Indian annual ambient air quality standard is achievable by completely mitigating emissions from household sources

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Exposures to ambient and household fine-particulate matter ($PM_{2.5}$) together are among the largest single causes of premature mortality in India according to the Global Burden of Disease Studies (GBD). Several recent investigations have estimated that household emissions are the largest contributor to ambient $PM_{2.5}$ exposure in the country. Using satellite-derived district-level $PM_{2.5}$ exposure and an Eulerian photochemical dispersion model CAMx (Comprehensive Air Quality Model with Extensions), we estimate the benefit in terms of population exposure of mitigating household sources—biomass for cooking, space- and water-heating, and kerosene for lighting. Complete mitigation of emissions from only these household sources would reduce India-wide, population-weighted average annual ambient $PM_{2.5}$ exposure by 17.5, 11.9, and 1.3%, respectively. Using GBD methods, this translates into reductions in Indian premature mortality of 6.6, 5.5, and 0.6%. If $PM_{2.5}$ emissions from all household sources are completely mitigated, 103 (of 597) additional districts (187 million people) would meet the Indian annual air-quality standard (40 $\mu g\ m^{-3}$) compared with baseline (2015) when 246 districts (398 million people) met the standard. At 38 $\mu g\ m^{-3}$, after complete mitigation of household sources, compared with 55.1 $\mu g\ m^{-3}$ at baseline, the mean annual national population-based concentration would meet the standard, although highly polluted areas, such as Delhi, would remain out of attainment. Our results support expansion of programs designed to promote clean household fuels and rural electrification to achieve improved air quality at regional scales, which also has substantial additional health benefits from directly reducing household air pollution exposures.

air pollution | PM2.5 | cooking | lighting | heating

Chronic exposure to $PM_{2.5}$ (i.e., particulate matter smaller than 2.5 μm) has detrimental effects on human health, including premature mortality (1–7). Multiple studies have established evidence of causal associations between exposure to $PM_{2.5}$ and cardiorespiratory health endpoints, including chronic obstructive pulmonary disease, ischemic heart disease, stroke, lung cancer, and child acute lower respiratory infection. Annual $PM_{2.5}$ exposure in India has been increasing in recent years (8, 9), primarily due to the rapid rise in pollution during the dry season (October–January). In 2017, this rise in pollution led the Indian Medical Association to declare a public health emergency in the National Capital Region of Delhi. Given the current situation, strict mitigation measures need to be implemented in India to meet at least the National Ambient Air Quality Standard (NAAQS) of 40 $\mu g\ m^{-3}$. Formulation of a successful clean-air management plan requires understanding the relative contributions of individual sources to average ambient $PM_{2.5}$ exposure at regional scales.

Several recent studies have attributed the largest share of ambient $PM_{2.5}$ exposure in India to household emissions, as opposed to vehicles, power plants, industries, and other sectors (10–14). Four major activities contribute mainly to household emissions: biomass burned for residential cooking, space- and water heating, and kerosene used for lighting. Relatively small amounts of coal are used in households nationally and use of kerosene for cooking has declined substantially in recent years. Different policy frameworks are likely required to mitigate each activity and/or source.

In this work, we develop seven scenarios based on current and plausible future mitigation policies and the estimated adaptive capacity of the exposed population. We quantify the contributions of individual household activities to ambient $PM_{2.5}$ exposure in India and examine the expected health benefits of scenarios to reduce emissions from these sources. We also identify the districts (equivalent to counties in other countries) that would meet the Indian NAAQS and World Health Organization (WHO) ambient air quality guidelines after complete mitigation of these household sources.

Scenario Development. The seven scenarios are defined in Table 1. We assess the potential benefit of each scenario by estimating (*i*) the decrease in population-weighted ambient $PM_{2.5}$ exposure and (*ii*) the averted premature mortality burden with respect to the 2015 annual population-weighted ambient $PM_{2.5}$, which is referred to as "baseline."

