manually-vetted data can be used to train neural networks to identify kiln technology and activity status. Our methodology is most directly applicable for other fixed-location emission sources detectable from satellites, such as small-scale industrial facilities, quarries, and illegal mining operations. This is particularly significant for the informal sector, which represents 41% of GDP in middle-income countries (*26*) and employs over half the global workforce (*27*), yet remains largely outside environmental regulation (*28*) due to costly traditional reporting and monitoring methods (*29*, *30*).

By demonstrating how to integrate accessibility-enhancing tools without greatly compromising accuracy, our approach expands the reach of environmental regulation to sectors previously considered too difficult or expensive to monitor systematically. This work provides a pathway for resource-constrained countries to achieve effective environmental governance through innovative combinations of satellite remote sensing, neural networks, and atmospheric models.

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Competing interests: Authors declare that they have no competing interests.

Data and materials availability: Underlying data and code (including emission factor compilation, gridded emissions data outputs, configuration and inputs for running air quality models, and results, data, and code underlying the figures used in the manuscript) are available at Zenodo via reference (*31*).

Supplementary Materials

Materials and Methods

Supplementary Text

Figs. S1 to S15

Tables S1 to S5

References (*32*–*63*)

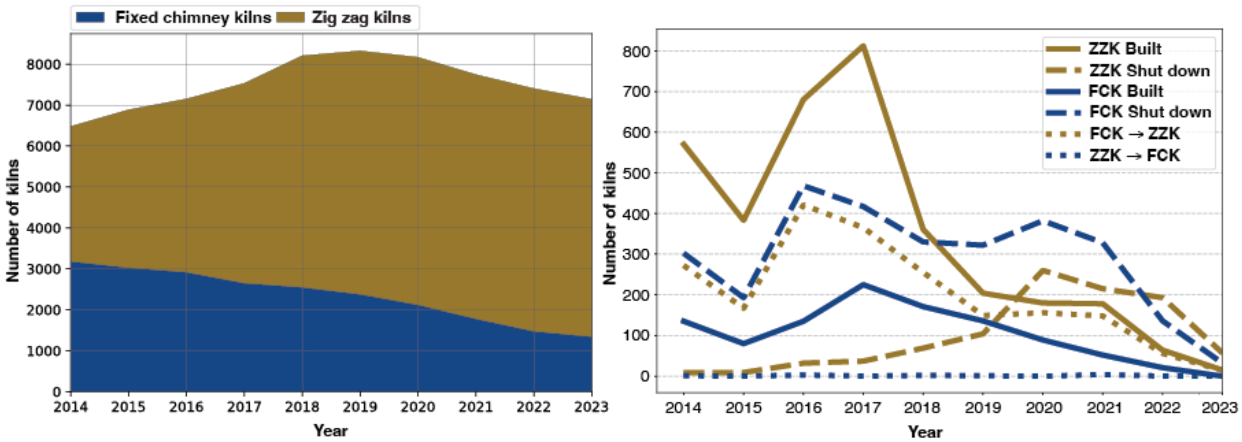

Fig. 1. Change in number of kilns over time. *Left*: Total brick kilns in Bangladesh each year, by kiln technology. *Right*: Changes in active brick kilns each year, by kiln technology (FCK: fixed chimney kilns, ZZK: zigzag kilns), and whether new kilns were built or shut down that year, or kilns switched technology (from FCK to ZZK and *vice versa*).

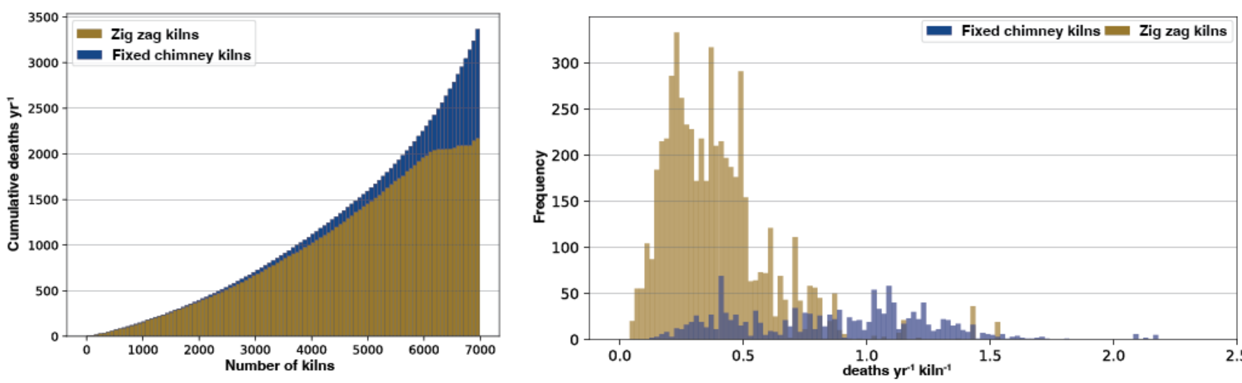

Fig. 2. Variation in health harms per brick kiln. *Left*: Cumulative annual mortality caused by pollution from currently active brick kilns in Bangladesh, ordered from least to most damaging, and decomposed by kiln technology. *Right*: The frequency distribution of mortality per brick kiln, by kiln technology.

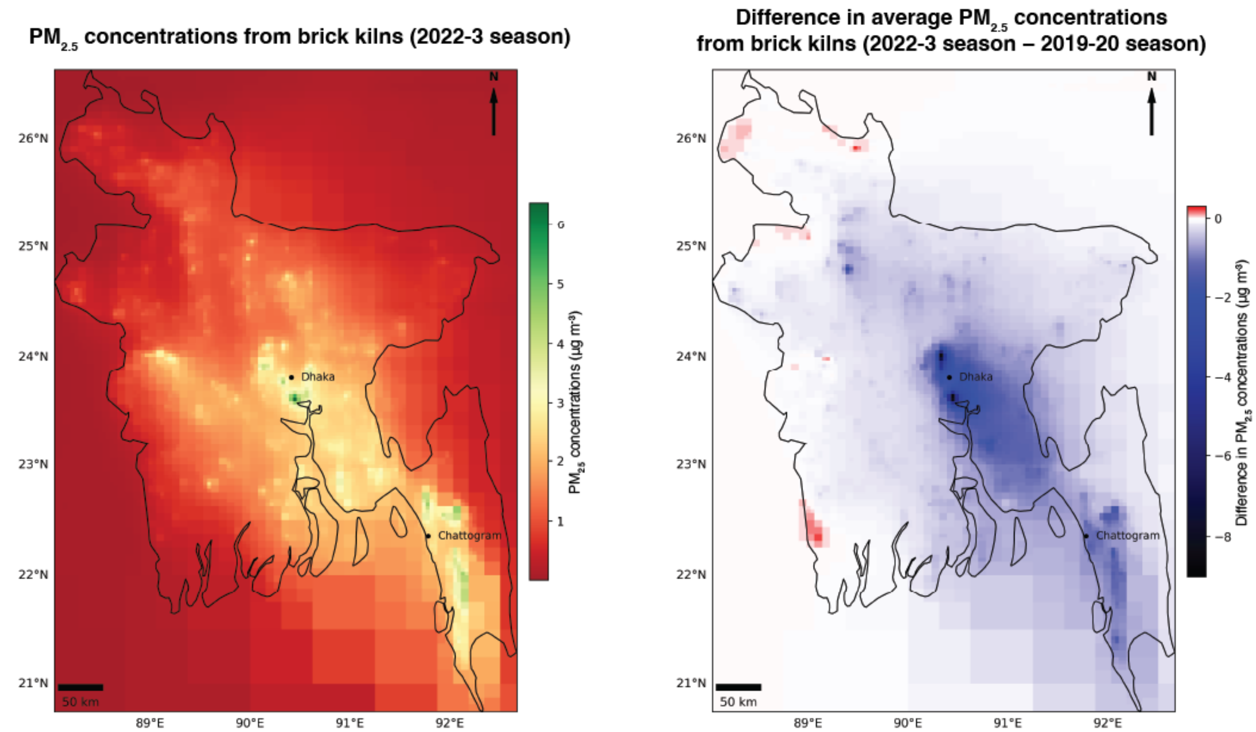

Fig. 3. Changes in pollutant concentrations from brick kilns. *Left:* Average changes in fine particulate matter ($PM_{2.5}$) concentrations from brick kilns in the 2022–2023 season (November–May) in the baseline emissions scenario (using the average emission factors), relative to a baseline with no brick kiln emissions. *Right:* Reductions in average changes in $PM_{2.5}$ concentrations in the 2022–2023 season, compared to a scenario with the same kilns as were present in the 2019–20 season (using the same atmospheric chemistry and transport). Here, lower (*i.e.*, more negative) values indicate areas where concentrations are lower than they would have been if the distribution and type of kilns were the same as in 2019–20.

