Mapping development and health effects of cooking with solid fuels in low-income and middle-income countries, 2000–18: a geospatial modelling study

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Summary

Background More than 3 billion people do not have access to clean energy and primarily use solid fuels to cook. Use of solid fuels generates household air pollution, which was associated with more than 2 million deaths in 2019. Although local patterns in cooking vary systematically, subnational trends in use of solid fuels have yet to be comprehensively analysed. We estimated the prevalence of solid-fuel use with high spatial resolution to explore subnational inequalities, assess local progress, and assess the effects on health in low-income and middle-income countries (LMICs) without universal access to clean fuels.

Methods We did a geospatial modelling study to map the prevalence of solid-fuel use for cooking at a 5 km × 5 km resolution in 98 LMICs based on 2·1 million household observations of the primary cooking fuel used from 663 population-based household surveys over the years 2000 to 2018. We use observed temporal patterns to forecast household air pollution in 2030 and to assess the probability of attaining the Sustainable Development Goal (SDG) target indicator for clean cooking. We aligned our estimates of household air pollution to geospatial estimates of ambient air pollution to establish the risk transition occurring in LMICs. Finally, we quantified the effect of residual primary solid-fuel use for cooking on child health by doing a counterfactual risk assessment to estimate the proportion of deaths from lower respiratory tract infections in children younger than 5 years that could be associated with household air pollution.

Findings Although primary reliance on solid-fuel use for cooking has declined globally, it remains widespread. 593 million people live in districts where the prevalence of solid-fuel use for cooking exceeds 95%. 66% of people in LMICs live in districts that are not on track to meet the SDG target for universal access to clean energy by 2030. Household air pollution continues to be a major contributor to particulate exposure in LMICs, and rising ambient air pollution is undermining potential gains from reductions in the prevalence of solid-fuel use for cooking in many countries. We estimated that, in 2018, 205 000 (95% uncertainty interval 147 000–257 000) children younger than 5 years died from lower respiratory tract infections that could be attributed to household air pollution.

Interpretation Efforts to accelerate the adoption of clean cooking fuels need to be substantially increased and recalibrated to account for subnational inequalities, because there are substantial opportunities to improve air quality and avert child mortality associated with household air pollution.

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Introduction

The deleterious health effects of household air pollution are long established: solid-fuel use, defined by WHO as primary reliance on wood, crop residue, coal, or dung for cooking, heating, and lighting,[1] was first associated with increased risk of respiratory infections in children in Papua New Guinea almost 50 years ago.[2] The fine particulate matter smaller than 2·5 μm ($PM_{2.5}$) generated by solid-fuel use is a complex mixture that causes harm to health through multiple pathways, including mucociliary dysfunction (which increases susceptibility to infection) and hyperinflammation or immunodeficiency (which can worsen disease prognosis).[3] Solid-fuel use results in $PM_{2.5}$ exposure both within the home and more broadly through emissions that contribute substantially to ambient air pollution.[4,5]

High-income countries have almost fully transitioned to clean fuels (ie, the prevalence of solid-fuel use is less than 5%).[6,7] Across low-income and middle-income countries (LMICs), the net effects of household air pollution—including health effects (US$1·4 trillion), lost productivity ($0·8 trillion), and environmental degradation ($0·4 trillion)—represent an immense annual cost, and thus access to clean and sustainable energy needs to be an essential part of the development agenda.[8] Clean cooking is core to proposed indicators for monitoring Sustainable Development Goal (SDG) 7 (target 7.1: universal access to clean fuels and technology), and has important synergies with goals related to health

Research in context

Evidence before this study

We did not do a formal systematic search of the literature. Previous analyses have quantified the cause-specific disease burden associated with household air pollution globally, including studies using integrated exposure–response curves and pooled meta-analysis from a systematic review. These efforts showed the substantial health effects associated with cooking with solid fuels but did not examine trends in the underlying prevalence of the use of solid fuel in depth. A study estimated the prevalence of primary reliance on specific fuel types at the global and national level over the past 30 years, including forecasts to 2030. Evidence that community-level drivers are the strongest predictors of clean fuel adoption implies that the operational scale of solid-fuel use is more granular and that failure to account for local patterns could obscure inequalities.

Added value of this study

We used geostatistical methods to estimate the prevalence of primary use of solid fuels for cooking and household air pollution at substantially higher resolutions than previous studies, which allowed us to do subnational trend analysis in 98 low-income and middle-income countries from 2000 to 2018. By aggregating these geospatial estimates to second-level administrative boundaries (districts), we were able

to provide actionable insights aligned to the scale of precision public health. We also made projections of progress to 2030, which suggested that few countries are on track to reach the Sustainable Development Goal of universal access to clean fuels within the coming decade. Finally, we combined our high-resolution estimates of the prevalence of solid-fuel use for cooking with exposure–response curves and equivalently resolved estimates of under-5 mortality from lower respiratory tract infections to quantify effects on child health.