The first scenario (P_C) assumes that the government successfully implements a policy to provide clean fuel for cooking to all

Significance

The Indian government has initiated programs to reduce household use of biomass cookfuels, but their motivation does not include ambient pollution reductions. We estimate ambient exposure reductions that result and subsequent health benefits of seven different scenarios that mirror plausible mitigation policies to address household energy needs currently met by biomass combustion for cooking and water- and space heating, and by kerosene for lighting. If all households transitioned to clean fuels, ∼13% of premature mortality in India could be averted from the reduction in ambient pollution, and the average ambient $PM_{2.5}$ concentration in the country would meet national $PM_{2.5}$ standards. These results will assist in assessing current policies and making decisions on future mitigation policies to tackle air pollution.

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Table 1. Definition of the scenarios formulated for the study

Scenarios	Cooking (%)	Space heating (%)	Water heating (%)	Lighting (%)
P_C	100	0	0	0
P_{CL}	100	0	0	100
P_{CLS}	100	100	0	100
Ideal	100	100	100	100
Progress A	75	50	50	75
Progress M	50	25	25	50
Progress S	25	0	0	25

The numeric values depict the percent mitigation of the particular household source. C = cooking, L = lighting, S = space heating, A = aspirational progress, M = moderate progress, S = slow progress.

solid-fuel–using families in the country, but does not implement any policies to counter emissions from space- and water heating and kerosene lighting. The second scenario (P_{CL}) assumes that, on top of "P_C," the government successfully implements policies that provide cheap and continuous electricity across India, which eradicates lighting via kerosene lamps in households.

We note that the Government of India (GoI) in 2016 launched Pradhan Mantri Ujjwala Yojana (15), which intends to provide 80 million "below poverty level" households with liquefied petroleum gas (LPG) by 2019. Under the program, about 75% of the planned LPG connections had been dispersed by January 2019 (16). GoI also initiated the Deen Dayal Upadhyay Grameen Jyoti Yojana (17) in 2014, which promises to electrify all villages in India, thus eradicating emissions from kerosene lighting. In view of these GoI mitigation schemes, it is expected that in the next few years solid-fuel cooking and kerosene lighting could be entirely replaced by clean fuels if the population adapts and adheres to the above-mentioned policies perfectly [which is often not the case, as discussed in previous studies (18, 19)].

"P_{CLS}" adds policies to mitigate space heating and assumes they are also efficiently undertaken such that there are no emissions of $PM_{2.5}$ from space-heating–related activities. Finally, the "ideal" scenario assumes full adoption of household air pollution mitigation policies, resulting in elimination of all major sources that result in household $PM_{2.5}$ pollution.

We acknowledge that "perfect" policies—ones that are fully distributed and implemented—in a socioeconomically and behaviorally diverse country like India are hypothetical and aspirational. To account for this, we develop three scenarios which consider three interim targets that set more realistic goals for reach and population uptake. "Progress A" assumes that policymakers and the population are fairly successful in achieving their mitigative and adaptative goals of eradicating usage of solid fuels in household activities. It assumes that 75% of all emission from residential cooking and lighting and 50% of all emission from space- and water heating in a district are eliminated. We note that although the transitions from traditional fuels to LPG and electric lighting are aspirational for many populations, it can be difficult to transition from usage of solid fuels for space- and water heating to clean fuels, as both activities consume large amounts of energy. Using clean fuels for these activities may not be perceived as cost-effective for the rural poor, justifying our lower expectation weights on space and water heating.

"Progress S" assumes "slow" progress of policies in terms of reaching communities and less complete adoption by targeted populations. It assumes that 25% of all emissions from residential cooking and lighting are mitigated and the government fails to devise any policy for mitigating space heating and water heating. "Progress M" assumes a moderate scenario, where 50% of the residential cooking and lighting are phased out and 25% of space- and water heating are eliminated.