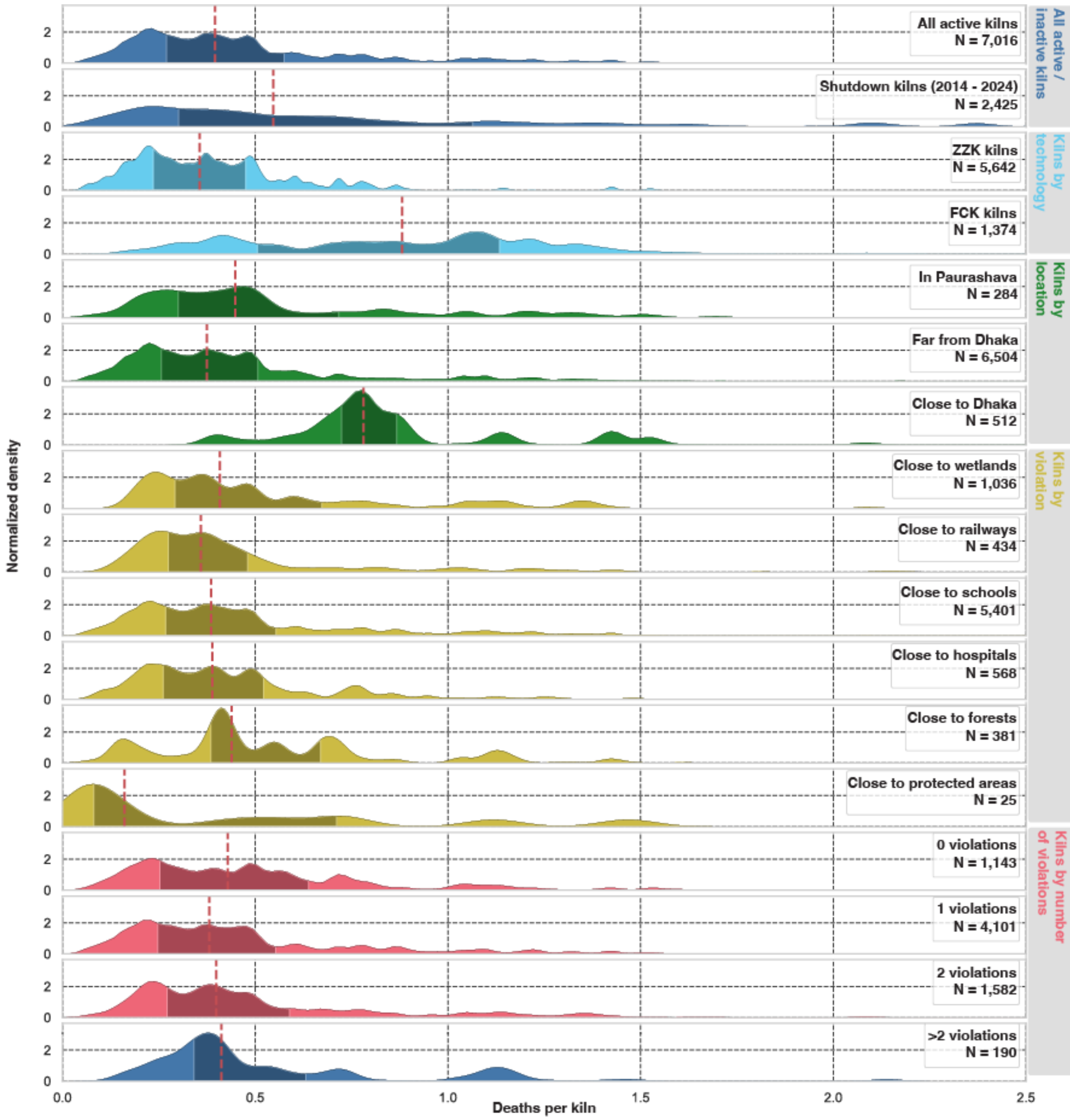

Fig. 4. Health harms of kilns by violation. The distribution of deaths per kiln across kilns in Bangladesh, decomposed by whether the kilns are active or shutdown (*dark blue*); their technology (*light blue*; ZZK = zigzag kilns, FCK = fixed chimney kilns); their location (*green*); and whether they are in violation of location-based laws (*yellow*); and the number of location-based violations they violate (*red*). “Close to Dhaka” refers to kilns in the following subdistricts: Dhamrai, Dohar, Gazipur Sadar, Kaliakair, Keraniganj, Nawabganj, Savar, and Sreenagar. Only 14 active kilns are not in violation of the requirement to have fewer than 50 households within a 1 km radius, so we exclude this violation from our analysis. “Protected areas” refers to ecologically critical areas. The median of each distribution is given by the red vertical dashed line. Distributions are shown as kernel density estimates, smoothed according to Scott’s Rule

with a bandwidth of 0.3. The darker portion of each plot lies within the 25th and 75th percentile of the distribution.

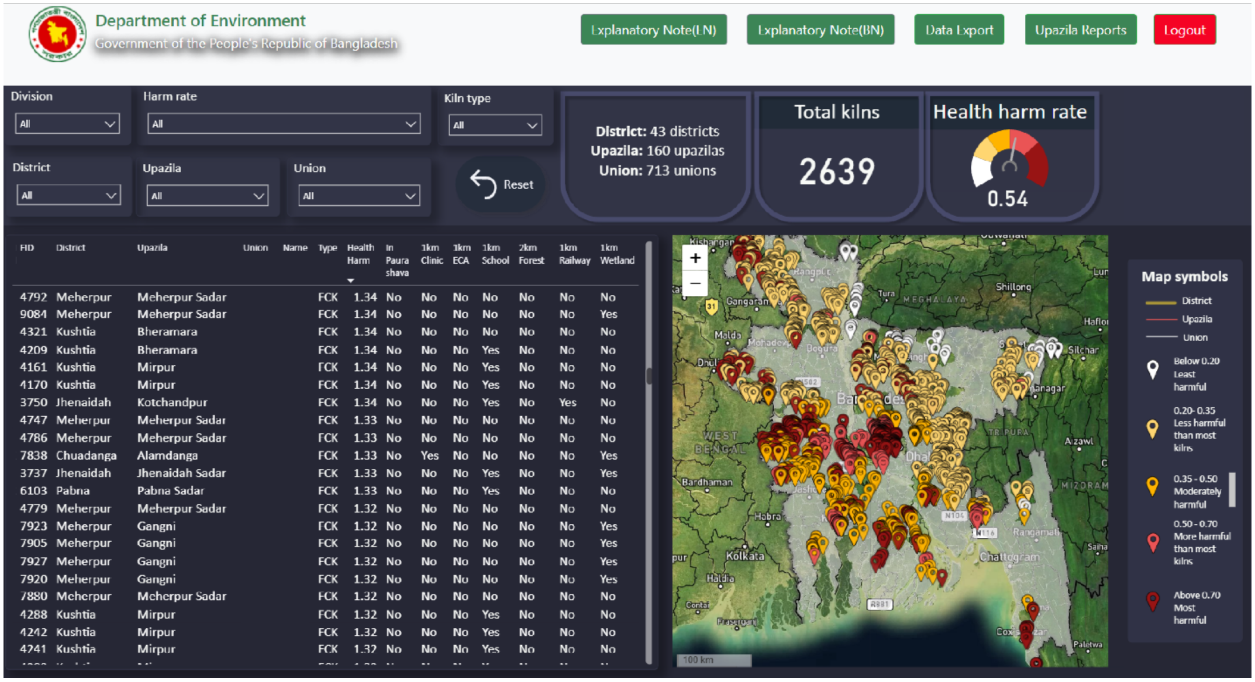

Fig. 5. A screenshot of our pollution source prioritization system (PSPS). Currently, it covers 160 subdistricts (out of 488) from 43 districts (out of 64) in Bangladesh. Areas not covered are grayed-out on the map. The PSPS provides the location, names, estimated public health harm, and estimated violations of the Brick Kiln Act for all individual kilns identified. Names and locations have been removed from this figure to preserve anonymity.

Supplementary Materials for

Mapping the health harm of Bangladeshi brick kilns

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The PDF file includes:

Materials and Methods
Supplementary Text
Figs. S1 to S15
Tables S1 to S5
References (*32–63*)

Materials and Methods

Estimating brick kiln locations and characteristics

Our approach to estimate brick kiln locations and characteristics closely follows Boyd *et al.* (*32*), which uses satellite Earth observation data and convolutional neural networks (CNN) to identify kilns. However, here we use updated years of satellite Earth observation data; we combine the results with other available datasets; we manually identify more detailed kiln characteristics (including their type and year constructed); and we determine which kilns are in violation of extant laws.

Boyd *et al.* (*32*) use the YOLO (You Only Look Once) v3 CNN architecture (*33*) for detecting kilns. Their initial training set used a thousand annotated kilns in a 120 km^2 region of Rajasthan, India, as collected and described in Boyd *et al.* (*32*). Here, we update Boyd *et al.* (*32*) for the years 2018, 2022, and 2024. For 2018, 2022, and the years covered by Boyd *et al.* (*32*), we use Airbus Pléiades imagery, which is very high resolution (50 cm pixels). For 2024, we used Planet Labs data, which is more up-to-date, with complete spatial coverage, but not as high in spatial resolution.

Along with the data compiled for this study for years 2018, 2022, and 2024, we use exant datasets from Lee *et al.* (*8*) for 2017 until 2019, and data from the Government of Bangladesh for years 2017 until 2018, derived from district-level surveys. We merge these datasets to compile our “Comprehensive Data”, treating kilns as non-identical across datasets if their coordinates were greater than 40m of each other. For kilns within 40m of each other across datasets, we manually ascertained whether they were the same kiln using Google Earth Pro. The methodology we develop for this study in 2024 found 90.6% of the brick kilns in the Comprehensive Data (see Table S3).

We manually verified activity status and kiln technology (FCK or ZZK) for all kilns based on satellite imagery, by parsing through historical satellite images (using Google Earth Pro) of each of the identified sites, including inactive sites (which could, in general, become active again in later seasons). Kiln activity status was determined through visual evidence of smoke emission, brick drying around the kiln during the firing season, chimney maintenance, and vegetation surrounding the site. If kilns classified as inactive were later found to be active, we classed them as continuously active, as short temporary shutdowns are difficult to distinguish from closures lasting a full season using satellite imagery alone. Using our approach, 9.7% of the total kilns in the Comprehensive Data were found to be inactive (see Table S3). Kilns that are observed to switch from active to inactive are considered “shut down”, although we do not observe whether this is from lack of profitability or government actions, or other reasons.

We determined the timing and length of the brick kiln season by surveying 563 brick kilns during the brick kiln season, and asking owners and managers which month they had first ignited the kilns, and when they would plan to stop operating the kiln. Then, we calculated the median start month (November) and median stop month (May of the following year).

Brick kiln violations

The Brick Kilns Act 2013 (and its amendment in 2019) imposes a set of restrictions in terms of where a brick kiln can be established, for the purpose of improving human health alongside other environmental concerns such as preventing deforestation. For eight such restrictions, we were able to find whether a kiln violated the bylaw. The bylaws that we could verify state that a kiln cannot be established within (a) 1 km of an educational institution; (b) 1 km of a healthcare facility; (c) 1 km of the railway; (d) 1 km of an "Ecologically Critical Area"; (e) 1 km of a wetland; (f) a Paurashava (the capital union of a subdistrict); (g) 2 km of a forest; (h) an area where more than 50 households live within a 1 km radius. Following Lee *et al.* (*8*), who calculate violations for schools and hospitals, we estimate whether each kiln is in violation of each bylaw by calculating the geodesic distance of each kiln with these other spatial variables. The data on locations of educational institutions, healthcare facilities, railways, forests, Paurashava, and wetlands are provided by the Local Government Engineering Division (*34*). Data on locations of ecologically critical areas are from the World Database of Protected Areas (*35*). For the regulation on households, we combine gridded population data across Bangladesh at 100m resolution (*59*) with estimates of the average people per household from the 2022 Bangladeshi Census.

Emissions inventory

To estimate emissions from brick kilns, we carried out a literature review of emission factors using Google Scholar. We included only papers that directly measured changes in pollutants that form or comprise fine particulate matter ($PM_{2.5}$), including: organic carbon (OC), black carbon (BC), sulfur dioxide (SO_2), nitrogen oxide (NO), volatile organic compounds (VOC), and primary $PM_{2.5}$. Our search terms "brick kiln" AND "emissions" AND "measurement" AND "SO2" OR "PM2.5" or "particulate matter" OR "NOx" OR "black carbon" OR "organic carbon" OR "VOC" OR "volatile organic carbon" AND "Bangladesh" OR "India" OR "Nepal" OR "Pakistan" found 65 reports or studies published in peer-reviewed journals. We excluded studies that either did not directly measure emissions in their results (*e.g.*, literature reviews), or studies that only measured emissions of pollutants that were not directly relevant to local particulate matter formation (e.g., CO_2, CO), or that were not in the study area (South Asia). We included additional studies that were referenced in the studies we found. Ultimately, we found 8 studies that met all our criteria (*36–43*).

Some papers sampled multiple kilns. We took each kiln as an independent measurement, so overall our emission factor estimates were based on 40 kilns. The firing technology was reported for all kilns. We considered only fixed chimney and zigzag kilns, which are by far the most common types in Bangladesh, and the only types we identify using satellite Earth observation data. We estimated average, technology-specific emission factors, as fixed chimney kilns are known to be more polluting than zigzag kilns.

Although some studies reported the fuel use, we did not estimate how the choice of fuel affected the emissions. It is also known that fuel types vary spatially in South Asia (*5, 44*), which may have effects on the pattern of pollution exposure. To our knowledge, reliable data on fuel use is not available for Bangladesh, but fuel use is likely to fluctuate based on what is available and their comparative prices. It is known that the dominant fuel source for brick kilns in the region is anthracite coal (*23*) (which was also the predominant fuel type used for the measurement studies).

Emission factors were either reported as mass of pollutant per kg brick or per kg fuel used. To convert these to emissions per kiln, we used technology-specific average estimates for the number of bricks produced per kiln (FCK: 3.3 million yr^{-1}; ZZK: 3 million yr^{-1}) (*45*), and for the fuel use per kiln (FCK: 210 kg hr^{-1}; ZZK: 230 kg hr^{-1}) (*46*). We further assumed that each brick weighed 3.5 kg (*47*) (assuming 3-hole bricks (*48*)). We assumed the kiln emissions are temporally uniform throughout the kiln season.