Implications of all the available evidence

Although some regions exhibited substantial progress from 2000, in many regions in low-income and middle-income countries, primary reliance on solid fuels for cooking was still ubiquitous in 2018. We noted substantial subnational disparities, leading to health inequalities. Local estimates highlight the outstanding challenge of attaining universal access to clean cooking fuels, and risk assessments showed that hundreds of thousands of children still die annually from lower respiratory tract infections associated with household air pollution. The economic downturn and increased public health strain associated with the ongoing COVID-19 pandemic suggest that our forecasts are likely optimistic, and that the transition to clean and modern fuels must be broadly accelerated to fulfil the bold ambitions of the Sustainable Development Goals.

(SDG 3), education (SDG 4), gender (SDG 5), urban development (SDG 11), climate change (SDG 13), and terrestrial ecology (SDG 15).[9] Prevention strategies targeting household air pollution are shifting towards supplying households with technology or fuels for clean cooking, such as liquefied petroleum gas or electricity.[10] Clean-fuel campaigns are often targeted subnationally, and even country-level programmes have shown heterogeneous patterns of adoption.[11,12] Previously, descriptive analyses of household air pollution and solid-fuel use have focused on a subset of relevant countries[13,14] or have been done globally but constrained by their spatial scale,[6,15] and were of little use for highlighting local patterns or identifying subnational inequality.

In this study, we generate the first high-resolution geospatial estimates of the prevalence of solid-fuel use (as indicated by primary fuel type) and the resulting household concentrations of $PM_{2.5}$ in 98 LMICS. Our aim was to assess growth in access to clean cooking fuels over the past two decades. We also use temporal trends from 2000 to 2018 to forecast the likelihood of achieving SDG target 7.1 by 2030. We further quantify the household-level relationship between household and ambient air pollution by juxtaposing our estimates with data for ambient exposure to $PM_{2.5}$ with equivalent spatial resolution to establish a robust indicator of total personal exposure to $PM_{2.5}$ air pollution. Finally, we combine our results with population data, $PM_{2.5}$ exposure–response

functions, and equivalently resolved geospatial estimates of mortality from lower respiratory tract infections (LRTIs) in children younger than 5 years—a case study designed to assess the health effects of residual solid-fuel use in this vulnerable population.

Methods

Data sources

Solid-fuel use was estimated on the basis of population-based household survey data, in which respondents indicated the primary cooking fuel being used in the household. These responses were mapped to one of eight categories: no cooking in household, electricity, gas, kerosene, coal, wood, crop waste, and dung. Coal, wood, crop waste, and dung were considered solid fuels, whereas the others were deemed clean fuels. We then constructed a binary indicator of solid-fuel use (primary reliance on solid fuels *vs* primary reliance on clean fuels).

98 LMICs were included in the analysis based on their Socio-demographic Index scores (a development index derived from education, fertility, and poverty estimates), which were calculated using values from the low, low-middle, and middle quintiles from the Global Burden of Disease 2019.[16] Sources of input data were only included for modelling if they were representative of the entire population during the time period and across the geographical area of measurement. Furthermore, certain sources were

excluded if the associated estimates seemed implausible based on expert review of estimates and comparison with other sources in the same country and time period. We excluded LMICs with populations of less than 1 million and those that did not have household survey data available (appendix p 2). In total, 663 household surveys were compiled and extracted (appendix p 84). The full database represented 2·1 million people from 2000 to 2018 and included geocoded information from 181 556 coordinates (points) and 417 650 subnational administrative boundaries (polygons). Further details about the data-extraction and data-processing sequence are in the appendix (p 4).

Definitions

In this study, we defined solid-fuel use as the household-level prevalence of primary reliance on solid fuels for cooking, which was described by the adminstrators of the included surveys as the fuel used most often for cooking in a household. In accordance with the Global Burden of Disease (GBD) 2019 study,[16] household air pollution was defined as the incremental concentration of $PM_{2.5}$ generated from cooking with solid fuels. We used the estimated ambient concentration of $PM_{2.5}$ in a location as the baseline exposure (appendix p 6). We subtracted this value from the total personal $PM_{2.5}$ exposure estimated for a solid fuel user: the difference represented the additional contribution of household air pollution to $PM_{2.5}$ exposure.

Statistical analysis

Available geospatial covariates with plausible a priori relationships with solid-fuel use were compiled for use in the prediction model (appendix p 4). We included seven indicators of urbanicity or development, which could be associated with increased access to clean-fuel technologies,[17] such as travel and night-time lights. We also included 16 environmental indicators that might be associated with access to fuelwood or other solid fuels,[18] including diurnal temperature range, elevation, and the normalised difference vegetation index (an indicator of whether a given observation contains live green material, which is calculated by comparing satellite images generated from visible and near-infrared light to estimate plant mass in the pixel). To account for potential multicollinearity, we used the variance inflation factor to analyse these covariates and filtered for each modelling region using a threshold of 5 (which was chosen to prioritise predictive over explanatory power).