Results

Population-weighted mean annual ambient $PM_{2.5}$ exposure in India in the baseline year, 2015, is estimated to have been 55 μg m^{-3}. Exposures vary widely across India, with the largest (>100 μg m^{-3}) exposure observed over the Delhi National Capital Region (Delhi NCR). Fig. 1 displays exceedances of annual ambient $PM_{2.5}$ exposure relative to the NAAQS and WHO-IT (Interim Target) 1 (35 μg m^{-3}), WHO-IT2 (25 μg m^{-3}), WHO-IT3 (15 μg m^{-3}), and the WHO-AQG (10 μg m^{-3}) across India in 2015. Overall in India, 58, 67, 83, 97, and 99% of districts have annual $PM_{2.5}$ exposure exceeding these guidelines, respectively. In Northwest India and across the Gangetic Plain, all districts have annual exposures higher than the NAAQS. In Central and West India, 82 and 50% of districts exceed the NAAQS, while in North, Northeast, and South India, only 22, 19, and 2% districts violate the NAAQS, respectively.

Fig. 2 depicts the percentage contribution of household sources toward ambient $PM_{2.5}$. There is a strong north–south gradient in the percentage contribution of household $PM_{2.5}$ toward ambient $PM_{2.5}$. It exceeds 40% in most of the districts in the Gangetic basin, while in the southern and central states the contribution is below 30%. Residential cooking contributes 20–50% (Fig. 3) of all household $PM_{2.5}$ emission across all districts, with higher contributions in districts with greater proportions of the population living in rural areas, which is again pronounced in the Gangetic basin. Space heating contributes more than 40% of all household emission in a few regions of North, Northeast, South, and West India and in the Himalayan foothills. Water heating contributes up to 30% of ambient $PM_{2.5}$ exposure with a north to south spatial gradient. Kerosene lighting contributes up to 10% of total emissions, without much spatial gradient. Overall, cooking is the largest contributor among all household sources, followed by space heating, water heating, and lighting.

Mitigation of Emission from Various Household Sources. In 2015, the baseline year, 58% of districts in India had $PM_{2.5}$ exposures above the NAAQS. The corresponding numbers are 68, 83, 98, and 99% for the WHO-IT1, WHO-IT2, WHO-IT3, and WHO guidelines, respectively (Fig. 4*A*). If the hypothetical ideal scenario (as seen in Fig. 4*A*) can be achieved, 103 more districts, housing 187 million people, would meet the NAAQS and ambient $PM_{2.5}$ exposure would fall below WHO-IT1, IT2, IT3, and the WHO-AQG in 104, 75, 26, and 2 additional districts, respectively. Successfully achieving the less ambitious Progress A scenario would add 72 additional districts below NAAQS. The corresponding numbers for Progress M, Progress S, P_C, P_{CL}, and P_{CLS} are 39, 11, 55, 61, and 86, respectively. In North Indian districts that do not meet Indian NAAQS standard even after achievement of the ideal scenario ($n = 248$), the annual ambient $PM_{2.5}$ exposure comes within 10 μg m^{-3} of the NAAQS in 115 districts, especially in the central and eastern parts of the Gangetic Plain (Fig. 4*B*). Only the Delhi NCR and some districts of Northwest India remain out of attainment with the Indian NAAQS standard by >30 μg m^{-3}—even under the ideal scenario. This may be due to the large share of dust (20, 21) and relatively larger (compared with the rest of the country) contributions of other outdoor sources (e.g., vehicular emission, crop waste, industry, and trash burning, etc.) to ambient $PM_{2.5}$ concentrations in this region. Fig. 4*B* summarizes the remaining reductions needed to meet the Indian NAAQS after implementation of an ideal scenario.

The population-weighted, all-India mean annual ambient $PM_{2.5}$ exposure decreases from 55 to 45 μg m^{-3} (a 17.6% decrease) if P_C is achieved and to 45 μg m^{-3} if the P_{CL} scenario is realized (Fig. 5). If space-heating emissions are additionally mitigated as in P_{CLS}, the all-India mean annual ambient $PM_{2.5}$ exposure drops to 41 μg m^{-3}; and, further, to 38 μg m^{-3} (below the NAAQS) if the ideal scenario is achieved. Achieving the least ambitious scenario,

