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 remotely-sensed data, machine learning, and air-quality models to locate 9,187 clay brick kilns (2014–2024), estimating their technology, activity status, and health effects. Active kilns peaked in 2019 and have since declined by 4% annually. Kiln emissions cause approximately 3,730 (764–11,890) excess deaths yearly (30% lower than 2019), with 25% of deaths attributable to 8% 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.

Introduction

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 the 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 of kiln construction and demolition have been unclear.

Here, we estimate the individual air quality-related health impacts of every brick kiln in Bangladesh active from 2014 until 2024. We combine remote sensing for Earth observation satellite imagery and neural networks to identify the location and characteristics (firing technology and activity status) of all brick kilns in Bangladesh, which we manually confirm for each kiln. 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.

Previous work (*8*, *13*, *14*) has mapped brick kiln locations in South Asia, but not detailed characteristics (firing technology or activity status). Some prior studies have estimated the health harms of the brick kiln sector in India (*15*) or some regions of Bangladesh (*4, 16*), or estimated the impact of the brick kiln sector in Bangladesh using rough estimates that do not rely on air quality models (*6*). No prior studies have estimated the air quality-related health impacts of each individual kiln, which would provide a basis for targeting enforcement of the Brick Kilns Act for the most harmful kilns.

Here, we evaluate the individual health harms of all brick kilns in Bangladesh that were active between 2014 and 2023. 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. Our methodology for creating such a system, by combining satellite Earth observation data and air quality models, is widely applicable for estimating the health harms of individual emission sources, even in countries where national emission inventories are lacking. Although we document trends in the health impacts of brick kilns in Bangladesh, our methodology is widely applicable for any emission sources detectable from satellite imagery, such as crop residue burning, landfill fires, and informal mining.

Results

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 (−4.0% yr^{-1}) and low rates of kiln construction (+1% yr^{-1}). The change in trends of brick kilns roughly coincided with the amendment and increased enforcement of the Brick Kilns Act, which was enacted in 2019.

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 more modern “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 have 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 7,061 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, Karaniganj 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 3,730 (model range: 764–11,890) 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 Information), 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 17× the health harms as the 99th percentile. Only 9% of kilns cause ~25% of the health harms, and 24% 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 340 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 between 2014 and 2024 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 protected 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 1,439 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 1,660 excess deaths yr^{-1}. By contrast, shutting down all 1,439 fixed chimney kilns (20% of all kilns) would avoid 1,440 deaths yr^{-1}, and switching their technologies to zigzag kilns will avoid around 930 deaths yr^{-1}. Shutting down the 502 kilns in subdistricts close to Dhaka (7% of total) would avoid ~500 deaths yr^{-1}, which is 64% of the benefits of the most efficient strategy (which shuts down the most damaging 7% of kilns to avoid ~780 deaths yr^{-1}). Enforcing both strategies (shutting down kilns close to Dhaka and fixed chimney kilns) would involve shutting down 27% of total kilns to avoid 1,900 deaths yr^{-1}, which is close to the most efficient strategy, achieving 95% of the avoided deaths for the same number of kilns.

Development of a 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 February 2025, officials in districts where the PSPS was deployed used 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.

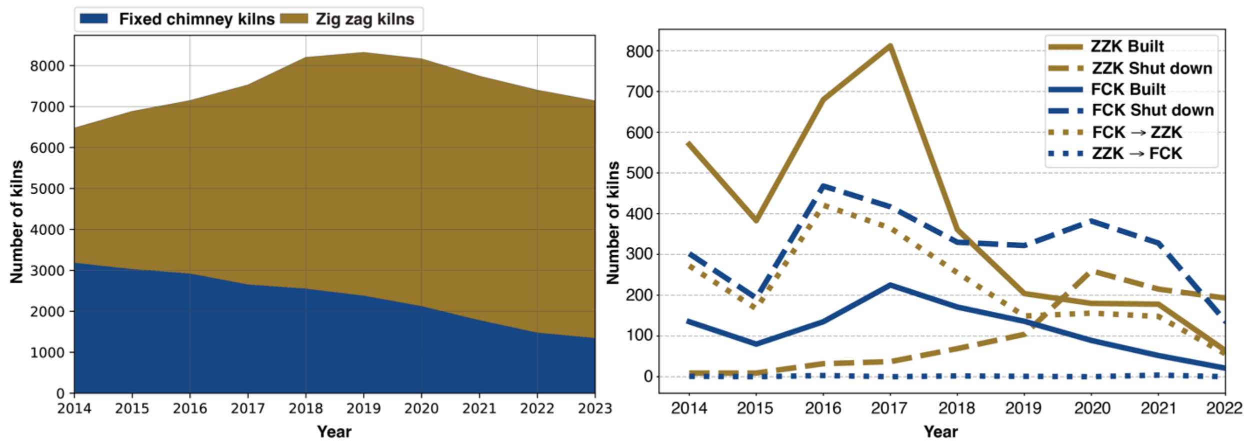

Figure 1. Change in number of kilns over time. *Left*: Total brick kilns in Bangladesh each year, by kiln technology. *Right*: Changes in active brick kilns each year, by kiln technology (FCK: fixed chimney kilns, ZZK: zigzag kilns), and whether new kilns were built or shut down that year, or kilns switched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

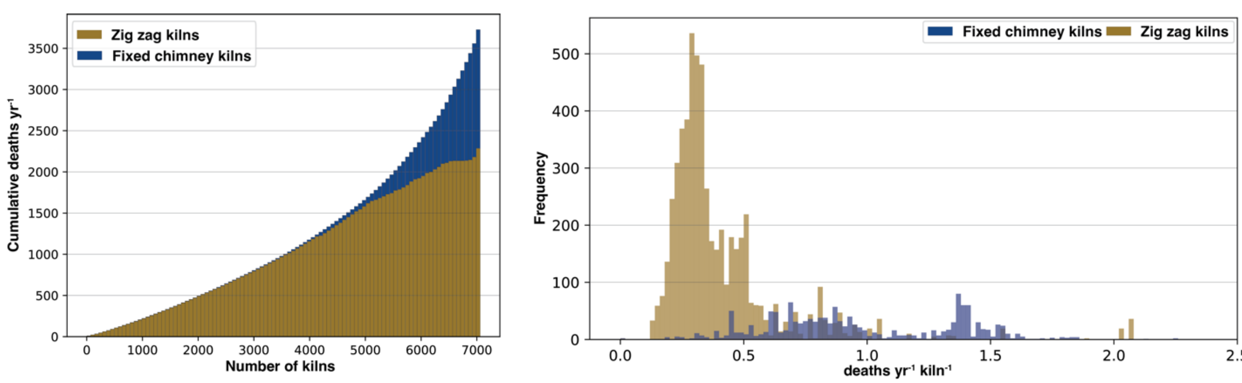

Figure 2. Variation in health harms per brick kiln. *Left*: Cumulative annual mortality caused by pollution from brick kilns in 2023, ordered from least to most damaging, and decomposed by kiln technology. *Right*: The frequency distribution of mortality per brick kiln, by kiln technology.

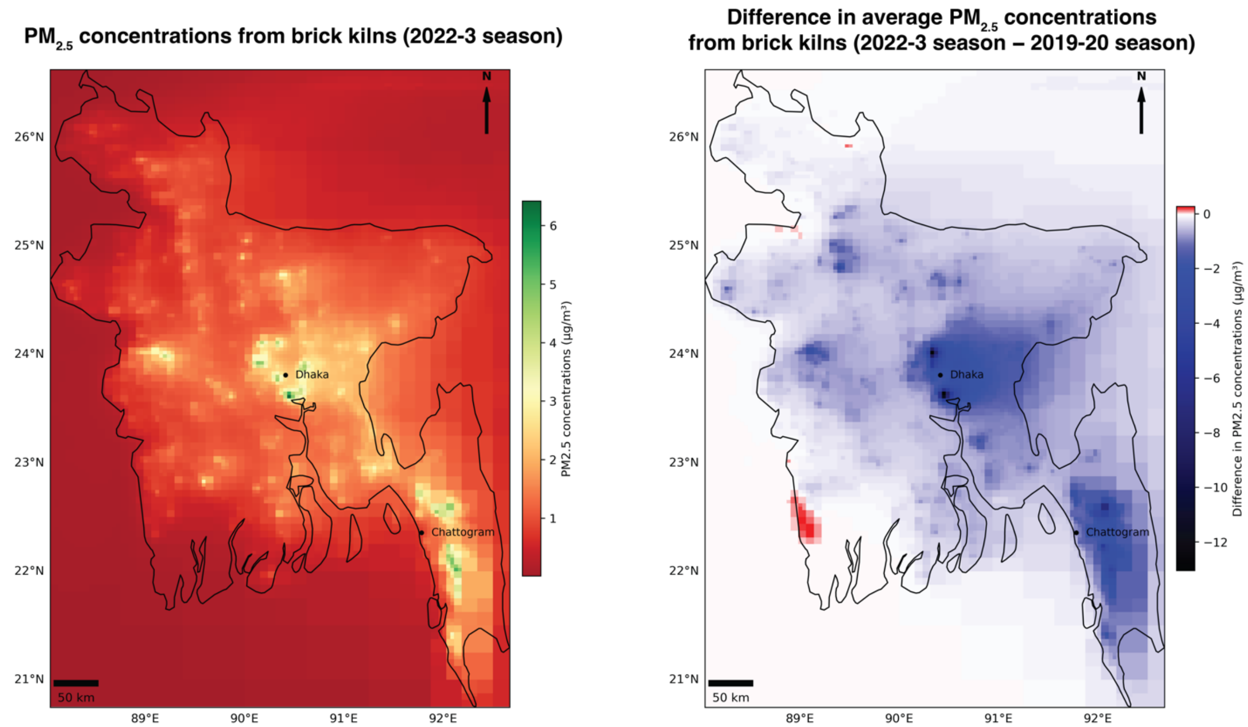

Figure 3. Changes in pollutant concentrations from brick kilns. *Left:* Average changes in fine particulate matter ($PM_{2.5}$) concentrations from brick kilns in the 2022–2023 season (November–May) in the baseline emissions scenario (using the average emission factors). *Right:* Reductions in average 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.