We used a Bayesian hierarchical modelling framework to model household exposure to solid-fuel use through a generalised linear mixed-effects model that was spatially explicit. Prevalence of exposure to solid-fuel sources was modelled using the observed number of household members exposed as binomial count data (C_d) among a sample size (N_d). Annual prevalence in each primary sampling unit (cluster; d) for each survey was the

modelled quantity, which was mapped to a geospatial raster location (i) for every year (t):

$$C_d|p_{i(d)}N_d \sim Binomial(p_{i(d)}N_d) \forall \text{ obs. clusters } d$$

$$logit(p_{i,t}) = \beta_0 + X_{i,\beta} + \varepsilon_{c(i)} + \varepsilon_{n(i)} + \varepsilon_i + Z_i$$

$$\sum_{h=1}^{3} \beta_h = 1$$

$$\varepsilon_c \overset{iid}{\sim} N(0,\gamma_c^2)$$

$$\varepsilon_n \overset{iid}{\sim} N(0,\gamma_n^2)$$

$$\varepsilon_i \overset{iid}{\sim} N(0,\sigma^2)$$

$$Z \sim GP(0,\Sigma^{space})$$

$$\Sigma^{space} = \frac{\omega^2}{\Gamma(\nu)2^{\nu-1}} * (kD)^\nu * K_\nu(kD)$$

The appendix (p 5) contains a detailed explanation of these calculations, including definitions of all other included variables.

Prevalence of solid-fuel use was modelled as a linear combination of three submodels (generalised additive models, gradient boosted decision trees, and lasso regression; appendix p 4), rasterised spatiotemporal covariate values, a correlated spatial random effect term (Z_i), country random effects (ε_c), survey-specific random effects (ε_n), and an independent nugget random effect (ε_i). The coefficient of each submodel (β), represented the predictive weighting within the logit link. A key strength of this approach is the ability to leverage residual correlation structures within the predictions to make more accurate estimates for data-sparse locations, while simultaneously propagating this dependence through to estimates of uncertainty in all indicators (appendix p 6). The posterior distributions were fit based on approximations in integrated nested Laplace approximation (R-INLA), with approximation of the stochastic partial differential equations to the Gaussian process residuals done in R (version 3.6.1).

Models were assessed on the basis of a five-fold out-of-sample cross-validation strategy that was stratified over space (appendix p 6). Estimates of bias (mean error), variance (root-mean-square error), coverage of data by 95% prediction intervals (appendix p 6), and correlations between predictions and observed data were used to assess the models (appendix p 6). In-sample and out-of-sample model validation plots were also produced comparing every country and first and second administrative unit estimated with the observed data for those units (appendix p 6).

Pixel-level estimates of solid-fuel use were calibrated to estimates from the GBD 2019 study using a previously described method[19] to preserve relative spatial patterns while ensuring comparability and incorporating information from national-level reports that could not be used within geospatial models. We defined calibration