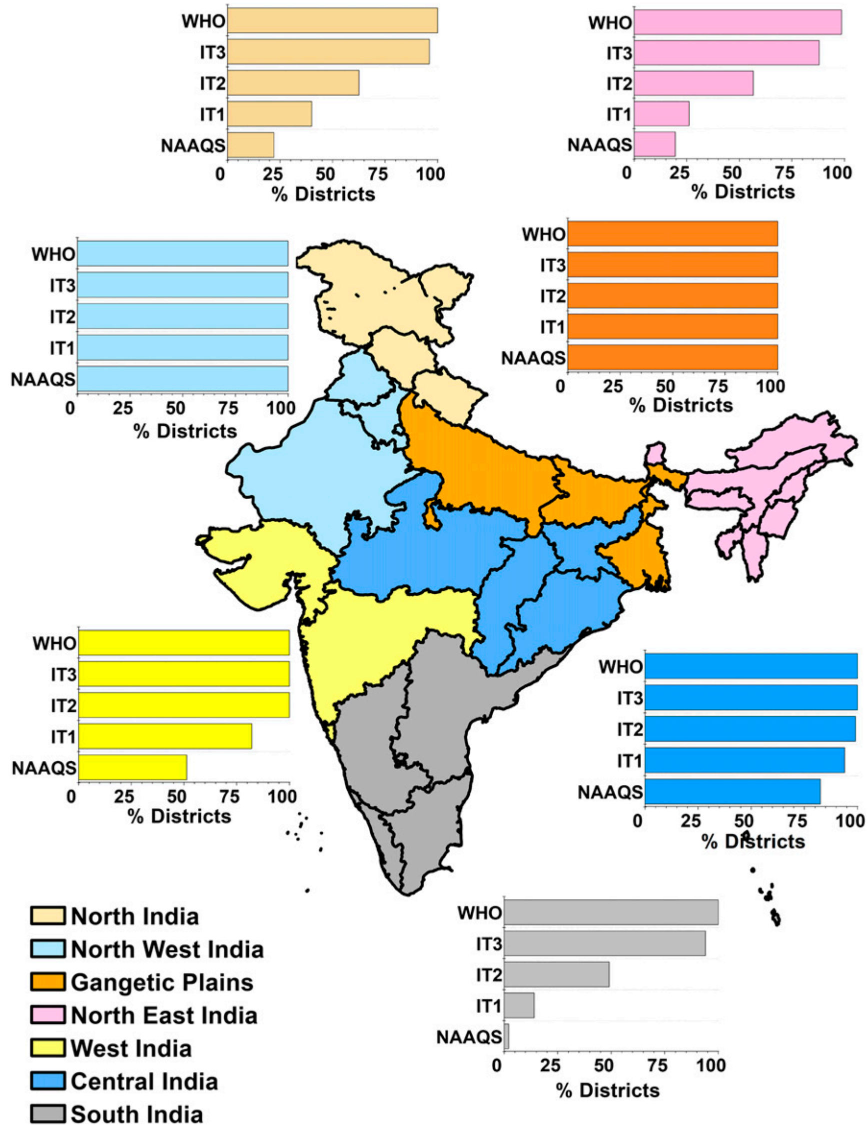

Fig. 1. Annual ambient $PM_{2.5}$ exposure exceedances in India with reference to Indian NAAQS and WHO air-quality guidelines in the baseline year, 2015. Indian NAAQS: 40 μg m^{-3}; WHO-IT1: 35 μg m^{-3}; WHO-IT2: 25 μg m^{-3}; WHO-IT3: 15 μg m^{-3}; WHO-AQG: 10 μg m^{-3}. Statistics (as inset figures) are shown as percentage of districts in each region exceeding the standard/guidelines.

Progress S would only reduce the average population-weighted $PM_{2.5}$ by 2 μg m^{-3} from the baseline year. Pursuing the more ambitious pathways—Progress M and Progress A—would reduce the population-weighted $PM_{2.5}$ exposure by 21 and 13%, respectively.

Expected Health Benefit. We estimate expected health benefits (Fig. 5) in terms of the percentage of premature deaths, relative to baseline premature mortality, that could be averted if our scenarios are implemented. Estimates are made with both the integrated exposure-response functions (22) and a linear risk function (*SI Appendix*, *Attribution Method*). Scenarios are described in detail in Table 1 and the results summarized in Fig. 5. Briefly, those labeled with a P represent complete displacement of unclean fuels for cooking (C), space heating (S), and lighting (L) in various combinations.