The emission factors for BC, OC, Total $PM_{2.5}$, and SO_2 across all 8 studies are shown in Figures S5–S8, showing several-fold discrepancies between measured studies. We pursue 3 different approaches to aggregating the emissions. Our inverse variance-weighted mean (IVW) emissions are generated from an inverse variance weighting of the emission factors, to account for the fact that the measurements have different uncertainties. For $PM_{2.5}$, BC, OC, and SO_2, the papers generally reported not just the emissions but the standard deviations derived from repeat measurements for each kiln. We constructed the average (inverse variance weighted) emissions for ZZK and FCK, using the formula

$$\hat{\mu} = \frac{\sum_i (\mu_i / \sigma_i{}^2)}{\sum_i (1/\sigma_i{}^2)}$$

The combined standard deviation was given by

$$\hat{\sigma} = \sqrt[2]{\frac{1}{\sum_i \left({}^1\!/_{\sigma_i{}^2} \right)}}$$

The inverse variance weighting approach gives lower emission estimates than the straightforward average of the emissions, because (by construction) it aligns more with results that have lower standard deviations, and those results tend to be lower (perhaps because measurement error varies as a percentage of the total). We also treat each kiln measurement as independent (even if they are from the same study), and thus weight studies higher if those studies measure more kilns (which especially favours a notable pair of studies in India from 2014 (*37*, *41*); see Supplementary Information for comparisons with existing literature). Our "average" emissions are generated from a straightforward mean of all independently reported results, which reduces those biases and aligns more with recent, seminal reports (*49*, *50*). We also report "maximum" emissions (the maximum of all independently reported results), to provide a reasonable upper bound of the health harms from brick kilns, and to reflect the possibility that kiln owners change their behaviour to pollute less when emissions are being measured.

Although our detailed literature review captures uncertainty in emissions, it is possible that the emissions measurements are systematically low, perhaps because kiln operators use cleaner fuels or better procedures when the measurements are taken, or that measurements are systematically taken from better-run kilns. Remote sensing data and measurement and source-apportionment techniques (*4*, *7*, *24*) may be able to better constrain the emissions from brick kilns under typical conditions, although these also come with uncertainties (*51*).

Only 2 studies listed VOC emissions (*40*, *43*), one of which (*43*) did not specify which chemical species of VOC were emitted. Not all species of VOC contribute to $PM_{2.5}$ formation, so we neglected the estimate of VOC emission in (*43*) from our study. Thus, the VOC estimates were derived from only one study (*40*), and were the same value per kg brick produced for both fixed chimney and zigzag kilns. This study listed the chemical species of VOC emitted, only a subset of which give rise to $PM_{2.5}$ formation. We included the following species, lumped into tracers for use in GEOS-Chem: benzene (2.60 E-04 g kg^{-1} brick), toluene (8.85 E-04 g kg^{-1} brick), alkenes with more than 4 carbon atoms (3.16 E-03 g kg^{-1} brick), alkenes with more than 3 carbons (3.48 E-04 g kg^{-1} brick), isoprene (7.77 E-04 g kg^{-1} brick), xylene (2.50 E-03 g kg^{-1} brick), other aromatics (3.79 E-04 g kg^{-1} brick), α-pinene (4.71 E-05 g kg^{-1} brick), and β-pinene (4.14 E-05 g kg^{-1} brick). Emissions factors across studies are shown in Figs S5–S8. The final emissions are given in Tables S4 and S5.

Total $PM_{2.5}$ is a size class of aerosols that comprises many emitted chemical species. After accounting for BC and OC emissions taken from the literature review, we assume the remaining fraction of Total $PM_{2.5}$ is fine mineral dust ("DST1" in GEOS-Chem), a large amount of which is emitted during clay brick firing (*52*).

In addition to the IVWM, average, and maximum emission scenarios, we compile a counterfactual emission inventory for 2019 that applies the average emission factors to only the kilns that were active in the beginning of 2019 according to our dataset (see above for details).

<u>GEOS-Chem simulations</u>

To estimate total health impacts of brick kilns, we ran the emission inventory in GEOS-Chem Classic (*10*), version 14. We ran a full chemistry simulation, where the chemical mechanism included complex secondary organic aerosol (SOA) formation with semi-volatile primary organic aerosol (*53*, *54*). Our simulation included 47 vertical layers and is driven by MERRA2 meteorology reanalysis. We performed a 2-year global spin-up at 4.0° × 5.0° resolution, to generate a restart file, and then we generated boundary conditions from 2022-05-01 until 2023-05-01 for our simulation over a custom nested region that covered all of Bangladesh (latitude: 10–40°; longitude: 80–100°). We regridded the restart file to 0.5° × 0.625° resolution, and performed further spin-up (to ensure the regridding had no impact) on a nested simulation at this resolution, to arrive at a restart file for 2022-11-01, the beginning of the brick kiln season.

Then, we ran our production simulation of GEOS-Chem on our nested domain at 0.5° × 0.625° resolution, from 2022-11-01 until 2023-05-01. We did this for standard emission inventories that included anthropogenic emissions from the Community Emissions Data System (CEDS) (*55*). Although CEDS does include Indian brick production-related emissions from the SMoG-India emission inventory (*56*), emissions from brick production in Bangladesh are not included, so there is no double-counting. We then perform simulations that include our emission inventory for brick kilns over Bangladesh, using the inverse variance-weighted mean emission factors derived from our literature review. To estimate the total changes in pollutant concentrations attributable to brick kiln production, we "zero-out" the changes in concentrations by subtracting the baseline concentrations from the concentrations derived in the other simulations. Concentrations shown here are annually-averaged (and so correspond to half the change in concentrations during the 6 month brick kiln season).

Health impact estimation

Similar to previous work (*20*), we estimate changes in all-cause mortality and mortality from 5 causes of death (lower respiratory infections, chronic obstructive pulmonary disease, stroke, ischemic heart disease, and lung cancer) attributable to long-term exposure to $PM_{2.5}$, using relationships derived from Burnett *et al.* (*57*). The demographic data (baseline, cause- and age-specific mortality rates and age profiles) were taken from the Global Burden of Disease Results Tool (*58*) using year 2019, the most recent data available. Our assessment of the harm of brick kilns does not take into account the potential for baseline mortality risk or other health risks to vary at a hyper-local level. Subnational demographic data was not available for Bangladesh. For spatial population data, we used 2020 projected population data gridded at 0.01˚ resolution from Gridded Population of the World (version 4) (*59*).

We use 2 different concentration response relationships from the Global Exposure Mortality Model (GEMM) (*57*): one that estimates all cause mortality attributable to long-term $PM_{2.5}$ exposure, and another that estimates mortality from 5 major causes of death: ischemic heart disease, stroke, chronic obstructive pulmonary disease, lung cancer, and lower respiratory infections. The concentration-response functions are non-linear and thus the excess deaths attributable to brick kilns depend on the total pollutant concentrations across space. We use total pollutant concentration surfaces from Hammer *et al.* (*60*), which combines GEOS-Chem simulations with satellite-derived aerosol optical depth and ground monitoring data, providing more accurate estimates of ambient $PM_{2.5}$ concentrations than GEOS-Chem outputs alone.

Further, we use 2 different approaches to estimating mortality, following Kodros *et al.* (*61*). One approach (the "attribution" method) estimates mortality from brick kilns proportionately with the fraction of total pollutant concentrations (including from non-brick-kiln sources) that they give rise to in each grid cell. The attribution method linearly apportions health harm from all sources to individual sources (such as the brick kiln sector), which is more appropriate for estimating the health harms of individual kilns as done here. The "subtraction" method estimates mortality from brick kilns by subtracting mortality caused by brick kiln pollution from mortality caused by total pollutant concentrations (including from non-brick-kiln sources). The subtraction method is more suitable for estimating the effects of policy decisions in aggregate, but is less suitable for reporting the cumulative health effects of individual kilns, as is reported here.

Our baseline scenario corresponds to the mean emissions, using the GEMM all-cause concentration response function, and the attribution method to estimate mortality. Results for all the 3 emission scenarios (and the counterfactual 2019 emission scenario), the 2 concentration-response functions, and the 2 mortality estimation methods, are given in Table S1.

Estimating kiln-specific health impacts

To estimate kiln-specific health impacts (see Figure S9), we use a reduced complexity air quality model, InMAP (*11*, *12*). InMAP is a linearization of a full-scale chemical transport model, designed to estimate changes in $PM_{2.5}$ concentrations from changes in emissions. It is able to simulate individual health impacts of each of the ~9,000 kilns (active and inactive) at high spatial resolution, which would be prohibitively computationally intensive using traditional methods. We use a nested version of InMAP that is parameterized by GEOS-Chem (following Thakrar *et al.* (*12*)) and only covers Bangladesh, rather than the world (grid cell resolution range: ~140 km – 4 km in urban areas). Furthermore, whereas previous versions of InMAP directly estimate annual average changes in pollutant concentrations, we parameterize InMAP on sub-annual GEOS-Chem results that better represent the meteorology and chemistry during the brick kiln period (which is only from November to May). This allows InMAP to capture the meteorology appropriate to the brick kiln season, which is typically drier and features a characteristic northwesterly wind over Dhaka (*62*).

InMAP has known biases in predicting changes in pollutant concentrations (*12*), and prior work has successfully applied correction factors to InMAP to reduce biases (*63*). Here, we apply linear scaling factors for each $PM_{2.5}$ species from brick kilns predicted by InMAP (Primary $PM_{2.5}$, particulate sulfate (pSO_4), particulate nitrate (pNO_3), particulate ammonium (pNH_4), and secondary organic aerosol (SOA)), derived by comparing results from the InMAP simulation with the results from the GEOS-Chem simulations that estimate changes in pollutant concentrations from brick kilns (see above for details). To allow comparison, the InMAP concentrations are regridded to match the GEOS-Chem grid at the surface, and the GEOS-Chem species are grouped to best match those given by InMAP. In GEOS-Chem, pNO_3 corresponds to AerMassNIT; pSO_4 corresponds to AerMassSO4; SOA is calculated from subtracting primary organic aerosol from total organic aerosol; and Primary $PM_{2.5}$ is calculated by subtracting all secondary components (scaled in accordance with how GEOS-Chem calculates $PM_{2.5}$) from total $PM_{2.5}$. Pollutant concentrations from InMAP are bias corrected using species-specific linear scaling factors to match GEOS-Chem. The scaling factors are: 0.2 for pNO_3 and Primary $PM_{2.5}$, and 2.2 for pSO_4. We do not scale changes in SOA concentrations, which are negligible in both GEOS-Chem and InMAP (and slightly negative in many locations in GEOS-Chem). Although brick kilns have no known NH_3 emissions, changes in pNH_4 concentrations derived from InMAP are estimated stoichiometrically, by multiplying the scaled pSO_4 concentrations by 18.04/96.06 and the scaled pNO_3 by 18.04/62.0049.

When compared with the GEOS-Chem simulation, the final InMAP results have an R^2 of 0.68 (population-weighted: 0.74), a normalized mean bias of –26.7% (population-weighted: –18.0%), and a normalized mean error of 48.5% (population-weighted: 41.4%) (See Figure S10). The InMAP results also capture similar spatial patterns (see Figure S11) and population-weighted speciated concentrations (see Figure S12) compared to the GEOS-Chem simulation, but at a higher spatial resolution (see Figure S11).