factors on the basis of comparison of draws from GBD outputs to population-weighted aggregations of our estimates at the highest level of spatial granularity available (either national or the first administrative level for select countries for which GBD-produced subnational estimates were available).
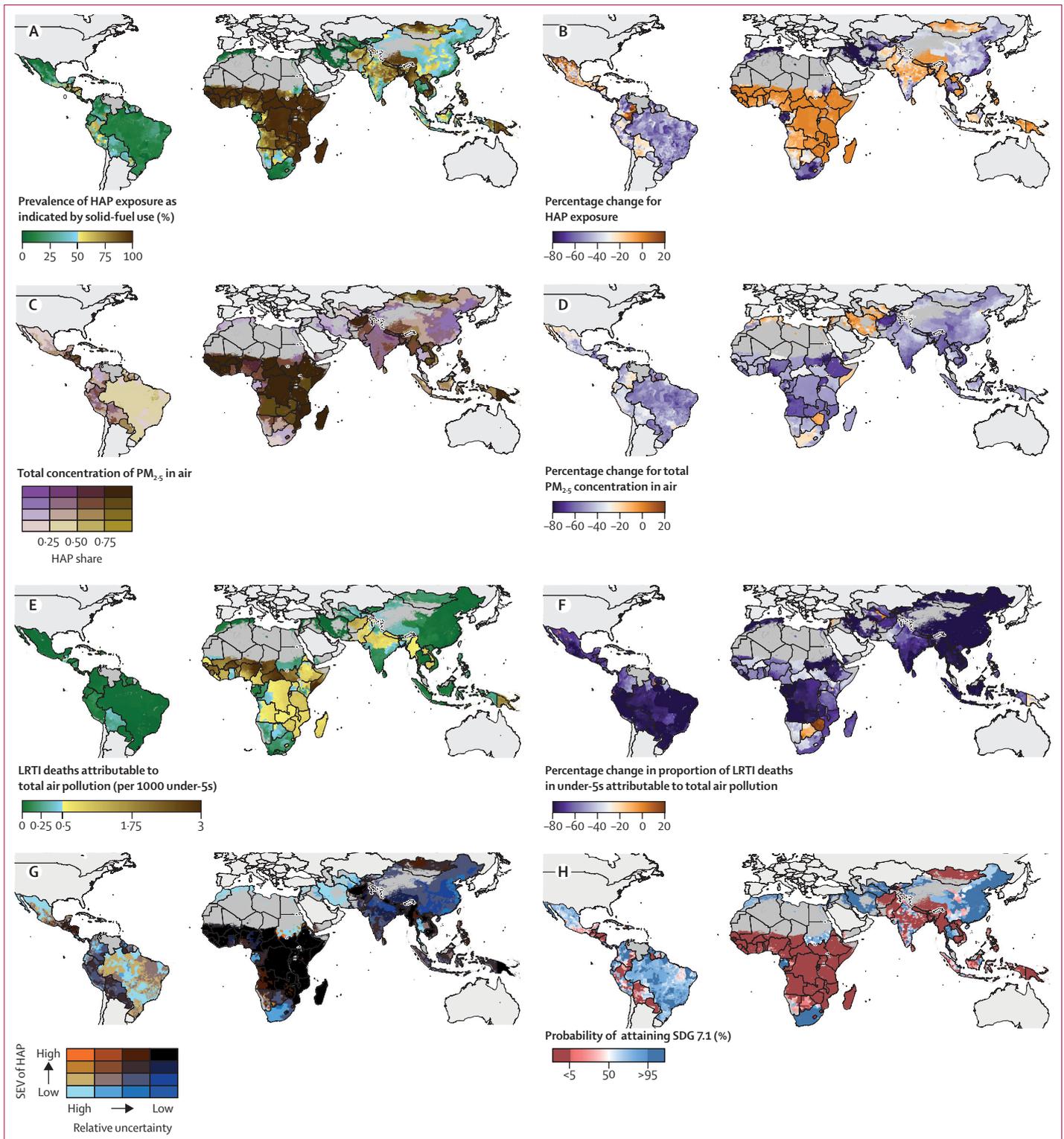
We combined the model output ($P(SFU)$) with geospatial estimates of population (pop) and ambient $PM_{2.5}$ exposure ($APM_{2.5}$) from the GBD 2019 study[16] to calculate personal total exposure to $PM_{2.5}$ pollution (TAP) (the sum of household and ambient air pollution in each 5 km×5 km grid cell i [pixel]):

$$HAP_{i,c,t}=(P(SFU)_{i,c,t} * pop_{i,c,t}) * HPM_{2.5\,c,t}$$

$$TAP_{i,c,t}=pop_{i,c,t} * APM_{2.5\,c,t} + HAP_{i,c,t}$$

$$TAP\ RR_{i,c,t,o}=IER(\frac{TAP_{i,c,t}}{pop_{i,c,t}})_o$$

$$TAP\ PAF_{i,c,t,o}= \frac{TAP\ RR_{i,c,t,o}}{TAP\ RR_{i,c,t,o}-1}$$

$$HAP\ N_{i,c,t,o}=TAP\ PAF_{i,c,t,o} * N_{i,c,t,o} * \frac{HAP_{i,c,t}}{TAP_{i,c,t}}$$

Estimates of the expected incremental $PM_{2.5}$ concentration generated in a household using solid fuels ($HPM_{2.5}$) for a given country (c) and year (t) from GBD 2019 were used to calculate the concentration of household air pollution in the exposed population.[20] The per-person annual average ambient $PM_{2.5}$ estimate from GBD 2019 ($APM_{2.5}$) was summed with the household air pollution concentration to calculate the total air pollution concentration. The fraction of total personal exposure to $PM_{2.5}$ air pollution contributed by household air pollution in each pixel was estimated to provide the household air pollution share ($HAP\%$). Finally, the per-person air pollution concentration in each pixel was used as an input to the GBD 2019 risk (IER).[16] curve for LRTIs to estimate a relative risk (RR) and population attributable fraction (PAF) for every $PM_{2.5}$-associated outcome (o) in each pixel. The population attributable fraction is a counterfactual estimate of the disease burden explained by a given risk factor, based on the level of exposure and

corresponding excess relative risk of disease.[16] The population attributable fraction for LRTIs was combined with pixel-level estimates[21] of under-5 LRTI mortality counts($N_{i,c,t,o}$) to estimate the count ($TAP\ N$) and rate of deaths from LRTIs that were attributable to total air pollution and specifically to household air pollution and ambient air pollution in each district.