Premature mortality due to ambient $PM_{2.5}$ exposure is estimated to be 0.88 (95% UI 0.3–1.5) million at baseline (the method used to estimate premature mortality is described in *SI Appendix*). This material contains details of household emission estimates and modeling. Following the optimal scenarios P_C, P_{CL}, and P_{CLS} would avert 7, 7, and 11%, respectively, of premature deaths across India annually from reduction of ambient exposures. Achieving the hypothetical ideal scenario could result in avoiding 13% of the all-India premature mortality burden. The more realistic scenarios (Progress A and Progress M) would avert an estimated 8 and 5% of the total premature mortality burden, respectively. The least ambitious Progress S scenario would avoid only 2% of the premature mortality at baseline. Using the Attribution method, we estimate that 270,000 (95% UI, 69,000–487,000) premature mortality can be averted per year under the ideal scenario.

Discussion

As of early 2016, around 43% of the Indian population (23) was still dependent on solid fuels for cooking, heating, and other household energy services. In this paper, we demonstrate the exposure and health benefits of mitigating household emissions sources on ambient air pollution exposures using several scenarios. Given that household $PM_{2.5}$ exposures in India are about three times higher than ambient exposures in many parts of the country

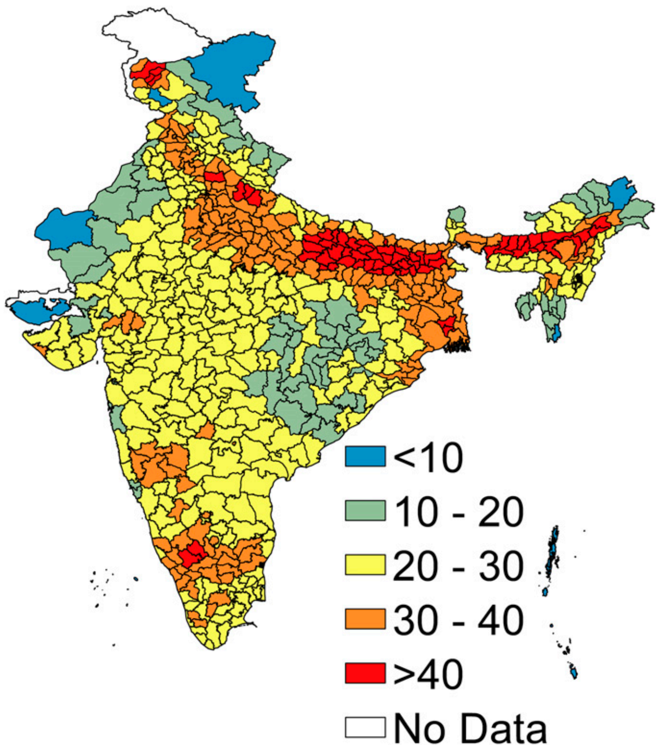

Fig. 2. Percentage of ambient $PM_{2.5}$ exposure that can be attributed to household $PM_{2.5}$ sources at baseline, 2015.

(24), however, there would be additional and substantial benefits for households as well, where direct exposures to solid-fuel combustion by-products are high. These are not estimated in this assessment, however.

Household interventions may be more socially acceptable and easier to implement than other forms of interventions (25) such as traffic restrictions (25–27) and industry closures that are often perceived as a hindrance to economic growth and disruptive of daily routines. However, despite aggressive new programs to provide clean energy to households, significant challenges remain in ensuring sustained use of clean fuels in households that receive an LPG stove (28) and in ensuring reliable and consistent electricity supplies to displace kerosene lamp usage.