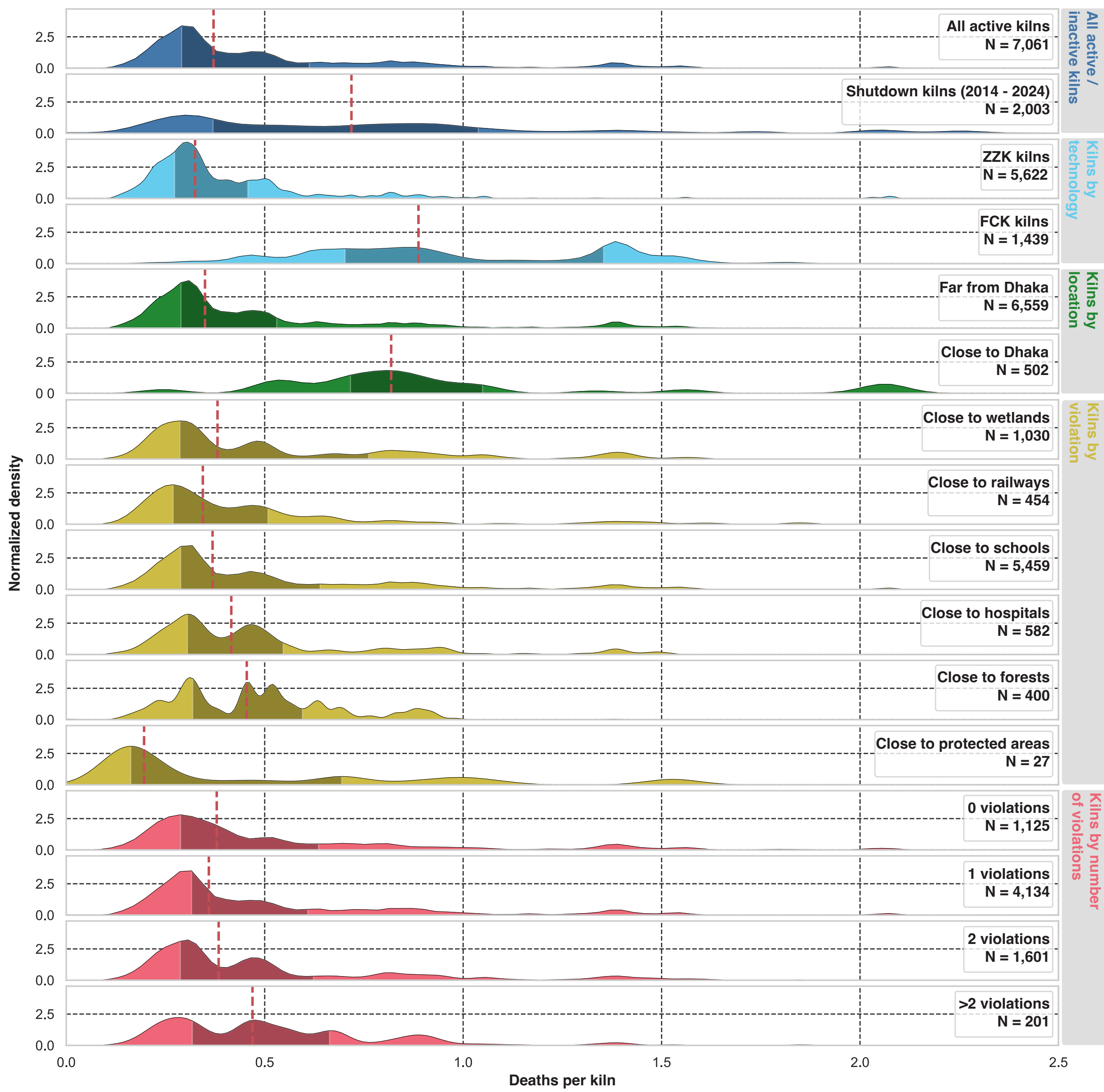

Figure 4. Health harms of kilns by violation. The distribution of deaths per kiln across kilns in Bangladesh, decomposed by whether the kilns are active or shutdown (*dark blue*); their technology (*light blue*; ZZK = zigzag kilns, FCK = fixed chimney kilns); their location (*green*); and whether they 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. 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.

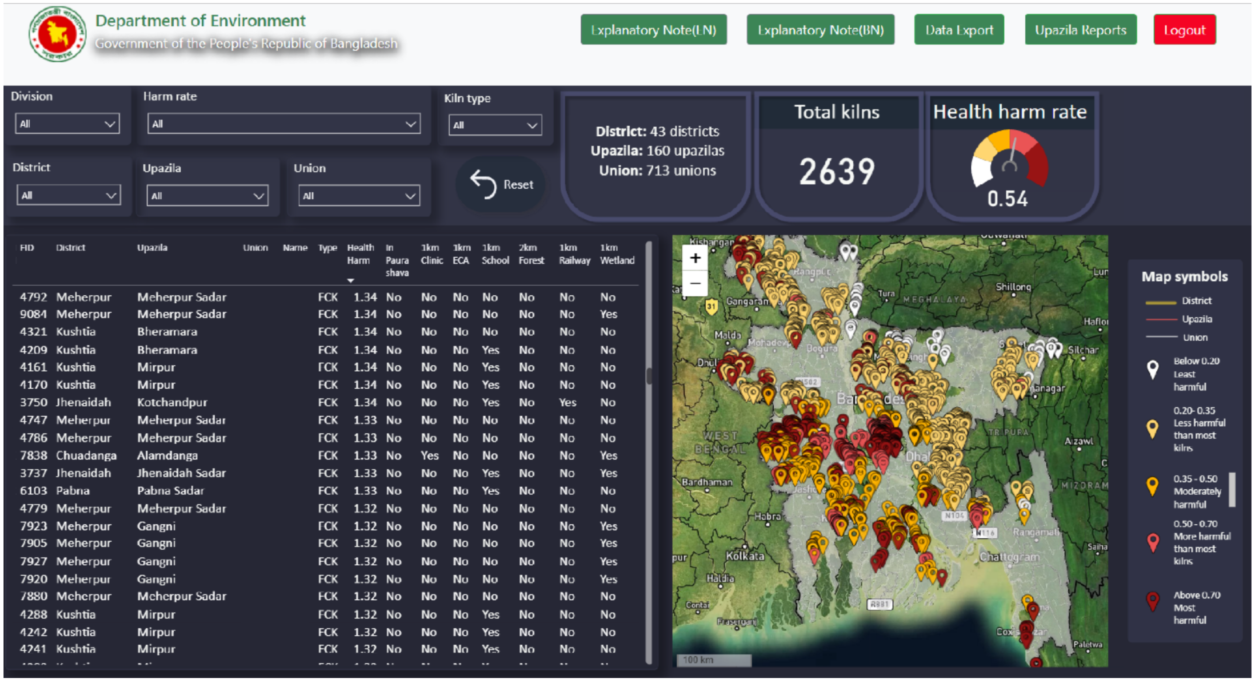

Figure 5: A screenshot of our pollution source prioritization system (PSPS). Currently, it covers 160 subdistricts (out of 488) from 43 districts (out of 64) in Bangladesh. Areas not covered are grayed-out on the map. The PSPS provides the location, names, estimated public health harm, and estimated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

Discussion

Low- and middle-income countries tend to suffer more from air pollution (*17*), yet they have fewer resources to address their burden, because of lack of regional and sub-sectoral emission inventories (*18*), sparse ground observations from air quality monitoring networks (*19*), less data on baseline health risks or demographic information, less availability of air quality models and capacity to use them (*12*), and less capacity to enforce environmental regulations. Increasingly, accessibility-enhancing tools such as satellite Earth observation data (*14, 20*), reduced-complexity models (*12, 21*), machine learning methods (*22*), and low-cost sensors (*23*) are being used to aid efficient air quality and environmental regulation in low- and middle-income countries, by drastically reducing the cost of assessing and monitoring environmental impacts.