All pixel-level indicators were population-weighted and aggregated to first (regions) and second (districts) administrative levels using shapefile boundaries from the Database of Global Administrative Areas shapefiles. We quantified within-country inequalities by using the range between the best-performing and worst-performing district for a given year and the average interpersonal difference, which estimates the average difference between any two districts in a country-year.[22] Absolute and annualised rates of change from 2000 to 2018 were computed to quantify temporal trends over the study period. This annualised rate of change was applied to 2018 values to project the summary exposure value (a risk-weighted summary measure of exposure prevalence)[16] to 2030 for assessment of the attainment of SDG indicator 7.1.2 (the proportion of population with primary reliance on clean fuels and technology, which is used as a tracking benchmark for SDG 7). We chose this target indicator because it corresponds most closely to our modelled proportion on the basis of previously published[23] methods that were consistent with the GBD 2019 study.[16] The annualised rate of change for solid-fuel use (P) was calculated at the draw level (i) for each pixel (m) by estimating the rate between each pair of adjacent years (t):

$$Annualised\ rate\ of\ change_{i,m,t}=logit(\frac{P_{i,m,t}}{P_{i,m,t-1}})$$

The annualised rate of change was then weighted across all years, such that more recent rates were additionally weighted. Weights (W) were defined as:

$$W_t=(t-200+1)^\omega$$

For this analysis, ω was defined using draws from a distribution generated empirically for this indicator in the GBD 2019 study, with a mean value of 2·3 and an SD of 0·41. The weighted annualised rate of change for each pixel was generated for each unit as:

$$Annualised\ rate\ of\ change_{i,m}=logit(\sum_{2000}^{2018} W_t * Annualised\ rate\ of\ change_{i,m})$$

Annualised rate of change estimates for 2018 were used to predict for 2030:

$$Proj_{i,m,2030}=logit^{-1}(logit(P_{i,m,2018}) + annualised\ rate\ of\ change_{i,m} * (2030-2018))$$

Figure 1: **Prevalence of, and change from 2000 to 2018, in solid-fuel use, household air pollution, total air pollution, and deaths attributable to LRTI in children younger than 5 years in low-income and middle-income countries**
(A) Mean prevalence of solid-fuel use for cooking, 2018 (as indicated by primary fuel type). (B) Total concentration of $PM_{2.5}$ in air by source, 2018. (C) Mean number of deaths from LRTIs (per 1000 children younger than 5 years) attributable to total concentration of $PM_{2.5}$ in air, 2018. (D) Overlapping terciles of mean risk-weighted prevalence (SEV) of HAP in 2018 and relative uncertainty. These data were used for our projections of SDG attainment in 2030. (E) Percentage change in mean proportion of solid-fuel use for cooking, 2000 to 2018. (F) Percentage change in total concentration of $PM_{2.5}$ in air, 2000 to 2018. (G) Percentage change in the proportion of LRTI deaths (per 1000 children younger than 5 years) attributable to total concentration of $PM_{2.5}$ in air, 2000 to 2018. (H) Probability of attaining SDG 7.1 by 2030. All panels are aggregated to the second administrative-level unit. Maps reflect administrative boundaries, land cover, lakes, and population. Grey-coloured grid cells had fewer than ten people per 1 km × 1 km grid cell and were classified as barren or sparsely vegetated, or not included in this analysis. HAP=household air pollution. $PM_{2.5}$=particulate matter of less than 2·5 μm in diameter. SEV=summary exposure value. LRTI=lower respiratory tract infection. SDG=Sustainable Development Goal.

Attainment probabilities for SDG indicator 7.1.2 were derived from the percentage of simulations in 2030 with summary exposure below 5%, a threshold chosen on the basis of estimates of solid-fuel use in high-income countries.[24] We used the R-INLA package in R (version 4.1.3) for our analyses. All code used in the analysis is available online.

Role of the funding source

The funder of the study had no role in the study design, data collection, data analysis, data interpretation, or the writing of the report.

Results

Subnational solid-fuel use prevalence was notably spatiotemporally heterogeneous (figure 1A), underscoring the importance of subnationally tracking cooking behaviours and corresponding measures of pollution. In 2018, 10·0% (95% uncertainty interval [UI] 7·4–13·9; appendix p 6) of the population in LMICs (593 million people) lived in districts where the prevalence of solid-fuel use exceeded 95%. National prevalence estimates masked substantial within-country heterogeneity (figure 2). For example, the average solid-fuel use prevalence in Guatemala was 52·0% (95% UI 40·0–63·2), but across just 140 km, prevalence ranged from 1·0% (0–3·3) in Zona 22, Guatemala City, to

91·6% (79·4–97·8) in Santa Eulalia, Huehuetenango. During the study period, the average interpersonal difference increased by 43·0% across all LMICs.