Several studies (10–14, 29) have confirmed that ambient $PM_{2.5}$ exposure can be reduced substantially in India by controlling household sources. Our results show that the all-India average annual ambient $PM_{2.5}$ exposure can be brought down below the Indian NAAQS standard by mitigating all household sources (our ideal scenario). While this scenario is aspirational and may seem hypothetical, it could be achieved through aggressive mitigation measures to promote clean-fuel usage across all household sources, not just cooking. Achieving comparatively pragmatic scenarios like Progress A and Progress M would also result in a large fraction of districts reaching the NAAQS standard and could help avoid considerable premature mortality. In most of the districts in the central and eastern Gangetic Plain, this would reduce the ambient $PM_{2.5}$ exposure closer to the Indian NAAQS. Districts that are out of attainment could be assisted by enforced policies to limit agricultural crop waste and open trash burning, to control industrial emissions, to restrain emissions from construction activities, to increase the frequency of mechanized cleaning of roads to limit on-road resuspension of dust, and/or to curb emissions from brick kilns.

In Delhi NCR, more stringent measures and large-scale shifts in practice have already been undertaken. These include switching the public transport system to Compressed Natural Gas (30) and the recent implementation of Bharat Stage - VI emissions standards to curb vehicular emission in this region (31, 32). A multipronged approach addressing both cleaner fuels for household purposes and other emissions sources is also necessary. Similar efforts are underway to implement a series of mitigation measures recommended by a steering committee formed by the Ministry of Health and Family Welfare, Government of India (33).

In districts where ambient $PM_{2.5}$ exposure is already lower than the NAAQS, curbing household emissions could help approach WHO guidelines. Reductions in both household and ambient $PM_{2.5}$ exposures are expected to improve standards of living in many ways, for example less time spent collecting fuel and fewer episodes of impaired visibility. Therefore, ongoing social programs should continue and their effectiveness should be ensured through rigorous monitoring and evaluation, iteration, and continued public financing. The public should be made aware of the health benefits of clean air through awareness campaigns to promote the use of cleaner fuels for cooking and the adoption of cleaner lifestyles to contribute to improved air quality and sustainable development.

China, another midincome country with substantial air pollution, also exhibits significant contribution of household sources to ambient pollution, although coal for space heating plays a bigger role than in India (34). Studies have estimated that the biggest impact on ambient pollution during 2005–2015 was actually from “natural” improvements in household fuels due economic growth and urbanization, rather than direct policies to control ambient pollution (35). China now has initiated promulgation of clean household fuels as part of its modern control strategy for addressing ambient air pollution (36). Ironically, neither in India nor China, however, are the full benefits of providing clean household fuels yet

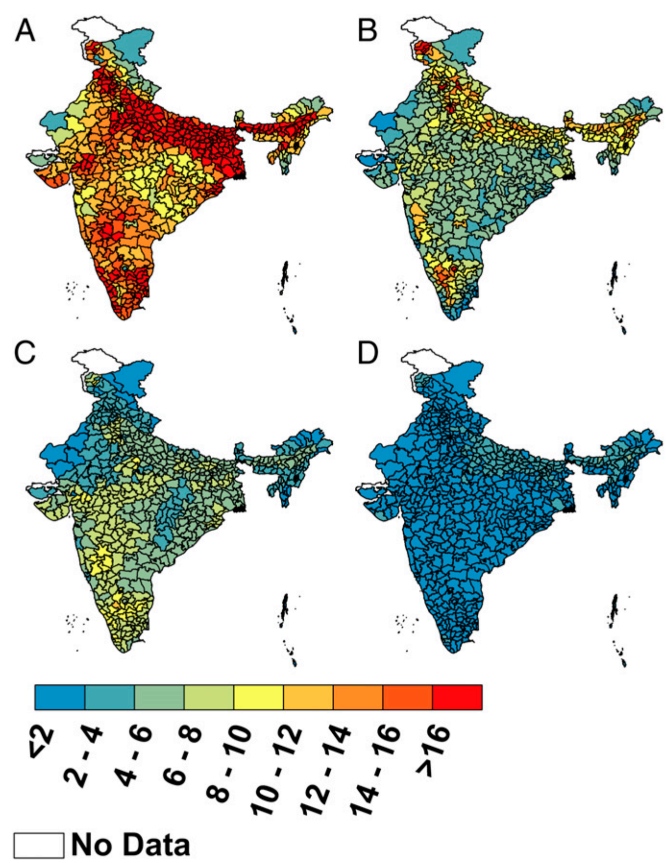

Fig. 3. Relative contributions (%) of biomass use for (*A*) solid-fuel cooking, (*B*) space heating, and (*C*) water heating and kerosene use for (*D*) lighting to annual ambient $PM_{2.5}$ exposure at the district level at baseline, 2015.