Creation of the pollution source prioritization system and Randomized Controlled Trial

We developed our pollution source prioritization system (PSPS) in collaboration with the Department of Environment of the Government of Bangladesh. The PSPS can be accessed by government officials once they have received a username and a password, but it is not publicly available. The PSPS contains information about the estimated excess mortality caused by each individual brick kiln. Based on how damaging each kiln is relative to other kilns, they are then classified into five categories: “Least harmful”, “Less harmful than most”, “Moderately harmful”, “More harmful than most”, and “Most harmful”. We also provide information on the estimated violations (described above) and the name of the kiln where available (if the

Government has a name associated with it). The PSPS has a user interface with an interactive map where the user can see all kilns covered by the PSPS. The pins indicating the location of each kiln are color-coded according to the five categories of health harm rates. The user can also filter and sort the list of kilns according to the kiln characteristics. Furthermore, if the user clicks on a specific kiln, they can receive directions to the kiln via Google Maps. Finally, the user can export any selection of data about the kilns to commonly-used export formats (PDF, Microsoft Excel, or Comma Separated Values (CSV) files). Thus, it is possible for government officials to use the information in the PSPS without being logged in.

Currently, the PSPS is being rolled out on an experimental basis, where we randomly selected two-thirds of districts to be partially covered by the PSPS, while one-third of districts are not covered and kept as "control" districts. Within the partially treated districts, we randomly selected half of the subdistricts to be covered by the PSPS, while the other half are kept as control subdistricts. Figure 5 provides a screenshot of the PSPS where kiln locations are presented in the covered districts while control districts are grayed out. The experiment is registered with the American Economic Associations Randomized Controlled Trial (RCT) Registry (ID: AEARCTR-0013521) and in future research we will measure the effect of the PSPS on various outcomes.

The PSPS was first rolled out on a pilot basis across 5 subdistricts from February 2023. We then improved the design based on feedback from the Department of Environment. The large-scale rollout of the PSPS started in February 2024, when a workshop was held to train all relevant government officials (including those in district offices covered by the PSPS, districts offices not covered by the PSPS, divisional headquarters, and the national headquarters) to use the PSPS. Between February and March 2024, we met with the government officials again in their respective district offices, and conducted personalized training sessions where they had more time to interact with the interface and ask questions. Finally, as there were large changes to the postings of government officials in September 2024, we conducted further personalized training sessions in each district office between October 2024 and February 2025.

Supplementary Text

Comparisons with other studies

There are few studies that estimate mortality attributable to brick kilns in Bangladesh. To our knowledge, the only other study that does so, Eil *et al.* (*6*), estimates that there are 6,100 deaths attributable to brick kilns in year 2015, which is similar to our study that estimates around 5,200 deaths attributable to brick kilns in 2015 (see Figure S4). Eil *et al.* (*6*) corroborates our findings despite not using an air quality model; rather, they estimate deaths from brick kilns based on the fractional share of pollutant emissions from the brick sector compared to other sectors.

One study (*5*) estimated around 25,000 deaths attributable to brick kilns in India, which (assuming ~140,000 kilns in India) is around 0.18 deaths $kiln^{-1}$ yr^{-1}, which is in the same range of our study which reports 0.49 (0.08–1.40) deaths $kiln^{-1}$ yr^{-1} for Bangladesh.

Our emission factors are derived from a systematic literature review of direct measurements from brick kilns, which we consider the most robust approach, given the absence of comprehensive, nationally representative emissions monitoring. However, real-world kiln operations may deviate from optimal conditions, resulting in higher emissions. Brooks et al. (*25*) report far greater $PM_{2.5}$ emissions from zigzag kilns than our average emission scenario, but are still within the range of our maximum emission scenario. Table S1 reports the total deaths using the same emissions as Brooks et al. (*25*) for both their baseline emissions and under the conservative effects of their policy intervention. Another recent, notable study (*64*) estimates changes in pollutant concentrations from brick kilns in Bangladesh, finding very large changes in SOA formation resulting from very high VOC emissions as reported in in Haque *et al.* (*43*). We chose to adopt far lower VOC emissions from Stockwell et al. (*40*) as they listed the chemical species of VOC emission, but we note the paucity of studies directly measuring VOC emissions from brick kilns is a major source of uncertainty.

A recent, seminal report (*49*) estimated pollutant concentrations from brick kilns across the Greater Dhaka Region, finding average $PM_{2.5}$ concentrations at ~15 μgm^{-3} in some areas during the 2019–2020 kiln season. We find very similar magnitude and spatial pattern to their results (see Figure S13) when using kilns from 2019–2020. However, when we update to the most recent season with data available, we find markedly lower pollutant concentrations. Our work thus highlights the large recent reductions in brick kiln emissions in Bangladesh that are not reflected in studies that only look at one kiln season. The recent report (*49*) uses similar emission factors to our study; see Figure S14 for Total $PM_{2.5}$ concentrations from our maximum emission scenario.

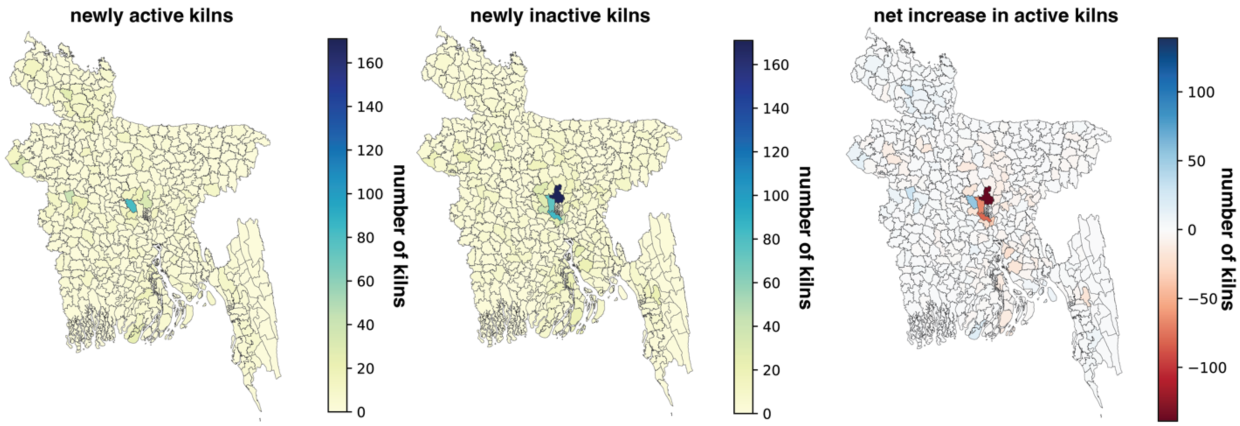


Fig. S1. Change in number of kilns over time by region, 2014 until 2023. *Left*: Change in number of newly active kilns by subdistrict (*upazila*) across Bangladesh. *Center*: Change in number of newly inactive kilns (*i.e.*, kilns that were previously active and are no longer active). *Right*: Net increase in active kilns (equivalent to the left panel minus the center panel).

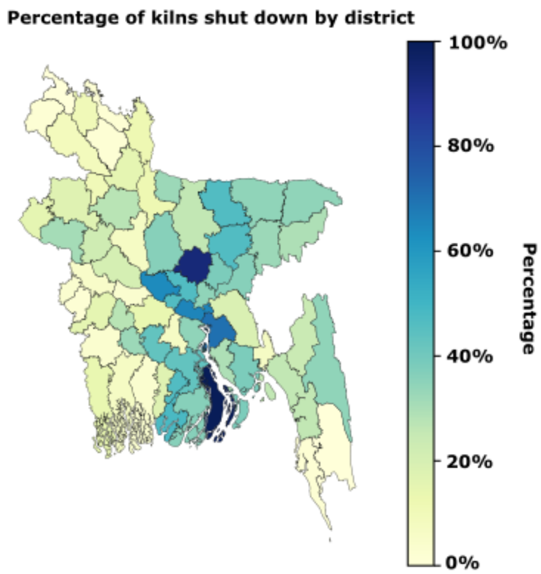


Fig. S2. Percentage of brick kilns shut down by district. The total number of deactivated kilns from 2014 until 2023 as a percentage of the total number of kilns that were active at any time between 2014 until 2023, aggregated by district. All districts had at least one active kiln during the period (minimum: 31; maximum: 597).

Fig. S3. Regional health harms of brick kilns. *Left*: The number of active brick kilns in each subdistrict (*upazila*) in Bangladesh in 2023. *Center*: The mean excess mortality per kiln caused by emissions from brick kilns in each subdistrict. *Right*: The total excess mortality caused by emissions from brick kilns in each subdistrict (equivalent to the left panel multiplied by the center panel). Note that this map shows the location of the kilns rather than where the mortality is occurring. *[NOTE: Figure S3 has not currently been made available.]*

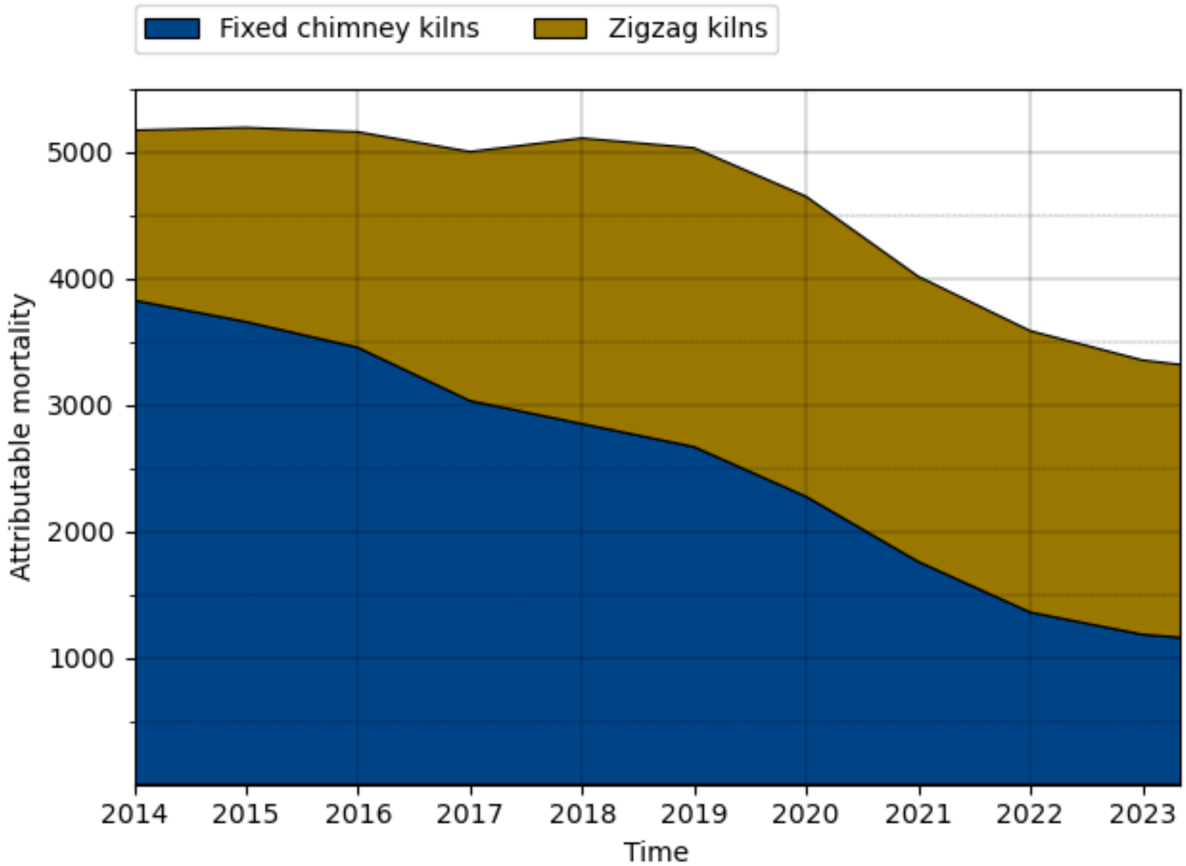


Fig. S4. Changing health harms from brick kilns. How deaths attributable to brick kiln emissions in Bangladesh would change if the number of kilns and their firing technologies were fixed at different points in time.