Prevalence of solid-fuel use fell across LMICs (figure 1E) from 67·8% (95% UI 67·1–69·0) in 2000 to 56·5% (53·8–57·9) in 2018, a relative decrease of 16·7% (14·3–21·6). Due to population growth, however, an additional 359 million (234 million–388 million) people were exposed to solid-fuel use in 2018. We estimated that, in 2018, 56·5% (53·9–57·9) of people in LMICs, roughly 3·38 billion (3·21 billion–3·45 billion) of the 5·96 billion in the study area (which rose from 4·4 billion in 2000) relied primarily on solid fuels for cooking. Projections for the year 2030 (figure 1D) suggest that only five countries (Iraq, Iran, Jordan, Syria, and Turkmenistan) across three regions, representing 3% of the 2018 study population, have a greater than 95% probability of achieving universal access to clean cooking fuels (figure 1H) in every district. District-level forecasting highlights the importance of using subnational estimation to monitor progress towards universal access. National trends suggest that Mexico has a 98% probability of meeting the threshold for universal access by 2030. However, this figure obscures local inequalities, because 14% of the population (nearly 19 million people in 2018) live in districts where the probability is less than 50%. In India, solid-fuel use
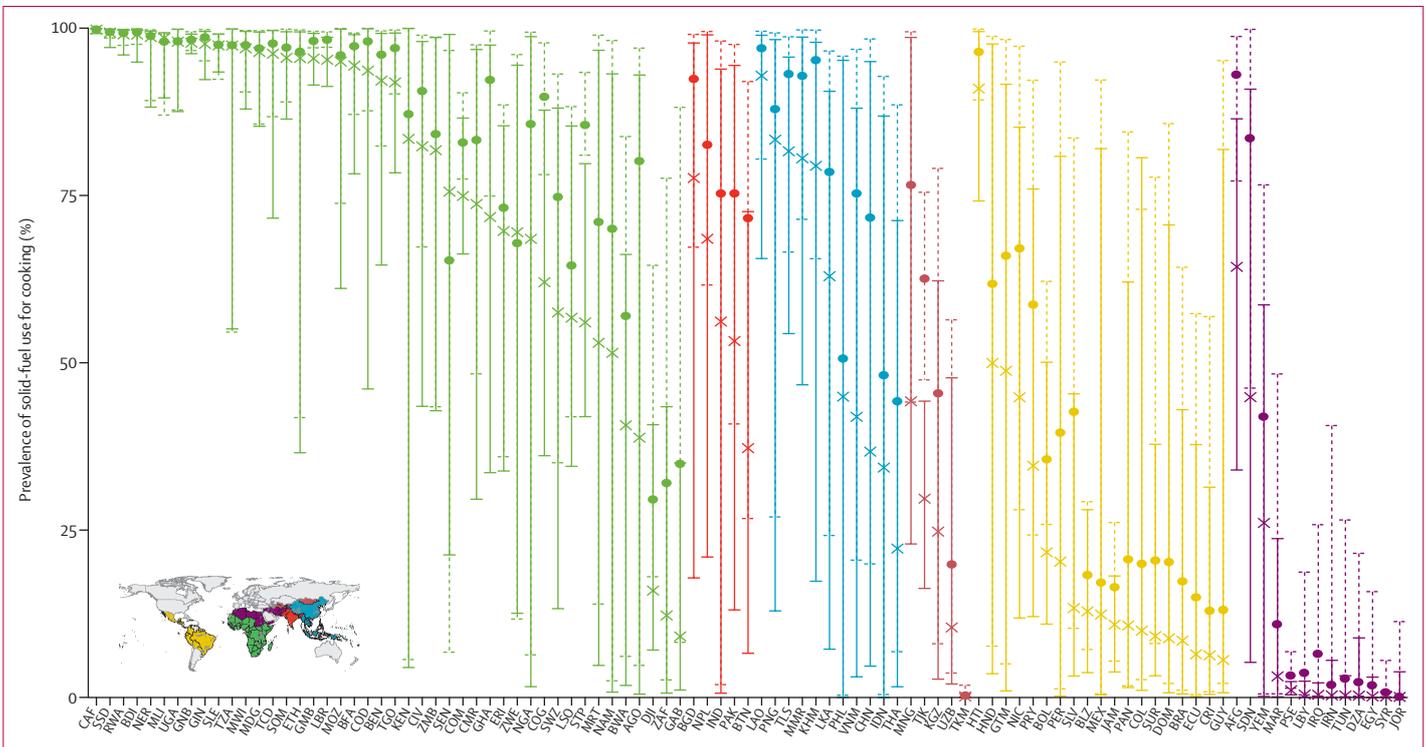
Figure 2: Geographical variations in the prevalence of solid-fuel use for cooking in 98 low-income and middle-income countries
Each bar represents the range of the prevalence of solid-fuel use for cooking (as represented by primary fuel type) across all districts within each country. The Xs and dashed bars represent the mean and range in 2000, whereas the dots and solid bars represent the mean and range in 2018. Countries are grouped according to geographical region and coloured according to the Global Burden of Disease 2019 super-regions (see inset thumbnail).[16] Each country is labelled by its ISO-3 code.
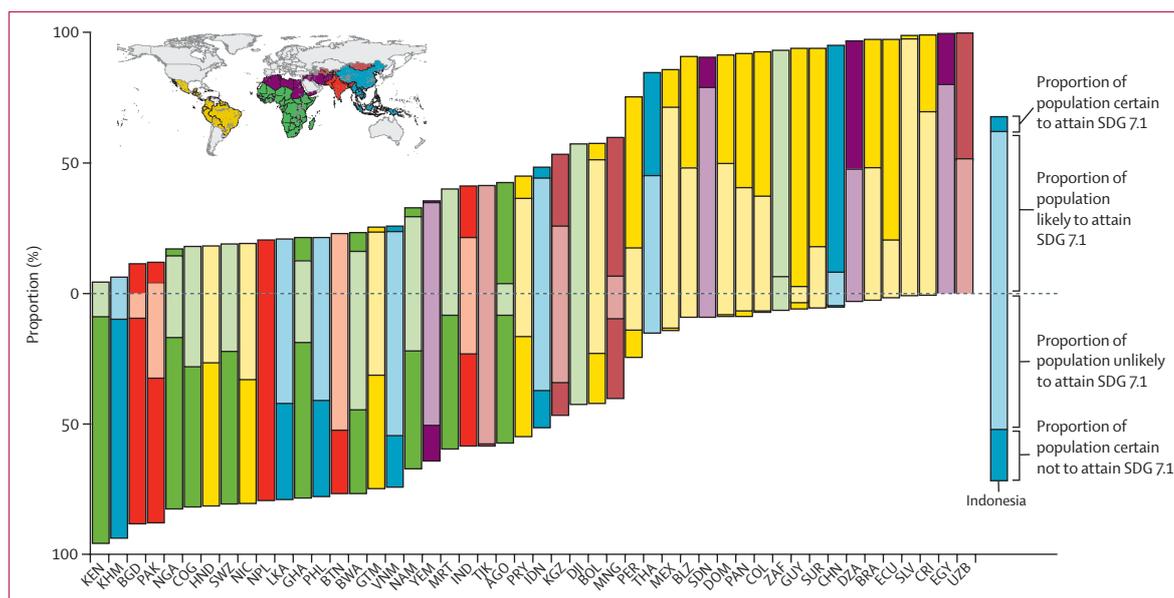
**Figure 3:** Projections of the probability of attainment of SDG 7.1 by 2030