Here, we demonstrate the successful application of such accessibility-enhancing tools for brick production, a major sustainability target for reducing greenhouse gas emissions (*24*), improving working conditions (*14*), and air quality. Our approach provides the most comprehensive and accurate picture of brick kilns in Bangladesh. The methodology can be repeated every year, and across all of South Asia, to get an understanding of how the sector is evolving. Our highly vetted data of kiln technology and activity can be used as training data for neural networks to identify kiln characteristics in future studies.

The methodology is highly policy relevant. We have aggregated our results into a user-friendly pollution source prioritization system, accessible to government officials through the internet. The system is currently being used to plan government regulation of brick kilns, which complements other notable ongoing policy-related research that aims to reduce kiln emissions through working directly with kiln owners (*25*).

Our methodology could also be used to understand the air quality-related health impacts of other industrial sectors, including those that are more informal and less understood than brick kilns. The informal sector represents 41% of GDP in middle-income countries (*26*) and employs more than half the global workforce (*27*), yet its environmental regulation remains a persistent challenge (*28*). Traditional methods of reporting, monitoring, and certifying informal institutions can be onerous and costly (*29*, *30*), which can make for inefficient enforcement. Our approach demonstrates how satellite Earth observation data, neural networks, and biophysical models can give a detailed picture of a sector without the need for costly surveying, and thus can be used to expand the reach of environmental regulation.

We demonstrate how to integrate accessibility-enhancing tools carefully, so as to not greatly compromise accuracy. We manually vet and compile all available datasets on brick kiln locations; we use a comprehensive literature review of emission factor measurements to generate 3 emission scenarios; and we use 3 approaches to attribute mortality to brick kilns for 2 different choices of concentration-response relationships. To estimate changes in pollutant concentrations, we use a combination of atmospheric models: GEOS-Chem, a state-of-the-science chemical transport model, and InMAP, a reduced complexity model that is essentially a linearization of a chemical transport model, designed to estimate small changes in concentrations as a result of changes in emissions. We use GEOS-Chem to assess and correct the biases of InMAP, and we use a nested, sub-annual parameterization of InMAP that better captures the chemistry and meteorology during the brick kiln season. The resulting model shows good agreement with GEOS-Chem predictions on the basis of spatial patterns, population-weighted average pollutant exposure, and population-weighted statistics ($R^2 = 0.70$, normalized mean bias = –4.6%), and is nevertheless 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 find that the air quality-related health impacts of brick kilns in Bangladesh are around 3,730 (model range:764–11,890) deaths yr^{-1}, or around 0.5 deaths $kiln^{-1}$ yr^{-1}. The adoption of zigzag kilns and the decline of fixed chimney kilns in the past decade has drastically reduced the emissions intensity of brick production in South Asia (*31*, *32*), an effect that we document for Bangladesh with satellite Earth observation data.

Our results for the individual kilns suggest that proximity to institutions and nature, implemented as violations of the Brick Kilns Act, is a poor proxy for health harm. 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, which is likely to make kilns close to hospitals and schools more damaging than assessed here. Furthermore, proximity-based regulations may be good proxies for environmental harms other than those on health. Our approach finds that the kilns that were actually shut down over the past decade have tended to be more harmful than average, generally because they are close to Dhaka or they are fixed chimney kilns and thus generate more pollution. Distance to Dhaka and firing technology tend to be good proxies of health harm. The data that our approach generates allows the government to both efficiently regulate and monitor brick kilns without having to rely on simplified and potentially inefficient heuristics, especially as we find that only 8% of kilns cause around a quarter of the health harms.

Data Access & Code Availability

Data and code, including those used to generate figures, are available at: https://github.com/SumilThakr/kilns.

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Methods

1. Estimating brick kiln locations and characteristics

Our approach to estimate brick kiln locations and characteristics closely follows Boyd *et al.* (*33*), 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.* (*33*) use the YOLO (You Only Look Once) v3 CNN architecture (*34*) 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.* (*33*). Here, we update Boyd *et al.* (*33*) for the years 2018, 2022, and 2024. For 2018, 2022, and the years covered by Boyd *et al.* (*33*), 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. To merge the datasets, we treated 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 90.5% of the brick kilns in the complete 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 of each of the identified sites, including inactive sites (which could, in general, become active again in later seasons). Using this approach, 9.7% of the total kilns in the complete data were found to be inactive in 2024 (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).

2. 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 seven 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. 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 (*35*). Data on locations of protected areas are from the World Database of Protected Areas (*36*).

There are also regulations stating that kilns cannot operate if there are more than 50 households living within a 1 km radius of the kiln. Our geospatial data does not allow us to assess whether kilns are in violation of this regulation; however, we are also not aware of any cases in which this regulation has been enforced (in part because it is difficult for the Department of Environment to assess it), so we exclude consideration of this regulation from our study.

3. 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 (*24, 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 (*15, 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 (*32*) (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 variance-weighted mean (VWM) 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

$$\hat{\sigma} = \sqrt[2]{\frac{1}{\sum_i \sigma_i}}$$

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 (*24*, *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*,*16*) 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, one of which (*40*, *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 this estimate of VOC emission from our study. Thus, the VOC estimates were derived from only one study (*40*), and were the same 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 S4–S7. 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 VWM, 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).

4. GEOS-Chem simulations

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 invariance-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).

5. Health impact estimation

Similar to previous work (*21*), we estimate changes in all-cause mortality and mortality from 5 causes of death (lower respiratory infections, cardio-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. 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, which we take from Hammer *et al.* (*60*).

Further, we use 3 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. However, because the total pollutant concentrations include the concentrations formed from all brick kilns, the existence of other kilns affects (and generally lowers) the individual impacts from each kiln. So, we also use a "linear" attribution method that individually uses the attribution method for each kiln (ignoring other kilns), and sums the results. 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 cumulate 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 linear 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 3 mortality estimation methods, are given in Table S1.

6. 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. 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. 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 a scaling factor that is the ratio of the top 5% of pollutant concentrations as predicted by InMAP and the top 5% of pollutant concentrations as predicted by GEOS-Chem, for each pollutant species. The scaling factors are: 0.11 for pNO_3, 0.12 for Primary $PM_{2.5}$, and 3.32 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 0.79 (population-weighted: 0.70), a normalized mean bias of –21.7% (population-weighted: –4.6%), and a normalized mean error of 42.5% (population-weighted: 35.8%) (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 far higher spatial resolution (see Figure S11).

7. 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 Information

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 5,500 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 0.52 (0.11–1.68) deaths $kiln^{-1}$ yr^{-1} for Bangladesh.

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.

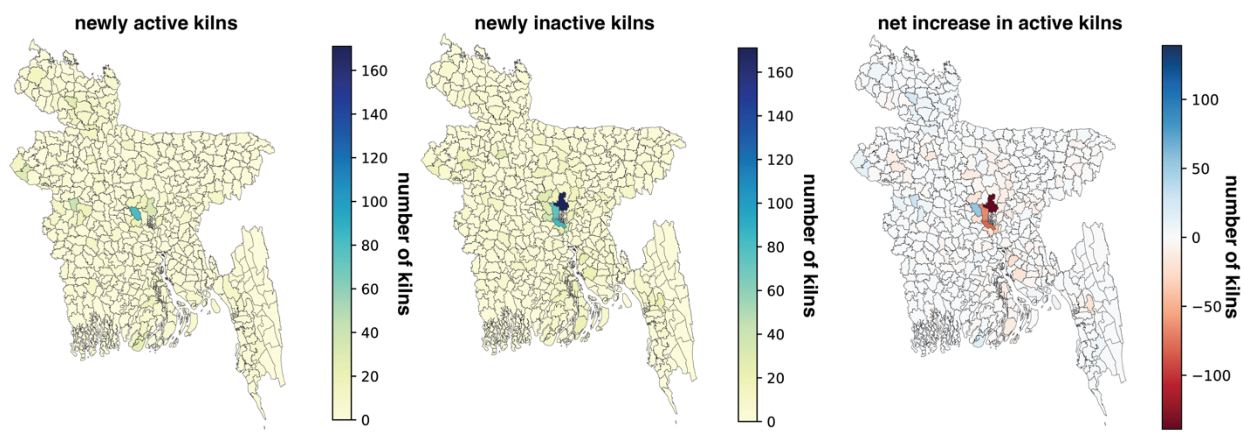


Figure S1. Change in number of kilns over time by region, 2014 until 2023. *Left*: Change in number of newly active kilns by subdistrict (*upazila*) across Bangladesh. *Center*: Change in number of newly inactive kilns (*i.e.*, kilns that were previously active and are no longer active). *Right*: Net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

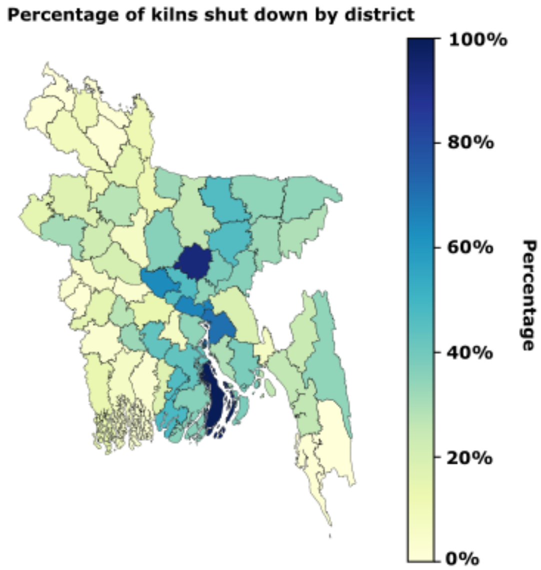


Figure S2. Percentage of brick kilns shut down by district. The total number of deactivated kilns from 2014 until 2023 as a percentage of the total number of kilns that were active at any time between 2014 until 2023, aggregated by district. All districts had at least one active kiln during the period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

Figure 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.]