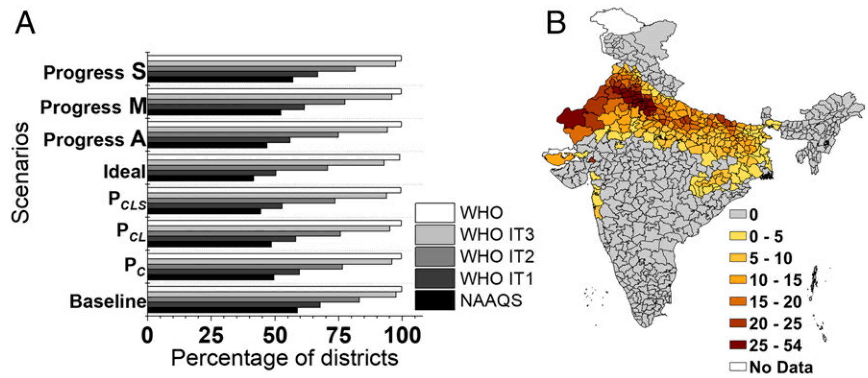

Fig. 4. (*A*) Percentage of districts where ambient $PM_{2.5}$ exposure exceeds various guidelines before and after mitigation of household emissions. Definition of the scenarios in the *y* axis are provided in Table 1 and (*B*) annual $PM_{2.5}$ exposure that needs to be further mitigated in each district after complete mitigation of household $PM_{2.5}$ to achieve Indian standard in that district.

considered in national policies, which would include benefits to the households themselves from lower pollution exposures as well as lower ambient pollution levels.

Methods

Ambient $PM_{2.5}$ Exposure. We consider ambient $PM_{2.5}$ exposure for 2015 as our baseline. Due to the paucity of ground-based measurements across the country in 2015, we utilize aerosol optical depth (AOD) retrieved by MISR (Multiangle Imaging SpectroRadiometer) at 17.6-km resolution to derive annual $PM_{2.5}$ over India. This approach has been described in detail in our previous study (37). In brief, we use a spatially and temporally varying daily conversion factor (η) simulated by the GEOS-Chem chemical transport model (8, 38) to convert AOD to surface $PM_{2.5}$. Inferred $PM_{2.5}$, after bias correction against coincident measurements of $PM_{2.5}$, has ∼8% uncertainty (8, 37). Summary statistics are derived at the district level from gridded satellite data using geographic information system.

Contribution of Individual Household Sources Toward Ambient $PM_{2.5}$ Exposure. The basic methodology for estimating emissions, in turn used for estimating the contribution of household air pollution toward ambient $PM_{2.5}$, is as follows:

$$E_{s,d,g,f,p} = \sum_{d}\sum_{g} EC_{f,s} * EF_p,$$

where *E* is total emissions at the state and district level, by fuel type and pollutant type; *EC* is energy consumption per capita per year, varying by state; *EF* is emission factor by pollutant for a state *s*, district *d*, fuel *f*, and pollutant *p*.

The emissions are broken down into four categories: biomass for (*i*) cooking, (*ii*) space heating, and (*iii*) water heating and kerosene for (*iv*) lighting. The emission factors for the fuel categories listed in the census reports are obtained from ref. 39 and GAINS (www.iiasa.ac.at/web/home/research/researchPrograms/air/GAINS.html). The fuel use patterns are linked to the fields from household-level components of Census of India, 2011, specifically (*i*) HH10 for cooking and heating and (*ii*) HH7 for lighting. The data are further segregated at the district level into urban and rural cooking and inside and outside cooking. Average energy consumed by a household for cooking is calculated based on National Sample Survey Office survey dataset, which lists the amount of food varieties cooked at the state level (39, 40). Heating emissions were further adjusted to account for spatial and temporal profiles in temperature, extracted at the grid level from Weather Research and Forecasting model simulations using National Centers for Environmental Prediction Reanalysis data. Pandey et al. (39, 40) conducted an uncertainty analysis in the form of Monte Carlo simulations. Overall uncertainty in the estimated emissions is >30%, mostly stemming from emission factors. Based on recent measurements, we assume minimal contribution of household biomass burning to precursors of secondary aerosols (41). No laboratory tests for the emission factors or surveys to ascertain the household energy consumption patterns were conducted under this study. More details about the methodology and data used in this study are provided in *SI Appendix*.