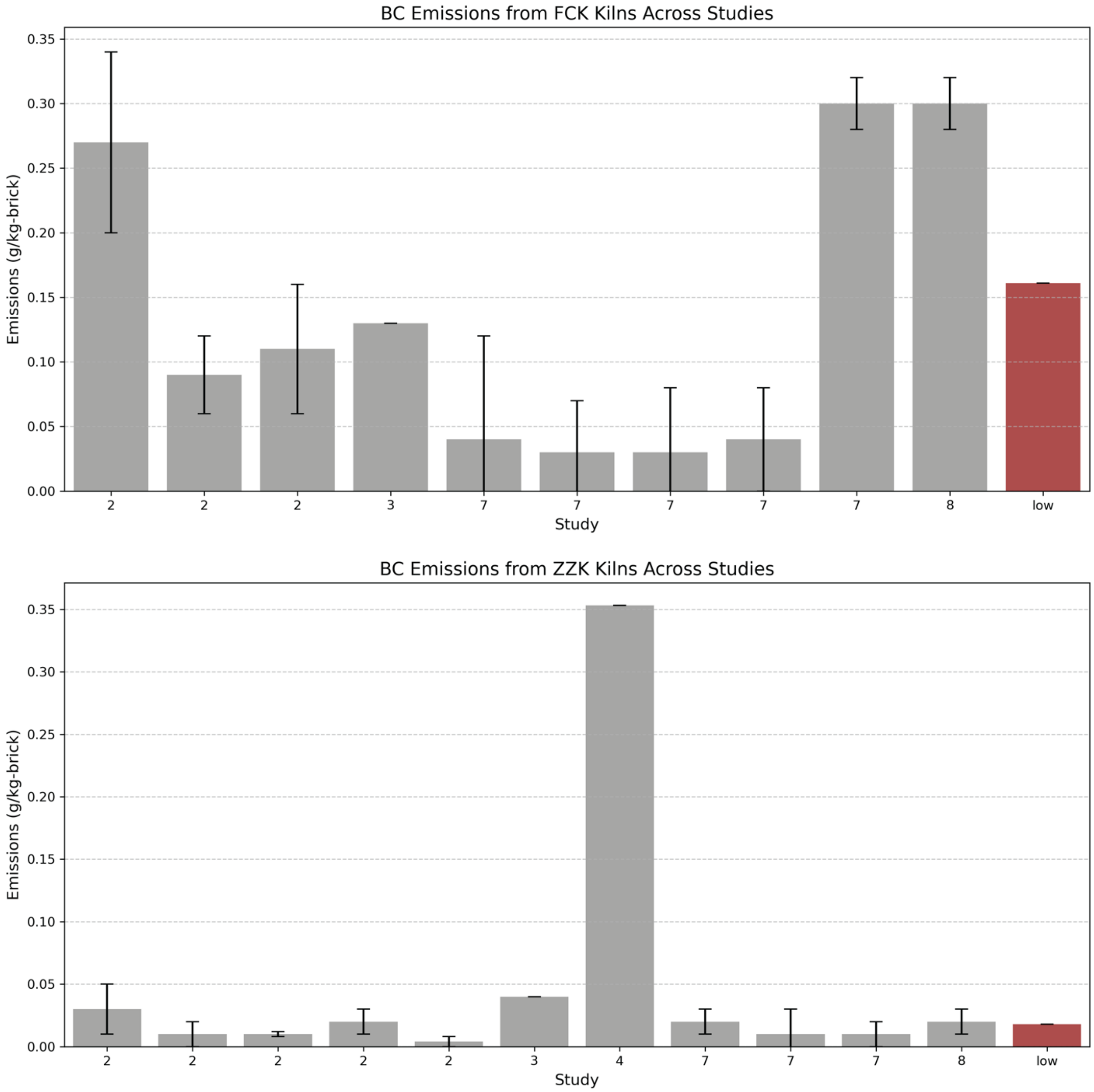


Fig. S5. Literature review of Black Carbon (BC) emissions. *Top*: BC emissions from fixed chimney kilns (FCK) across the 8 studies included in the literature review. *Bottom*: BC emissions from zigzag kilns (ZZK) across the 8 studies included in the literature review. Error bars denote one standard deviation above and below the mean. "Low" corresponds to the inverse-variance-weighted mean emissions from the studies. The study numbers refer to: 1. Nasim *et al.* (*36*); 2. Weyant *et al.* (*37*); 3. Lalchandani *et al.* (*38*); 4. Jayarathne *et al.* (*39*); 5. Stockwell *et al.* (*40*); 6. Rajarathnam *et al.* (*41*); 7. Nepal *et al.* (*42*); and 8. Haque *et al.* (*43*). Unreported standard deviations are shown here as 0.0 but in calculating the "low" emissions, the average standard deviations are imputed.

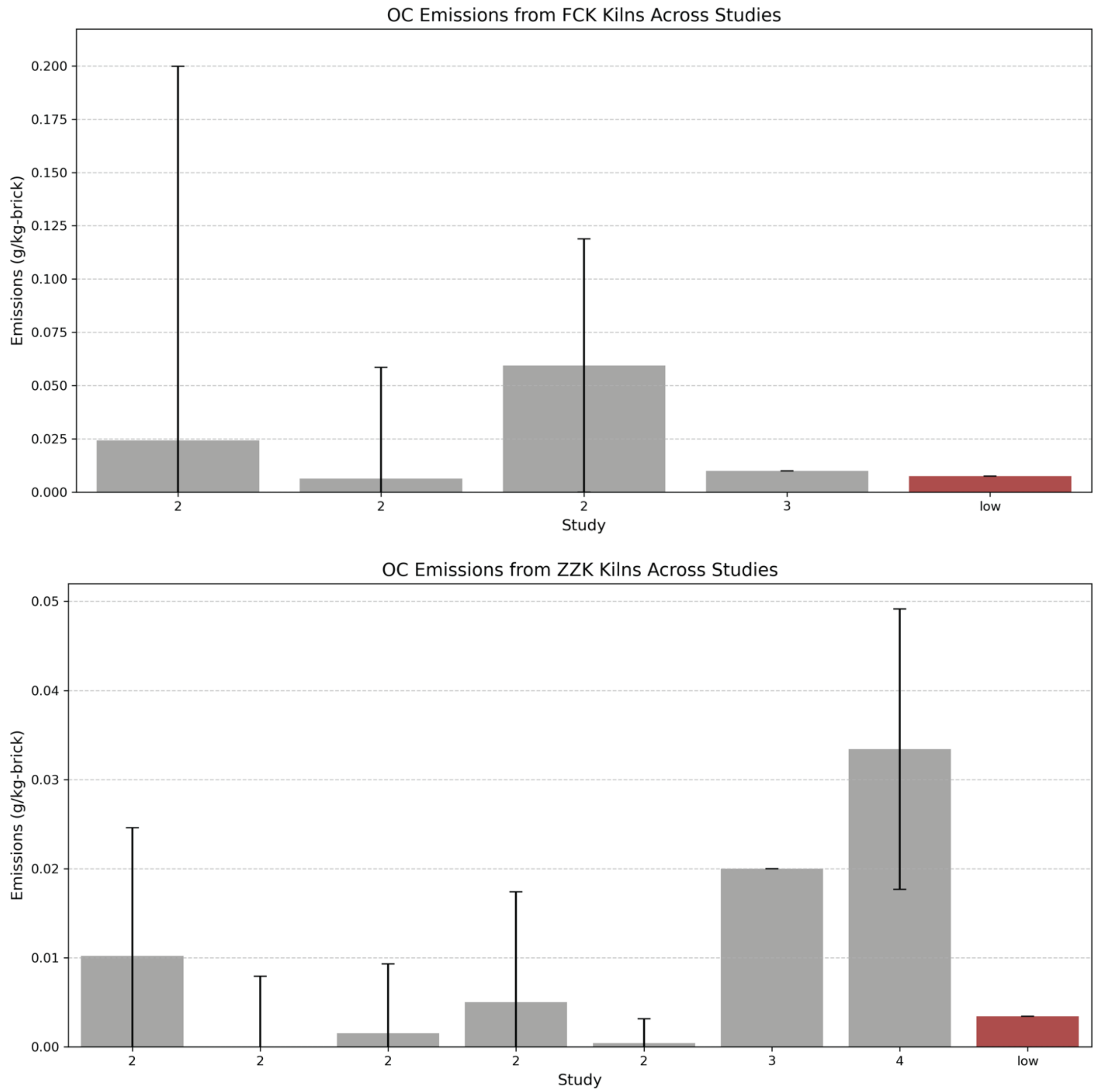


Fig. S6. Literature review of Organic Carbon (OC) emissions. *Top*: OC emissions from fixed chimney kilns (FCK) across the 8 studies included in the literature review. *Bottom*: OC emissions from zigzag kilns (ZZK) across the 8 studies included in the literature review. Error bars denote one standard deviation above and below the mean. "Low" corresponds to the inverse-variance-weighted mean emissions from the studies. The study numbers refer to: 1. Nasim *et al.* (*36*); 2. Weyant *et al.* (*37*); 3. Lalchandani *et al.* (*38*); 4. Jayarathne *et al.* (*39*); 5. Stockwell *et al.* (*40*); 6. Rajarathnam *et al.* (*41*); 7. Nepal *et al.* (*42*); and 8. Haque *et al.* (*43*). Unreported standard deviations are shown here as 0.0 but in calculating the "low" emissions, the average standard deviations are imputed.