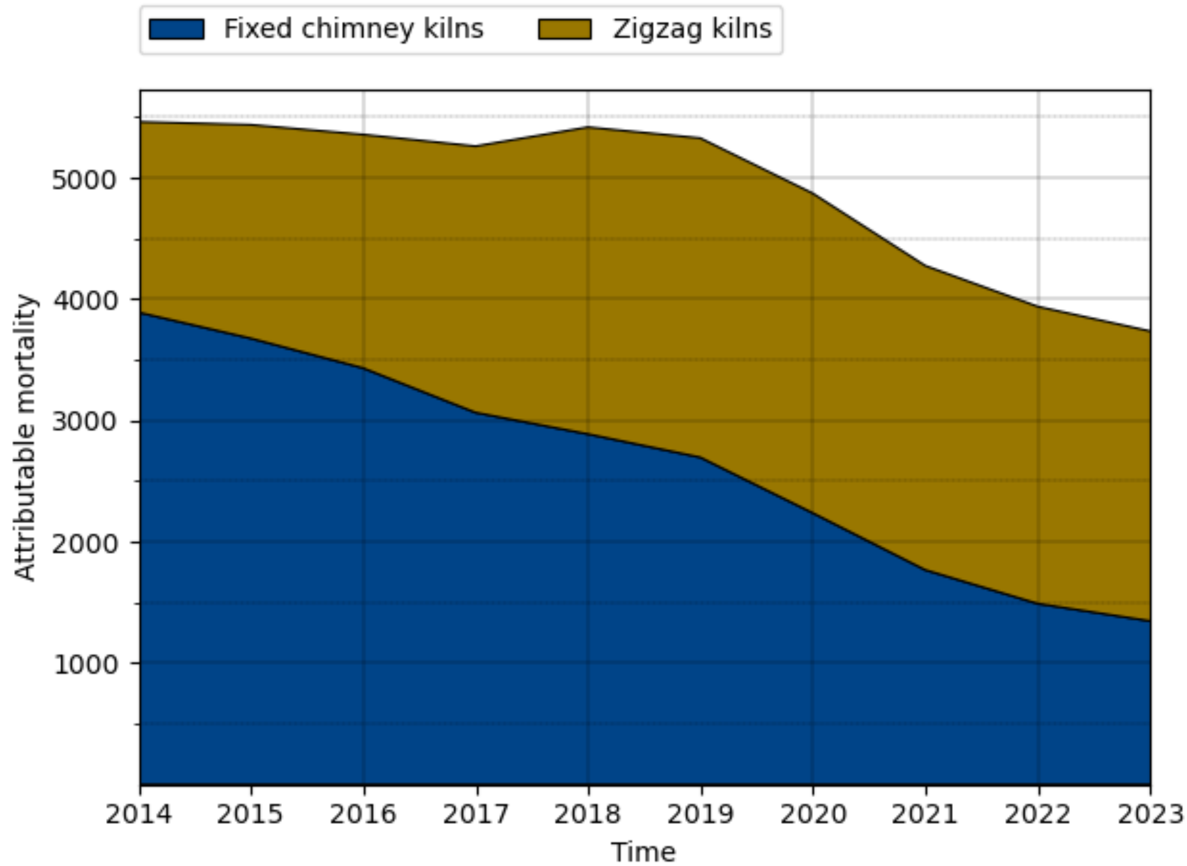


Figure S4. Changing health harms from brick kilns. How deaths attributable to brick kiln emissions in Bangladesh would change if the number of kilns and their firing technologies were fixed at different points in time.

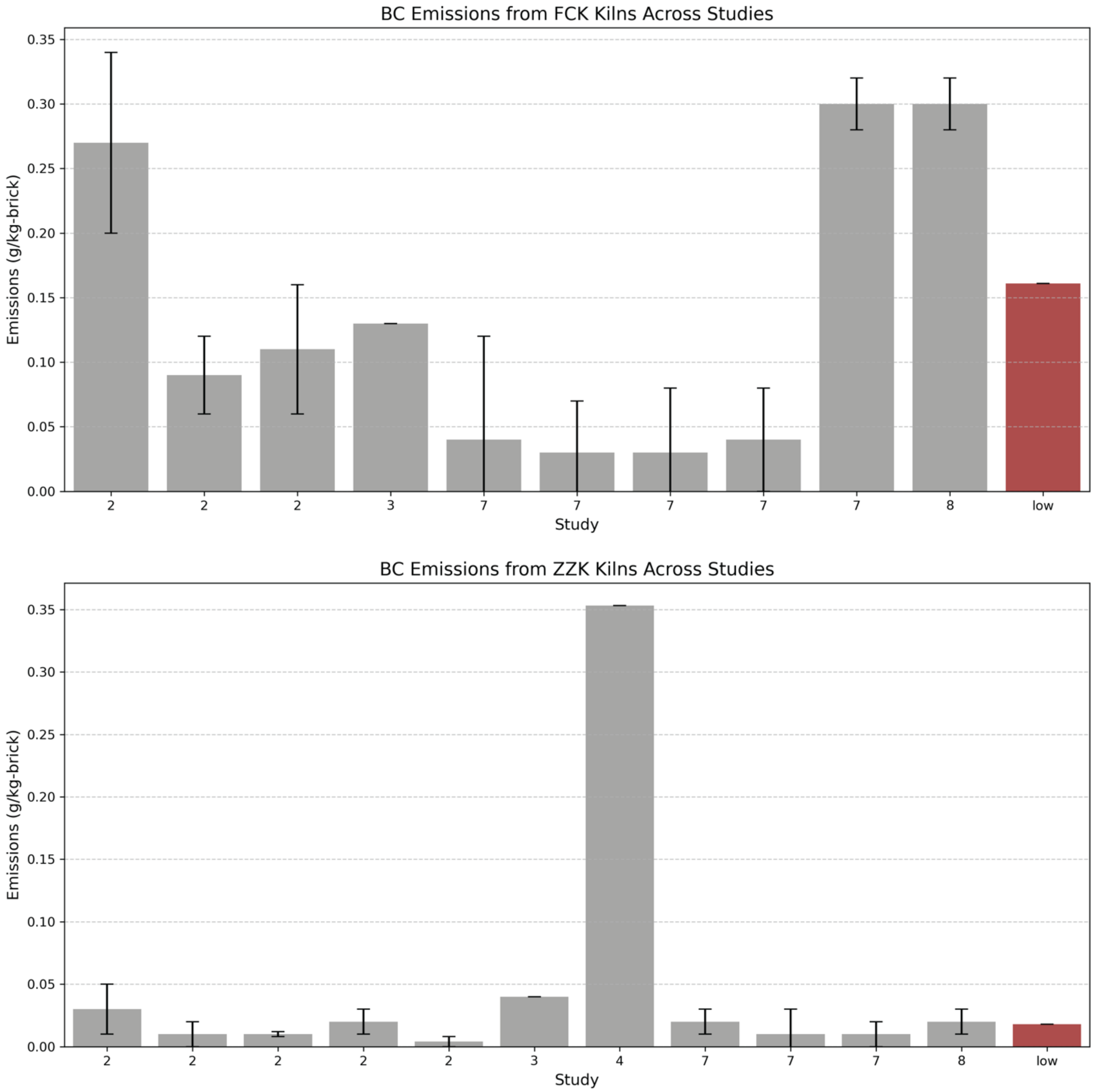


Figure S5. Literature review of Black Carbon (BC) emissions. *Top*: BC emissions from fixed chimney kilns (FCK) across the 8 studies included in the literature review. *Bottom*: BC emissions from zigzag kilns (ZZK) across the 8 studies included in the literature review. Error bars denote one standard 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. (*37*); 2. Weyant et al. (*24*); 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.