Progress towards SDG 7.1 was monitored by estimating access to clean cooking fuel across the study period, calculating the annualised rate of change and forecasting to 2030. The bars represent the share of population living in districts that were projected (with 95% certainty) to be above (negative values) or below (positive values) a threshold of 5% for attainment in 2030. The translucent, lighter-coloured sections of the bars represent projections in districts with less certainty (greater than 50%, but less than 95%). The bars are coloured according to Global Burden of Disease 2019 super-regions (see inset thumbnail).[16] Only the 48 countries where at least one district was projected to be above the threshold and at least one was projected to be below the threshold were included. Each country is labeled by its ISO-3 code. SDG=Sustainable Development Goal.

prevalence has substantially decreased, and the national attainment probability is up to 33%. Locally, however, more than 35% of people (482 million people in 2018) lived in districts where the forecasted probability of attainment is less than 5%.

Moderate rates of change and the shortening timeline for achievement of the SDGs suggest that few districts that had not already achieved the target of universal access to clean cooking fuels in 2018 will do so by 2030. In 2018, 3·8 billion people in LMICs (ie, 65·7% of the population) lived in districts that did not meet the threshold for universal access to clean cooking fuel. Our projections suggest that only 22·0% (835 million) of these people live in a district that is forecasted to meet the threshold by 2030. Countries with the largest share of districts that were above the threshold in 2018 but on track to meet it by 2030 included Gabon (where 93·9% of the population that has yet to meet the goal lives in districts that are projected to meet it by 2030), China (82·9%), South Africa (66·5%), Mongolia (52·7%), Suriname (40·5%), Ecuador (27·6%), and Uzbekistan (24·6%). In 27 countries, every district is projected to remain above the 5% threshold by 2030 with high certainty (figure 1H). In the 48 countries containing both districts that are projected to meet the threshold and districts projected to fail to meet it, the proportion of the population living in a district that is not on track (as of 2018) ranged from less than 1% (14459 people) in Uzbekistan to 95% (49 million people) in Kenya (figure 3).