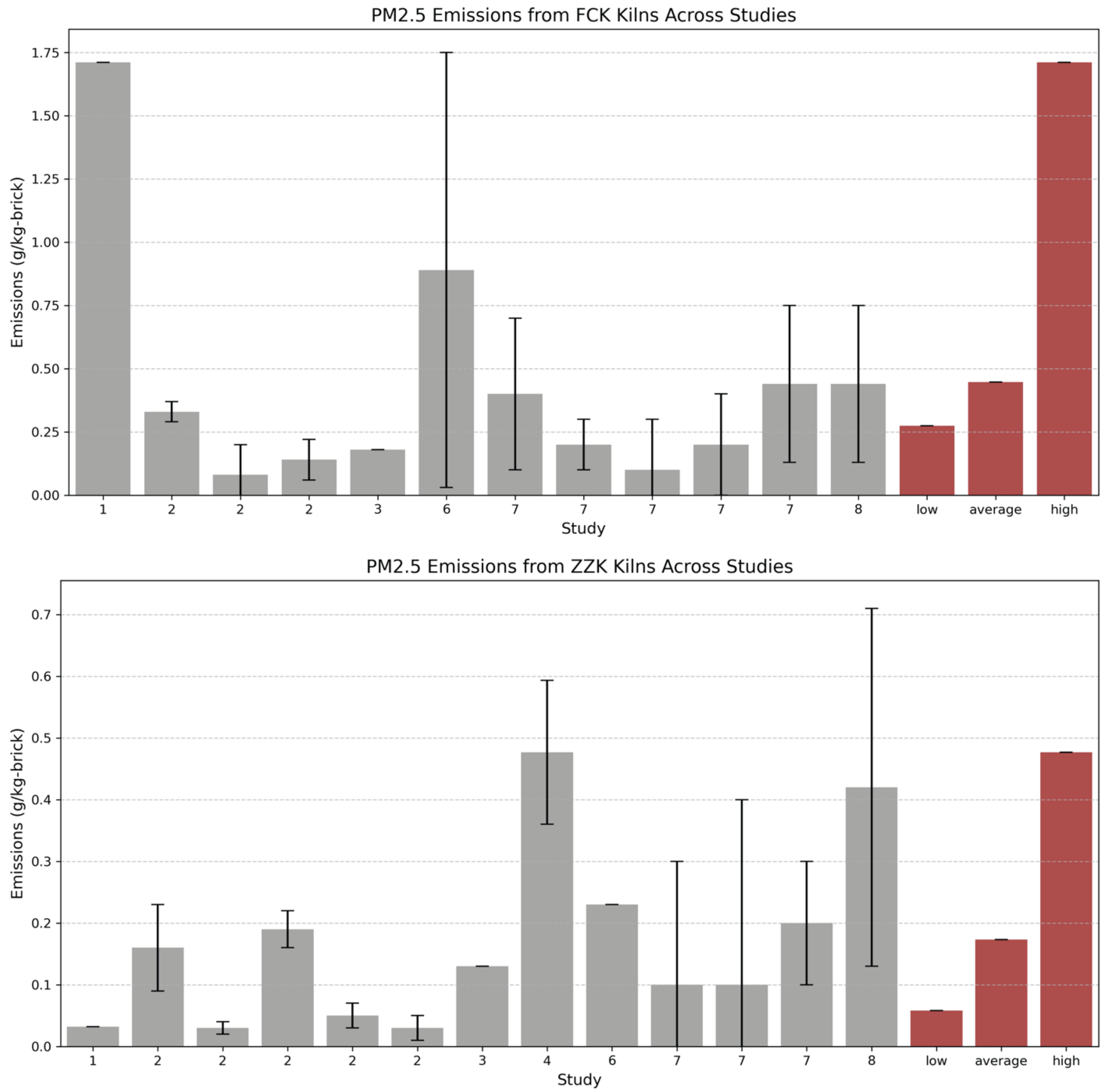


Fig. S7. Literature review of fine particulate matter ($PM_{2.5}$) emissions. *Top*: $PM_{2.5}$ emissions from fixed chimney kilns (FCK) across the 8 studies included in the literature review. *Bottom*: $PM_{2.5}$ emissions from zigzag kilns (ZZK) across the 8 studies included in the literature review. Error bars denote one standard deviation above and below the mean. "Low" corresponds to the inverse-variance-weighted mean emissions from the studies; "average" corresponds to the straightforward mean emissions across studies; "high" corresponds to the maximum measured emissions across studies. The study numbers refer to: 1. Nasim *et al.* (*36*); 2. Weyant *et al.* (*37*); 3. Lalchandani *et al.* (*38*); 4. Jayarathne *et al.* (*39*); 5. Stockwell *et al.* (*40*); 6. Rajarathnam *et al.* (*41*); 7. Nepal *et al.* (*42*); and 8. Haque *et al.* (*43*). Unreported standard deviations are shown here as 0.0 but in calculating the "low" emissions, the average standard deviations are imputed.

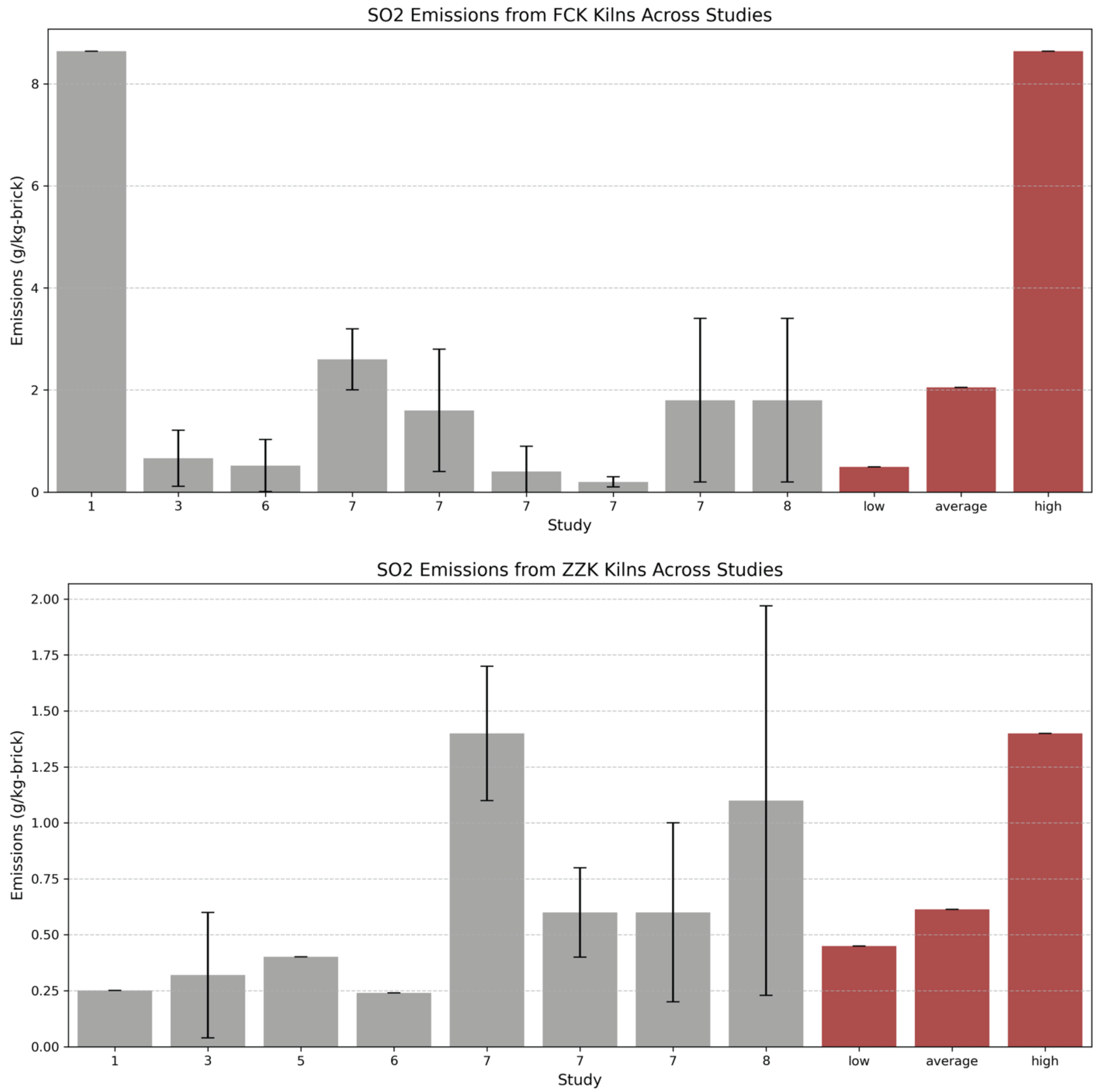


Fig. S8. Literature review of sulfur dioxide (SO_2) emissions. *Top*: SO_2 emissions from fixed chimney kilns (FCK) across the 8 studies included in the literature review. *Bottom*: SO_2 emissions from zigzag kilns (ZZK) across the 8 studies included in the literature review. Error bars denote one standard deviation above and below the mean. “Low” corresponds to the inverse-variance-weighted mean emissions from the studies; “average” corresponds to the straightforward mean emissions across studies; “high” corresponds to the maximum measured emissions across studies. The study numbers refer to: 1. Nasim *et al.* (*36*); 2. Weyant *et al.* (*37*); 3. Lalchandani *et al.* (*38*); 4. Jayarathne *et al.* (*39*); 5. Stockwell *et al.* (*40*); 6. Rajarathnam *et al.* (*41*); 7. Nepal *et al.* (*42*); and 8. Haque *et al.* (*43*). Unreported standard deviations are shown here as 0.0 but in calculating the “low” emissions, the average standard deviations are imputed.

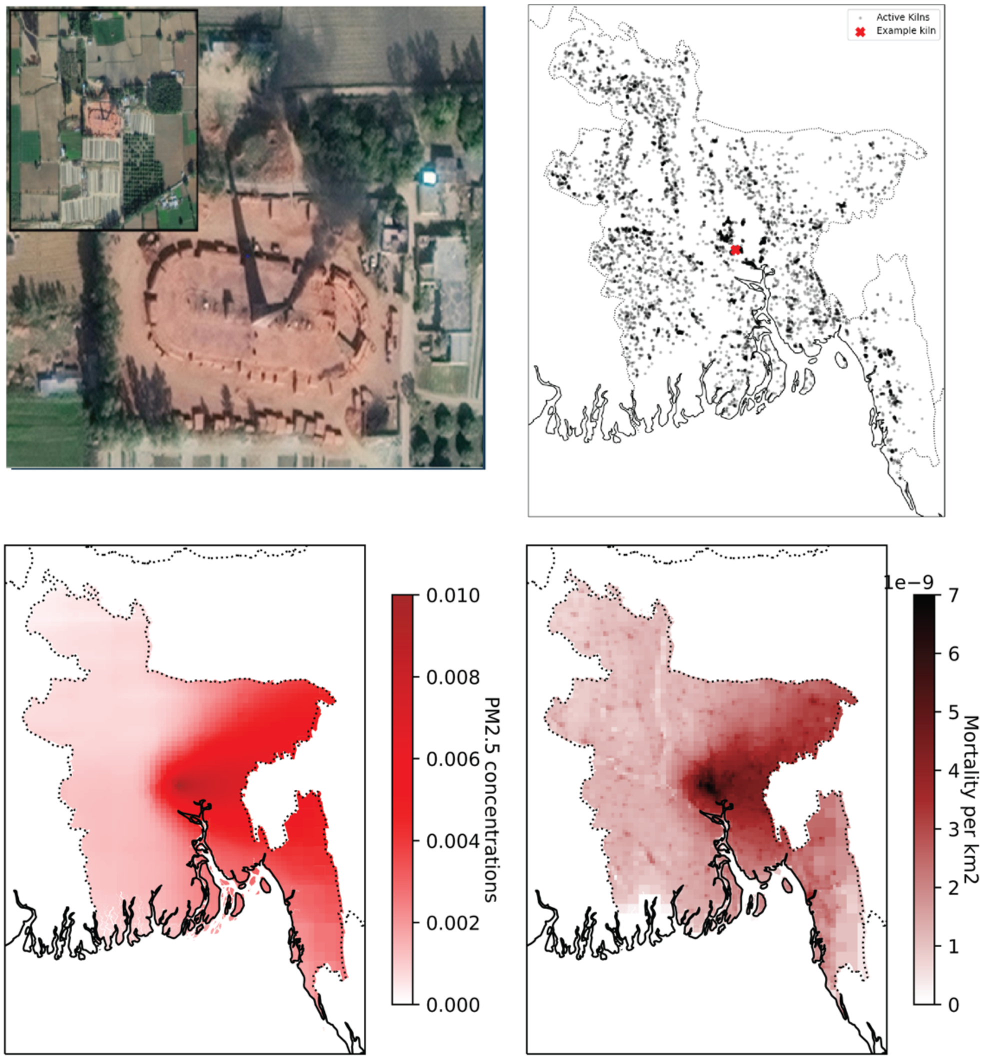
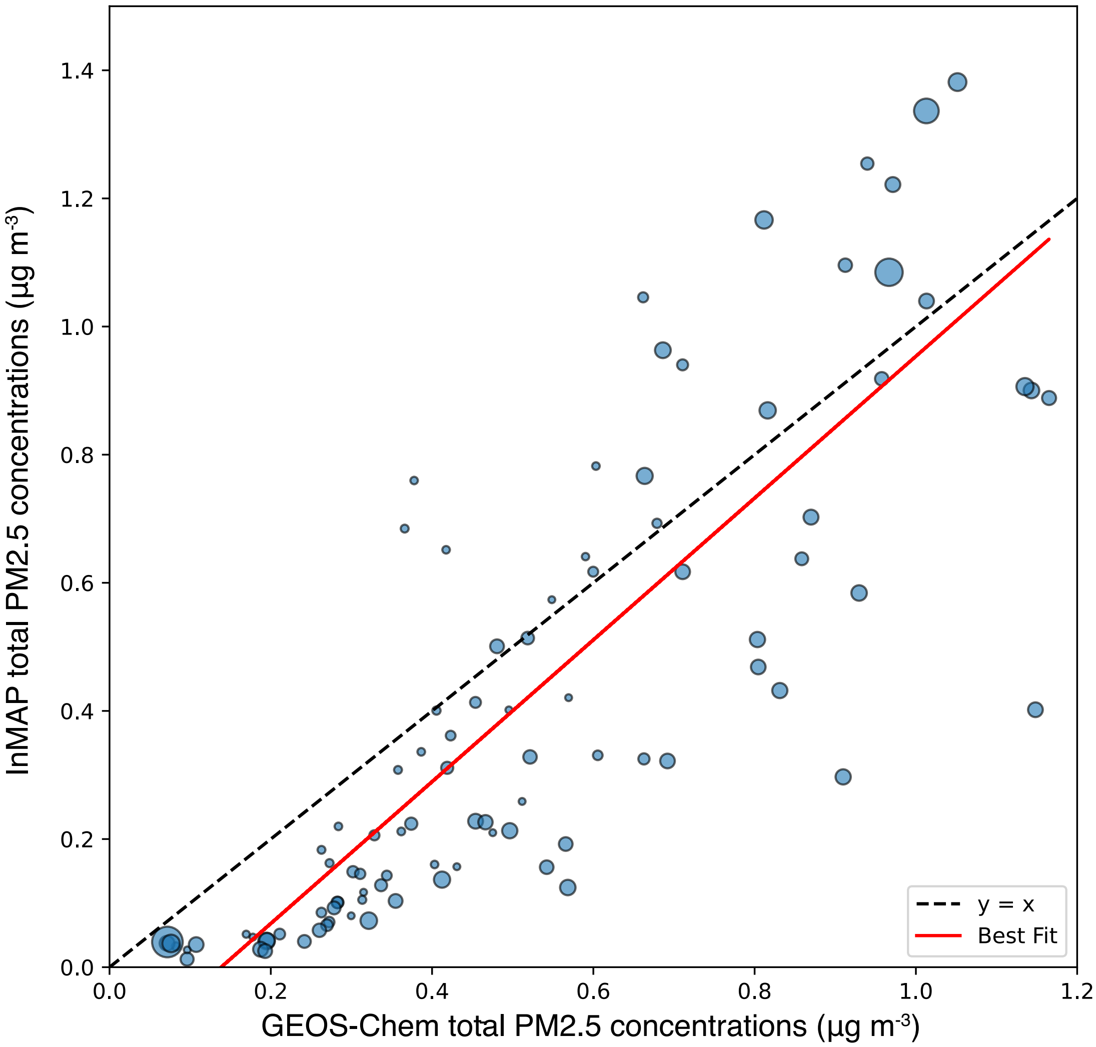