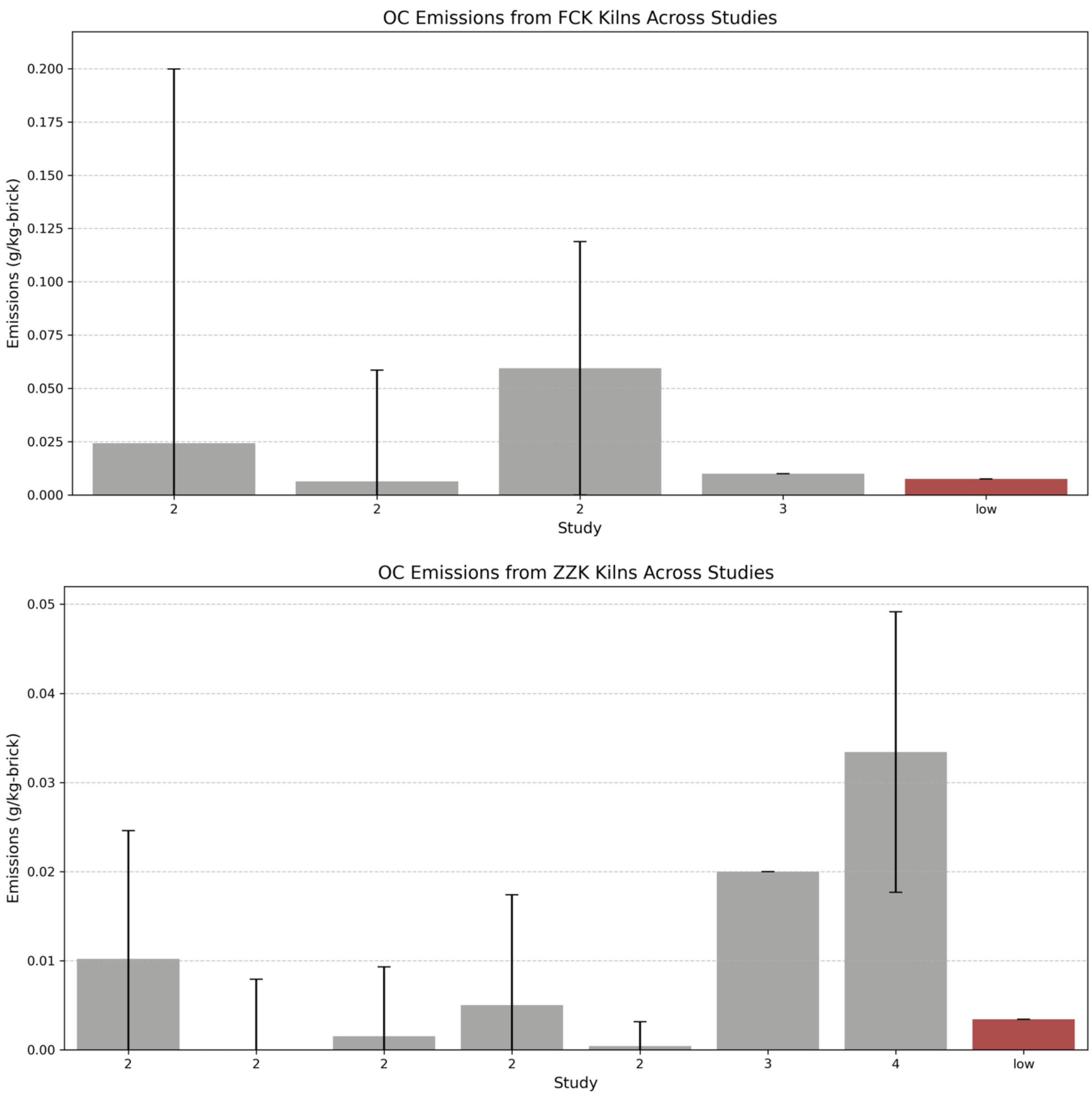


Figure S6. Literature review of Organic Carbon (OC) emissions. *Top*: OC emissions from fixed chimney kilns (FCK) across the 8 studies included in the literature review. *Bottom*: OC emissions from zigzag kilns (ZZK) across the 8 studies included in the literature review. Error bars denote one standard 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. (*37*); 2. Weyant et al. (*24*); 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.

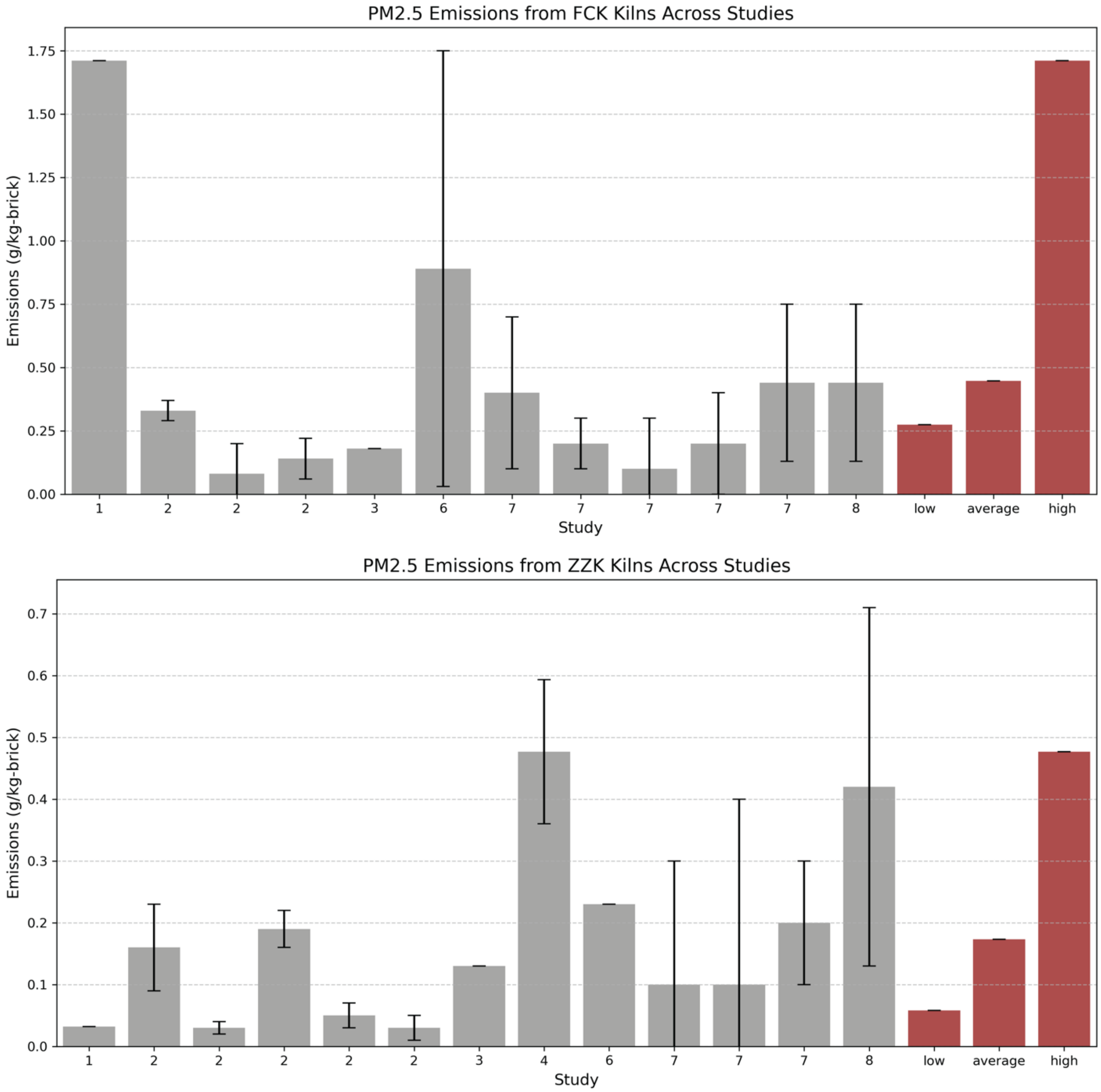


Figure S7. Literature review of fine particulate matter ($PM_{2.5}$) emissions. *Top*: $PM_{2.5}$ emissions from fixed chimney kilns (FCK) across the 8 studies included in the literature review. *Bottom*: $PM_{2.5}$ emissions from zigzag kilns (ZZK) across the 8 studies included in the literature review. 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. (*37*); 2. Weyant et al. (*24*); 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.