The Comprehensive Air Quality Model with Extensions (CAMx) (42–45), an Eulerian photochemical dispersion model, was utilized for dispersion modeling and for estimating the contribution of household emissions toward ambient $PM_{2.5}$ exposure. The emission inventory preparation and modeling framework is discussed in detail in *SI Appendix*, Figs. S1–S4. The model has been validated to perform satisfactorily in earlier studies (42, 46).

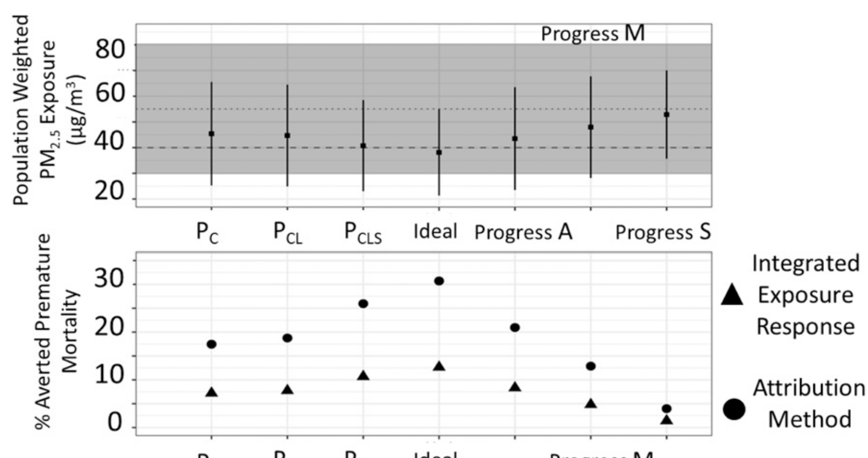

Fig. 5. Changes in population-weighted mean (±1σ shown by error bars) annual ambient $PM_{2.5}$ exposure (*Top*) and percentage averted premature mortality based (*Bottom*). The range of baseline $PM_{2.5}$ estimate is shaded in the top; the mean value is indicated by the dotted line. The dashed horizontal line in the top represents the Indian NAAQS. See text for details.

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To estimate the contribution of each household activity (residential cooking, space heating, water heating, and lighting) toward ambient $PM_{2.5}$ we use the following equation:

$$f_{i,j} = \sum_{j=1}^{N} fh_i \times fe_{i,j},$$

where $f_{i,j}$ is the fraction of ambient $PM_{2.5}$ in a district i contributed by a household activity j. fh_i is the fraction of ambient $PM_{2.5}$ contributed by household burning of solid fuels during the above-mentioned household activities simulated using the CAMx model. The percentage of ambient $PM_{2.5}$ that can be attributed to household $PM_{2.5}$ is depicted in Fig. 1. $fe_{i,j}$ represents the fraction of the total household emission in a district that can be attributed to a particular source j. The percentage contribution of each of the four household activities toward ambient $PM_{2.5}$ exposure is represented in Fig. 3.

Averted Premature Mortality. We estimate the percentage changes in premature mortality (%*Av*) for diseases which are established to have causal relationships with exposure to ambient $PM_{2.5}$ (2, 47–49) (chronic obstructive pulmonary diseases, ischemic heart diseases, stroke, and lung cancer) for each of the above-mentioned scenarios, m, as follows:

$$\%Av_m = \frac{(M - M_m)}{M} \times 100,$$

where M is the estimated premature mortality due to $PM_{2.5}$ exposure for the baseline year, 2015; M_m is the estimated premature mortality for $PM_{2.5}$ exposure for each of the developed scenarios, m. Details about estimation of premature mortality are described in *SI Appendix*.

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