Fig. S9. Illustration of methodology. *Top left*: Brick kiln location and type are identified by satellite imagery. *Top right*: All kilns in Bangladesh are geospatially located. An example kiln is identified with a red 'X'. *Bottom left*: The change in pollutant concentrations (relative to baseline concentrations without the brick kiln) are estimated for each brick kiln (here, shown for the example kiln), using a reduced-complexity air quality model. *Bottom right*: The change in mortality risk associated with the increase in pollutant concentrations from each brick kiln (here, shown for the example kiln) are estimated.



R^2:	0.68	**NMB:**	–26.7%	**NME:**	48.5%
pop-wtd.:	0.74	*pop-wtd.*:	–18.0%	*pop-wtd.*:	41.4%

Fig. S10. Air quality model comparison. Changes in average fine particulate matter ($PM_{2.5}$) concentrations from the GEOS-Chem simulation against the InMAP results regridded to the GEOS-Chem grid (0.5° × 0.625°). Both simulations use emissions corresponding to the 2022–2023 season using inverse variance-weighted mean emission factors. NME: normalized mean error; NMB: normalized mean bias. The red line corresponds to the population-weighted line-of-best-fit. Marker width corresponds to relative population size of the grid cell (more populous cells have proportionally larger marker widths).

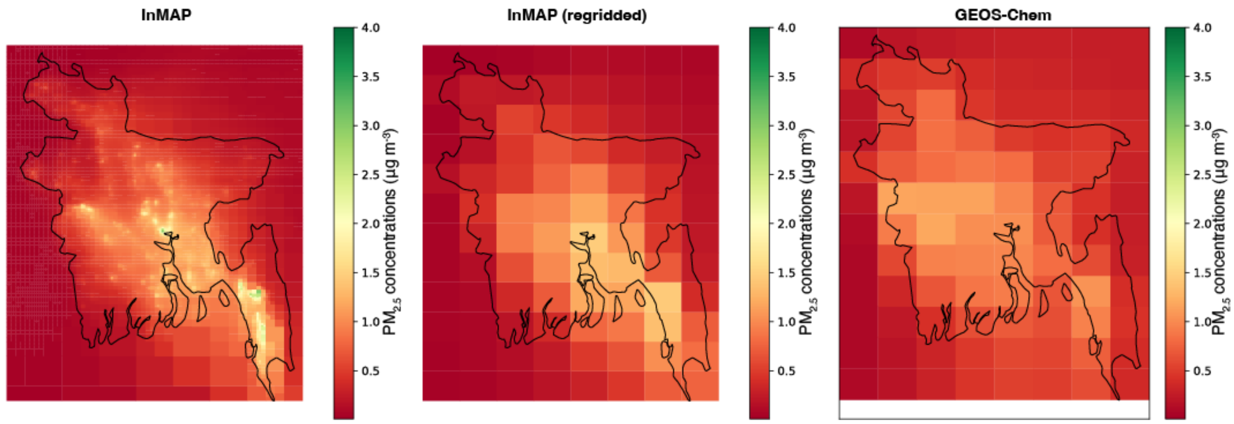


Fig. S11. Changes in pollutant concentrations from brick kiln emissions across Bangladesh. *Left*: Changes in average fine particulate matter ($PM_{2.5}$) concentrations from the InMAP simulation (native grid). *Middle*: Changes in $PM_{2.5}$ concentrations from the InMAP simulation, regridded to the GEOS-Chem grid (0.5° × 0.625°). *Right*: Changes in $PM_{2.5}$ concentrations from the GEOS-Chem simulation. Simulations here correspond to the 2022–2023 season, using inverse variance-weighted mean emission factors. All changes are relative to a baseline scenario with no brick kiln emissions.

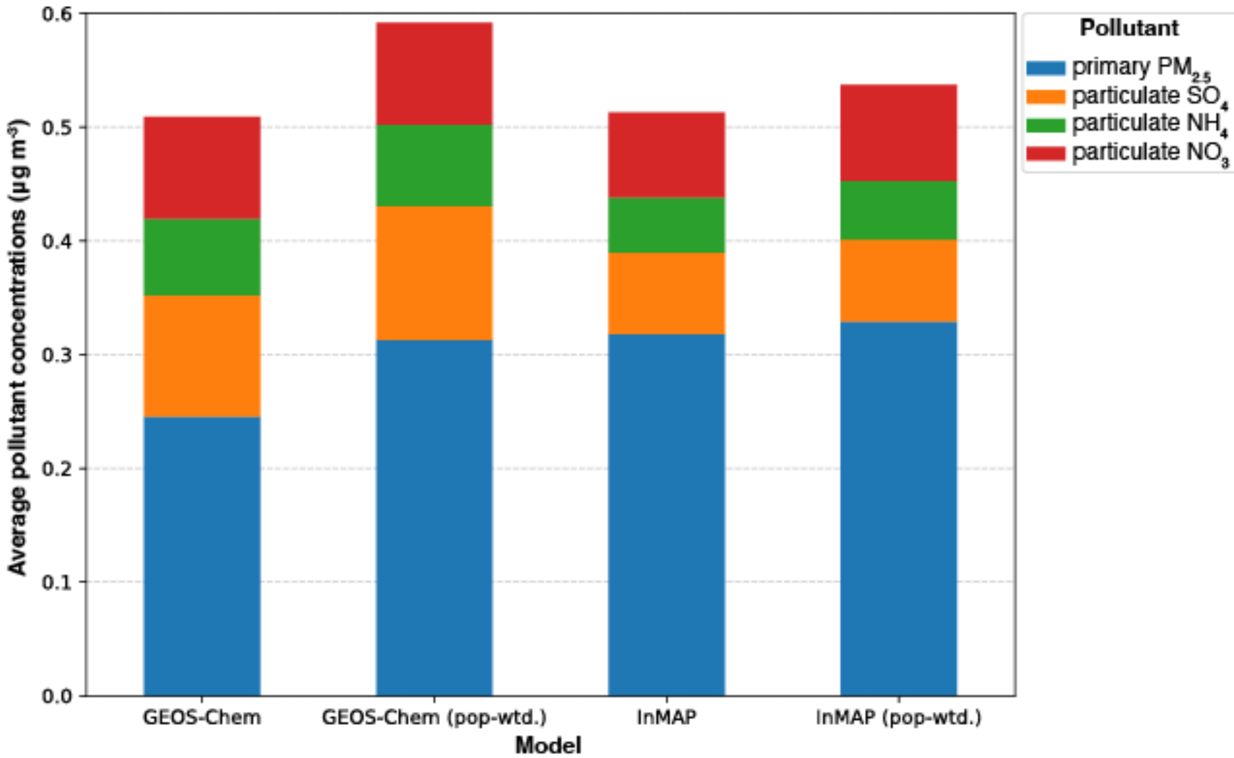


Fig. S12. Population-weighted concentrations. Changes in average and population-weighted-average concentrations of fine particulate matter ($PM_{2.5}$) from brick kilns during the 2022–2023 season, using inverse variance-weighted mean emission factors, from the GEOS-Chem and InMAP simulations. Pollutant concentrations are shown by $PM_{2.5}$ species. Primary $PM_{2.5}$ includes mineral dust, primary organic aerosol, and black carbon concentrations. Changes in secondary organic aerosol concentrations were negligible in all model simulations and are not shown here.