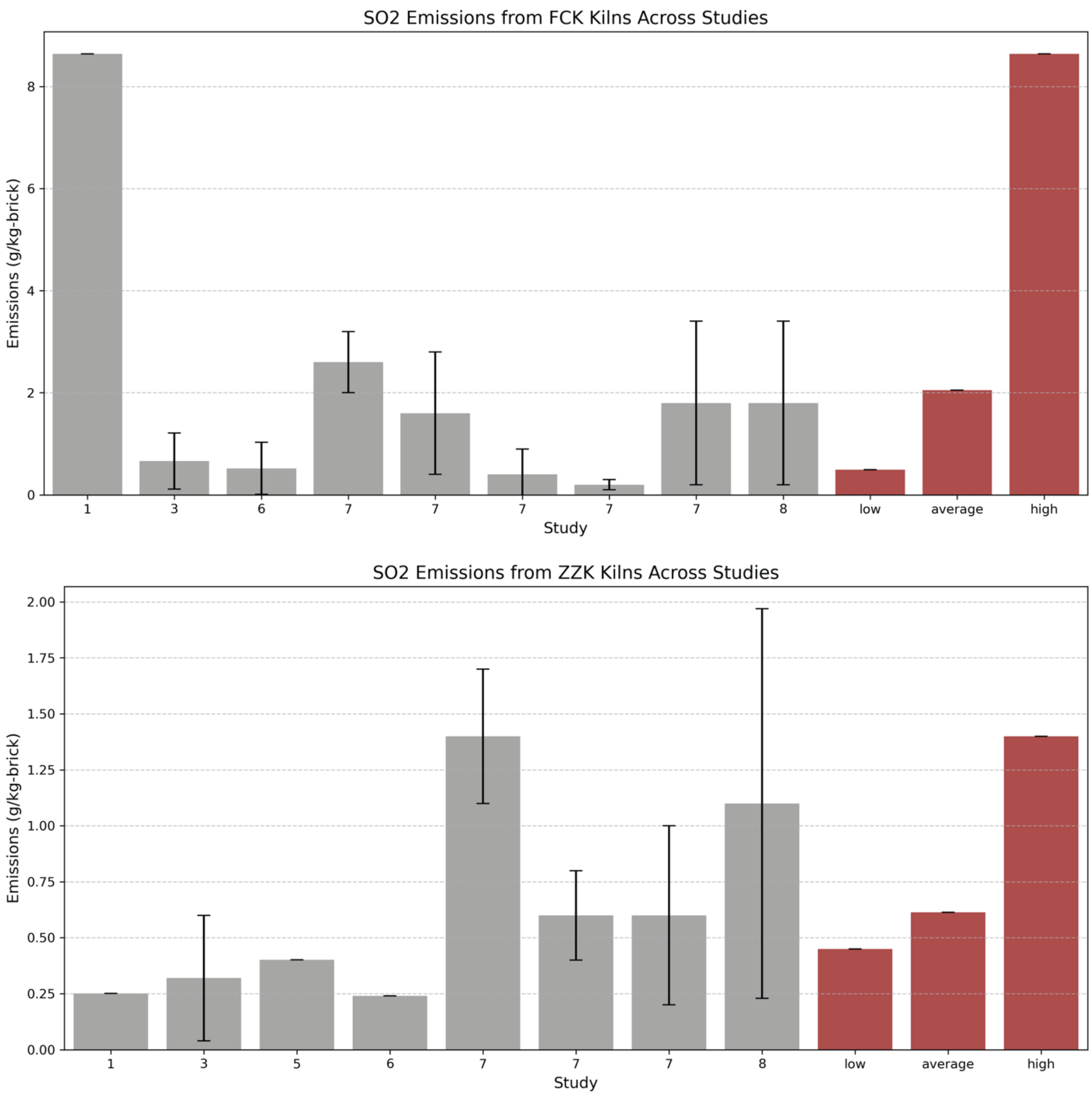


Figure S8. Literature review of sulfur dioxide (SO_2) emissions. *Top*: SO_2 emissions from fixed chimney kilns (FCK) across the 8 studies included in the literature review. *Bottom*: SO_2 emissions from zigzag kilns (ZZK) across the 8 studies included in the literature review. Error bars denote one 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. (*37*); 2. Weyant et al. (*24*); 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.

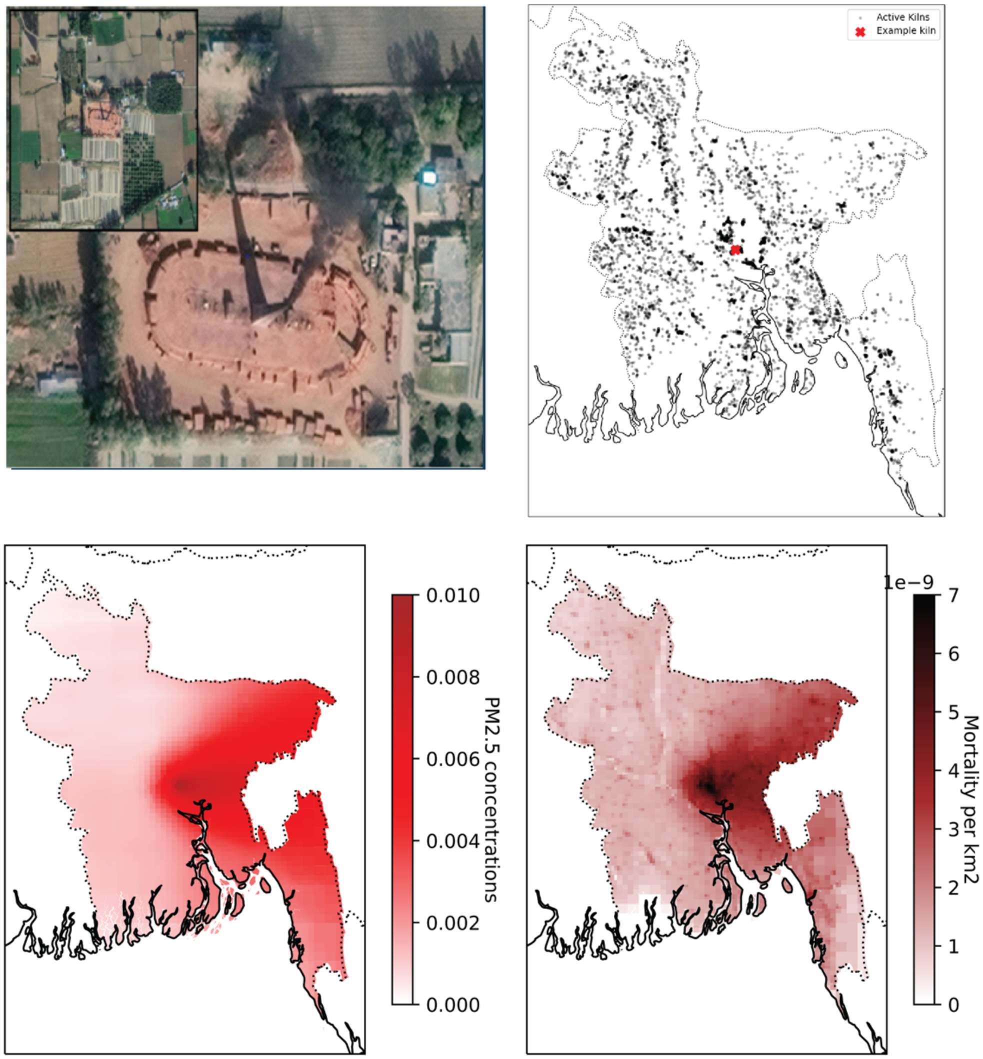
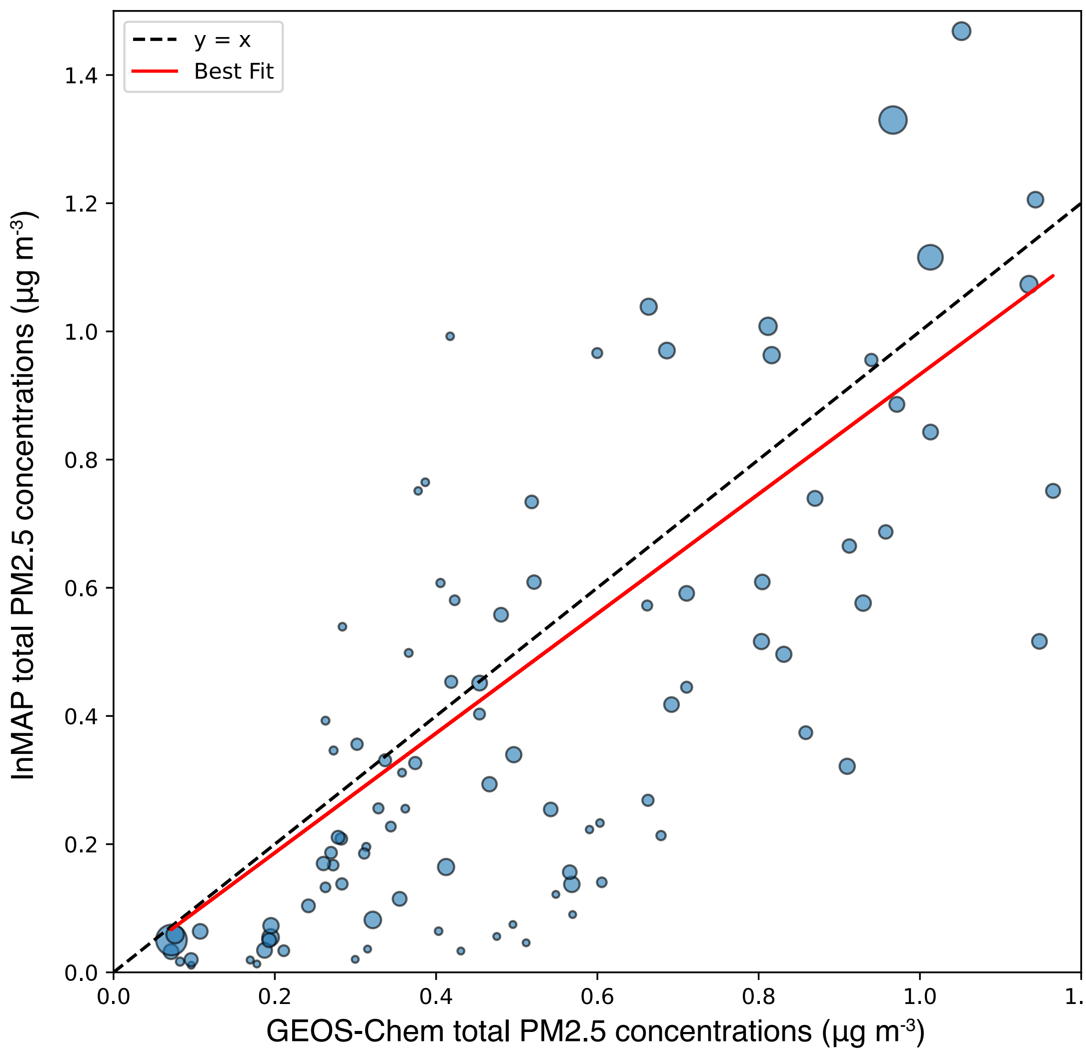


Figure S9. Illustration of methodology. *Top left*: Brick kiln location and type are identified by satellite imagery. *Top right*: All kilns in Bangladesh are geospatially located. An example kiln is identified with a red 'X'. *Bottom left*: The change in pollutant concentrations are estimated for each 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:	0.79	**NMB:**	–21.7%	**NME:**	42.5%
pop-wtd.:	0.70	*pop-wtd.*:	–4.6%	*pop-wtd.*:	35.8%

Figure 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 invariance-weighted mean emission factors. NME: normalized mean error; NMB: normalized mean bias. The red line corresponds to the population-weighted line-of-best-fit.

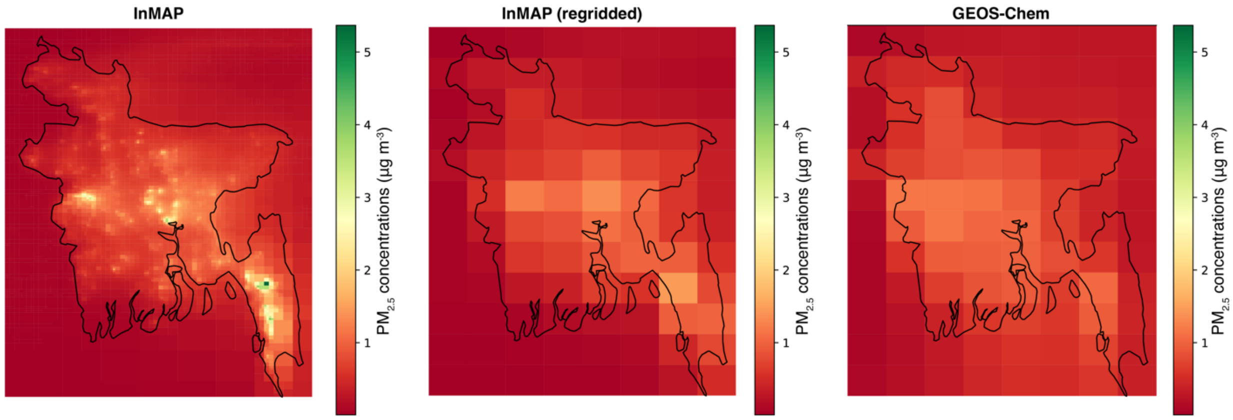


Figure S11. Changes in pollutant concentrations across Bangladesh. *Left*: Changes in average fine particulate matter ($PM_{2.5}$) concentrations from the InMAP simulation (native grid). *Middle*: Changes in $PM_{2.5}$ concentrations from the InMAP simulation, regridded to the GEOS-Chem grid (0.5° × 0.625°). *Right*: Changes in $PM_{2.5}$ concentrations from the GEOS-Chem simulation. Simulations here correspond to the 2022–2023 season, using invariance-weighted mean emission factors.

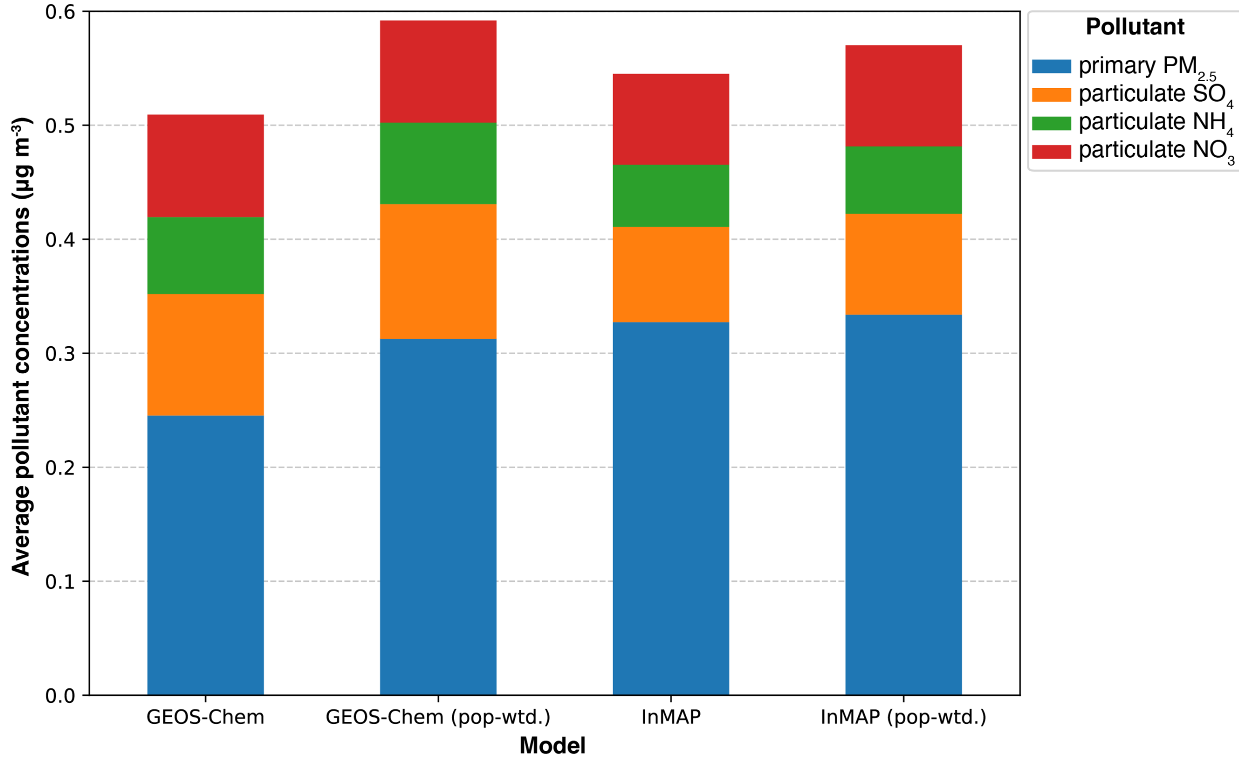


Figure S12. Population-weighted concentrations. Changes in average and population-weighted-average concentrations of fine particulate matter ($PM_{2.5}$) from brick kilns during the 2022–2023 season, using invariance-weighted mean emission factors, from the GEOS-Chem and InMAP simulations. Pollutant 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.