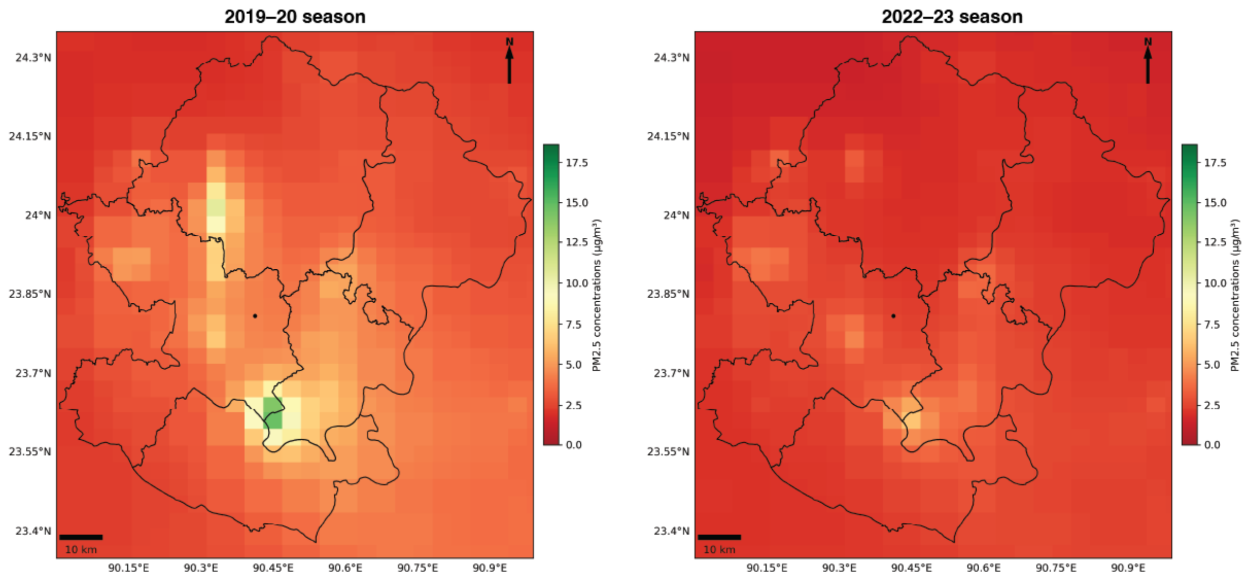


Fig. S13. Changes in pollutant concentrations across Dhaka. Changes in average concentrations of fine particulate matter ($PM_{2.5}$) from brick kilns during the 2019–2020 (*left*) and 2022–2023 (*right*) season, using mean emission factors, across the Greater Dhaka Area.

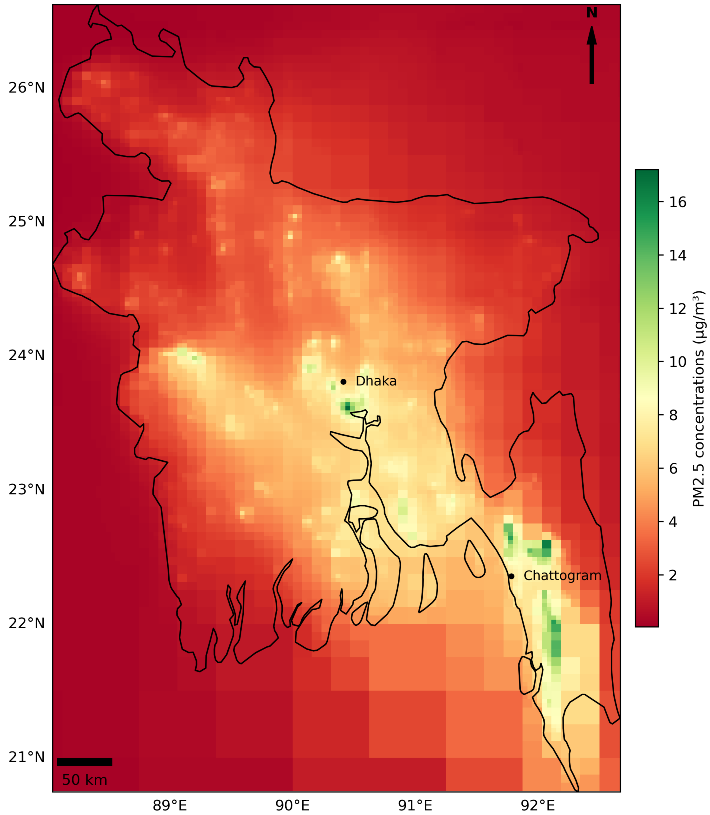


Fig. S14. Changes in pollutant concentrations across Bangladesh using maximum observed emission factors. Changes in average fine particulate matter ($PM_{2.5}$) concentrations from the InMAP simulation during the 2022–2023 season, using the maximum observed emission factors.

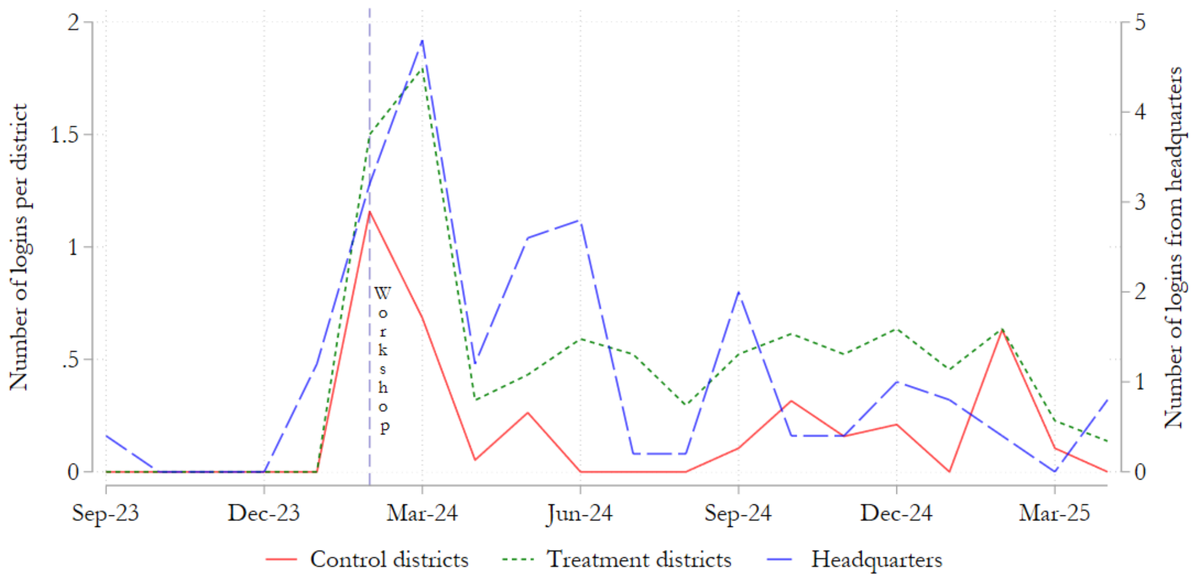


Fig. S15. Pollution Source Prioritization System (PSPS) usage. Number of logins per district and from headquarters into the PSPS by Department of Environment (DoE) officials since September 2023. The vertical line corresponding to the month (February 2024) when the PSPS was officially launched through a workshop held at the DoE headquarters. We use two y-axes. The left y-axis measures the logins per district while the right y-axis measure the total number of log-ins from headquarters.

Emission scenarios	Concentration-response function	Mortality estimation method	Excess deaths
mean	GEMM 5COD	attribution	1,687
	GEMM all-cause	attribution	3,380
	GEMM 5COD	subtraction	1,414
	GEMM all-cause	subtraction	2,600
Inverse variance-weighted mean	GEMM 5COD	attribution	659
	GEMM all-cause	attribution	1,321
	GEMM 5COD	subtraction	555
	GEMM all-cause	subtraction	1,020
maximum	GEMM 5COD	attribution	4,934
	GEMM all-cause	attribution	9,890
	GEMM 5COD	subtraction	4,091
	GEMM all-cause	subtraction	7,502
2019 kilns (mean emissions)	GEMM 5COD	attribution	2,422
	GEMM all-cause	attribution	4,853
	GEMM 5COD	subtraction	2,020
	GEMM all-cause	subtraction	3,711
Higher zigzag kiln emissions scenario	GEMM 5COD	attribution	2,837
	GEMM all-cause	attribution	5,684
	GEMM 5COD	subtraction	2,366
	GEMM all-cause	subtraction	4,346
Zigzag kiln policy intervention	GEMM 5COD	attribution	2,665
	GEMM all-cause	attribution	5,340
	GEMM 5COD	subtraction	2,224
	GEMM all-cause	subtraction	4,087

Table S1. Excess deaths from brick kiln pollution. Changes in mortality attributable to brick kilns during the 2022–2023 kiln season under different choices of emission scenario, concentration-response function, and mortality estimation method. The 2019 emission scenario describes a counterfactual scenario where all and only the kilns active by the beginning of year 2019 (when kiln numbers peaked) are active in the 2022–2023 season. The "GEMM 5COD" and "GEMM all-cause" concentration response functions refer to the Global Exposure Mortality Model (*57*) functions for the 5 major causes of death ("5COD"), and for all-cause mortality. The mortality estimation method is similar to that described in Kodros *et al.* (*61*).

	(1) Logins	(2) Minutes Spent
Covered District	0.38***	91***
	(0.13)	(28)
Observations	960	960
Clusters (Number of Districts)	64	64
Control Mean	0.24	46
Month FE	Yes	Yes
Obs. Level	Month-District	Month-District

Table S2. Impact of District Inclusion on PSPS Usage. This table shows the effect of a district being covered by the PSPS on the usage of the PSPS by officials from that district. The effect is measured by an ordinary least squares regressions where we are comparing districts that are partially covered by the tracker (Covered District) with those that were pure control district for which the PSPS did not show any information. The extent to which a district is using the PSPS is measured by the number of logins and minutes spent logged in by officials assigned to that district at the start of the experiment. All data is at the district by month level and showing the sums of logins and minutes spent by all officials in that district in that month. A month fixed effect has been applied and the standard errors (in parenthesis) have been clustered at the district level. * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$.

		YOLO-derived data	
		Not Identified	Identified
Comprehensive Data	Verified to be inactive	N/A	9.7%
	Verified to be active	9.4%	80.8%

Table S3. Validation of satellite Earth observation data showing the percentage of brick kilns identified in this study ("YOLO-derived data") that were identified (and verified as active) in the Comprehensive Data (derived from a combination of multiple datasets). Values are given as a percentage of the total (active or inactive) kilns in the Comprehensive Data. Activity is based on the latest image.

Scenario	Kiln type	Emissions (g/kg-brick)			
		$PM_{2.5}$	SO_2	NO	VOC
Avg	FCK	0.45	2.1	0.06	0.0084
	ZZK	0.17	0.61	0.05	0.0084
Max	FCK	1.7	8.6	0.06	0.0084
	ZZK	0.48	1.4	0.06	0.0084
IVWM	FCK	0.27	0.49	0.06	0.0084
	ZZK	0.06	0.45	0.05	0.0084

Table S4. Emissions used in this study. Emissions of key pollutants considered for both fixed chimney kilns (FCK) and zigzag kilns (ZZK) for the mean ("Avg"), maximum ("Max"), and the inverse variance-weighted mean ("IVWM") scenarios, as derived from a review of the available literature. See Table S5 for emissions of volatile organic compounds, black carbon, and organic carbon.

Scenario	Kiln type	Emissions (g/kg-brick)							
		BC	OC	Benzene	Toluene	Alkanes (>4C)	Alkenes (>3C)	Isoprene	Xylene
Avg	FCK	0.16	0.01	0.0003	0.001	0.003	0.0003	0.001	0.003
	ZZK	0.02	0.003	0.0003	0.001	0.003	0.0003	0.001	0.003
Max	FCK	0.3	0.02	0.0003	0.001	0.003	0.0003	0.001	0.003
	ZZK	0.35	0.03	0.0003	0.001	0.003	0.0003	0.001	0.003
IVWM	FCK	0.16	0.01	0.0003	0.001	0.003	0.0003	0.001	0.003
	ZZK	0.02	0.003	0.0003	0.001	0.003	0.0003	0.001	0.003

Table S5. Detailed emissions used in this study. Emissions of all pollutants considered for both fixed chimney kilns (FCK) and zigzag kilns (ZZK) for the mean ("Avg"), maximum ("Max"), and the inverse variance-weighted mean ("IVWM") scenarios, as derived from a review of the available literature. See Table S4 for emissions of total fine particulate matter ($PM_{2.5}$), sulphur dioxide (SO_2), and nitrogen oxide (NO).