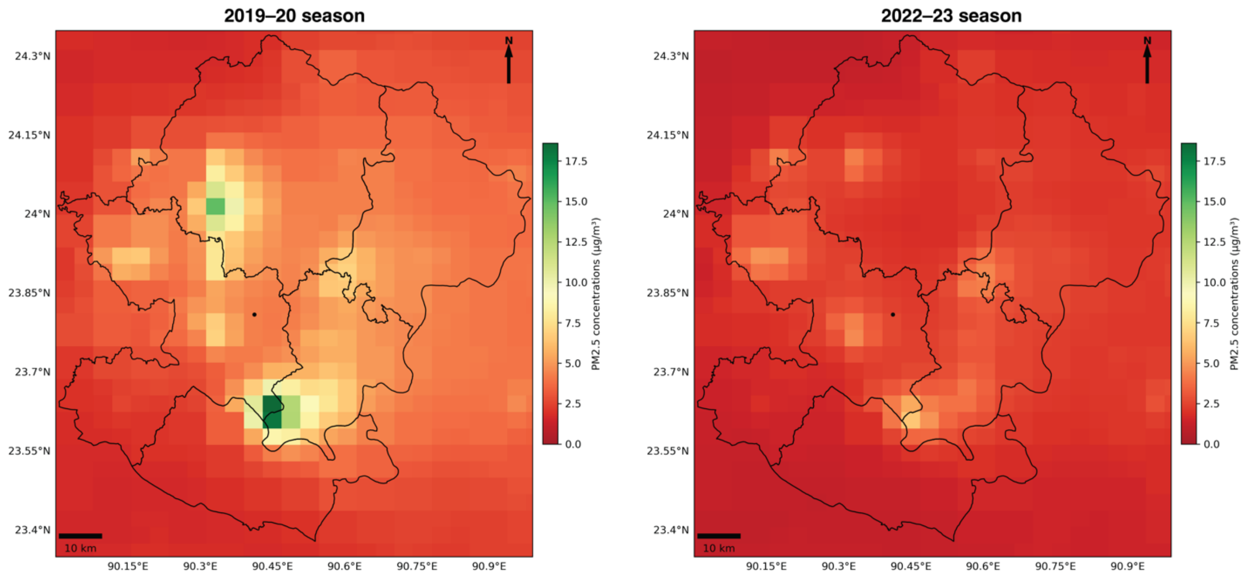


Figure S13. Changes in pollutant concentrations across Dhaka. Changes in average concentrations of fine particulate matter ($PM_{2.5}$) from brick kilns during the 2019–2020 (*left*) and 2022–2023 (*right*) season, using mean emission factors, across the Greater Dhaka Area.

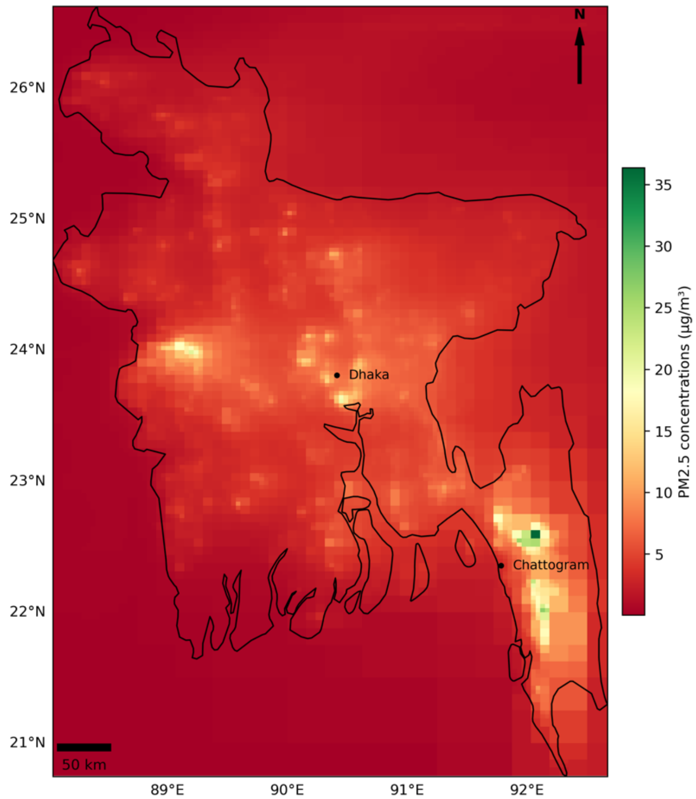


Figure S14. Changes in pollutant concentrations across Bangladesh using maximum observed emission factors. Changes in average fine particulate matter ($PM_{2.5}$) concentrations from the InMAP simulation during the 2022–2023 season, using the maximum observed emission factors.

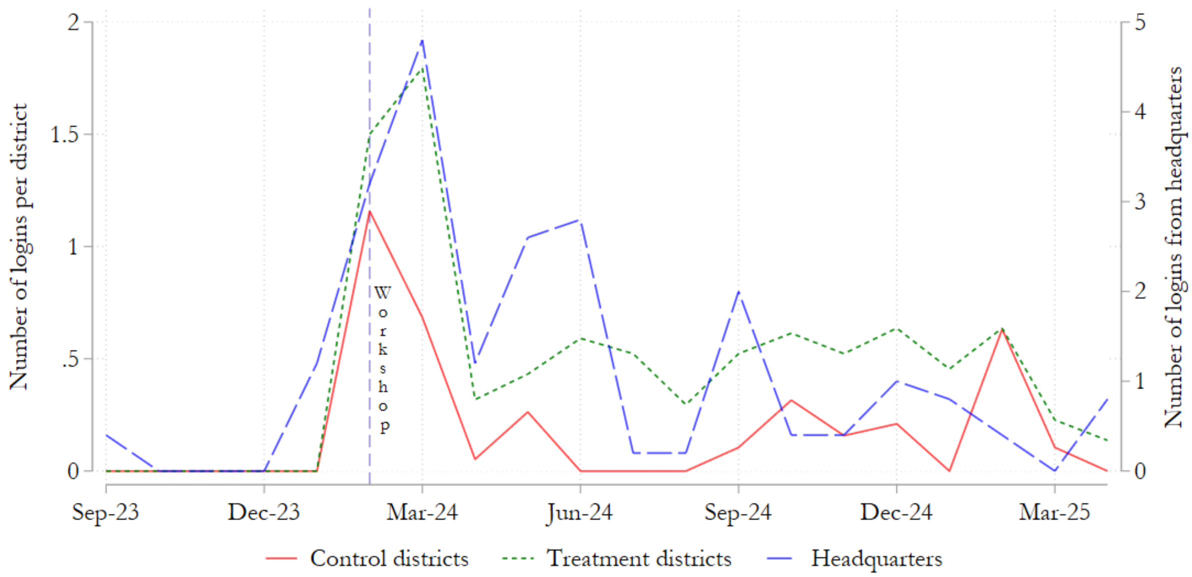


Figure S15: Number of logins per district and from headquarters into the Brick Kiln Tracker by Department of Environment (DoE) officials since September 2023. The vertical line corresponding to the month (February 2024) when the Brick Kiln Tracker was officially launched through a workshop held at the 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.

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 are active in the 2022–2023 season. The "GEMM 5COD" and "GEMM all-cause" concentration response functions refer to the Global Exposure Mortality Model (*56*) 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*).

Emission scenarios	Concentration-response function	Mortality estimation method	Excess deaths
mean	GEMM 5COD	attribution	1,617
	GEMM all-cause	attribution	3,235
	GEMM all-cause	attribution (linear)	3,726
	GEMM 5COD	subtraction	1,338
	GEMM all-cause	subtraction	2,448
invariance-weighted mean	GEMM 5COD	attribution	921
	GEMM all-cause	attribution	1,843
	GEMM all-cause	attribution (linear)	1,916
	GEMM 5COD	subtraction	764
	GEMM all-cause	subtraction	1,409
maximum	GEMM 5COD	attribution	5,967
	GEMM all-cause	attribution	11,890
	GEMM all-cause	attribution (linear)	11,028
	GEMM 5COD	subtraction	4,617
	GEMM all-cause	subtraction	8,454
2019 kilns (mean emissions)	GEMM 5COD	attribution	2,732
	GEMM all-cause	attribution	5,457
	GEMM all-cause	attribution (linear)	5,259
	GEMM 5COD	subtraction	2,195
	GEMM all-cause	subtraction	4,028

Table S2. Impact of District Inclusion on PSPS Usage. This table shows the effect of a district being covered by the PSPS (Brick Kiln Tracker) 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.

	(1) Logins	(2) Minutes Spent
Covered District	0.38*** (0.13)	91*** (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 S3. Validation of satellite Earth observation data showing the percentage of brick kilns identified in this study in 2024 ("YOLO-derived data") that were identified (and verified as active) in the complete data (derived from a combination of multiple datasets). Values are given as a percentage of the total (active or inactive) kilns in the complete data. Activity is based on the latest image.

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

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"), high and low scenarios, as derived from a review of the available literature. for the straightforward mean ("avg"), the maximum ("max"), and the variance-weighted mean (VWM). See Table S4 for emissions of volatile organic compounds, black carbon, and organic carbon.

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
VWM	FCK	0.27	0.49	0.06	0.0084
	ZZK	0.06	0.45	0.05	0.0084

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"), high and variance-weighted mean scenarios, as derived from a review of the available literature. for the straightforward mean ("avg"), the maximum ("max"), and the variance-weighted mean (VWM). See Table S5 for emissions of total fine particulate matter ($PM_{2.5}$), sulphur dioxide (SO_2), and nitrogen oxide (NO).

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
VWM	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