The total concentration of PM$_{2.5}$ air pollution to which people were exposed was nearly halved (mean decrease 47·2% [95% UI 46·4–47·7]) from 2000 to 2018 (figure 1F). However, in 2018, only 14·9% (10·9–18·4) of people in LMICs lived in districts that met WHO's air quality interim target[25] of 35 μg/m³ (figure 4A), and 80% of people were exposed to annual concentrations greater than 44 μg/m³ (for comparison, in 2000, 80% of the population lived in pixels with concentrations that were almost double that value, at 82 μg/m³ or more). Globally, the proportion of the total particulate matter concentration contributed by household air pollution decreased from 66·3% (64·8–70·0) in 2000 to 46·5% (43·2–47·8) in 2018. Household air pollution contributed most of the total PM$_{2.5}$ air pollution in 69 of 98 countries in 2000, and 50 of 98 in 2018, suggesting a risk transition for the main source of particulate matter exposure in LMICs.

We focused our case study on the effects of particulate matter on child health, given the availability of analogous high-resolution geospatial estimates for mortality attributable to LRTIs in children younger than 5 years.[21] Over the study period, the population attributable fraction of fatal LRTIs associated with total exposure to PM$_{2.5}$ air pollution in all LMICs fell from 45·7% (95% UI 32·2–57·6) in 2000 to 38·4% (24·9–51·9) in 2018, a relative reduction of 16·5% (95% UI 9·0–26·5). Nearly half of fatal LRTIs in 2018 were attributable to total exposure to PM$_{2.5}$ air pollution in sub-Saharan Africa
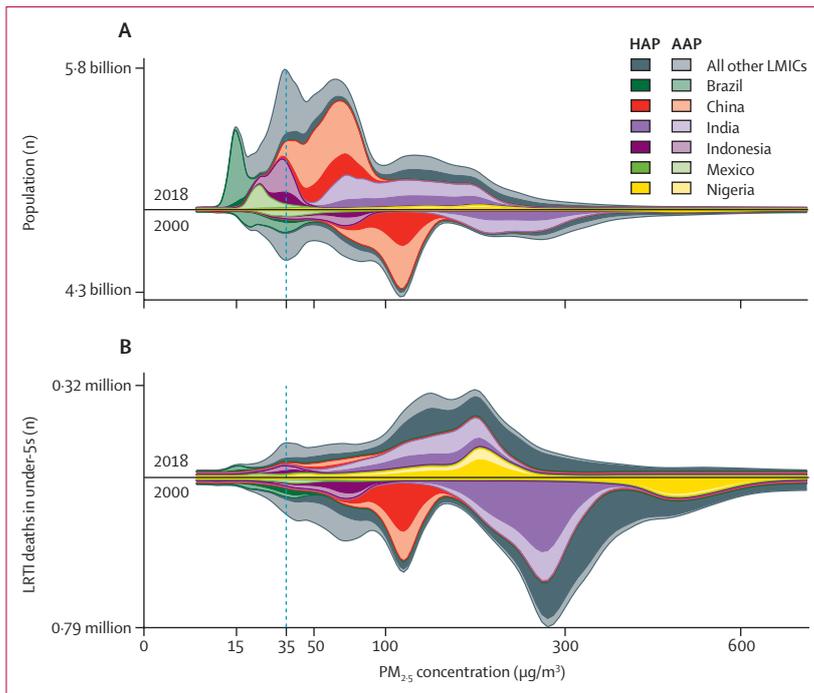
Figure 4: All-age population (A) and LRTI deaths attributable to total PM$_{2.5}$ concentrations in air in children younger than 5 years (B) in 2000 and 2018, distributed as a function of PM$_{2.5}$
Within each distribution, the darker shading represents the portion of air pollution contributed by household sources, whereas the lighter shading represents the portion contributed by ambient sources. The plotted data represent local smoothing of normalised distributions that were computed over 400 logarithmically spaced bins. The dashed vertical line indicates WHO's interim threshold for PM$_{2.5}$ air pollution (35 μg/m³). The y-axis labels provide the total area under the curve. Data for all other LMICs included in the study are broken down by country in the appendix (p 42). LRTI=lower respiratory tract infection. HAP=household air pollution. AAP=ambient air pollution. PM$_{2.5}$=particulate matter of less than 2·5 μm in diameter. LMICs=low-income and middle-income countries.

(49·8% [36·4–61·4]). Across LMICs, most fatal LRTIs were attributable to total exposure to PM$_{2.5}$ air pollution in 10·0% (0·0–22·3) of districts. We estimated that, across LMICs in 2018, 320 000 (218 000–408 000) children died from LRTIs attributable to air pollution (figure 1D) compared with 747 000 (533 000–932 000) in 2000. This reduction was driven largely by reductions in solid-fuel use: the number of LRTI deaths attributable to household air pollution in children younger than 5 years fell by 65·5% (62·3–68·6). However, an estimated 205 000 (147 000–257 000) children still died from LRTIs attributable to household air pollution in 2018. These deaths are now associated with lower pollution concentrations (figure 4B): the median was 202 μg/m³ in 2018, compared with 326 μg/m³ in 2000. Across LMICs, the share of attributable under-5 LRTI mortality that was driven by household versus ambient particulates fell from 79·6% (77·4–81·6) in 2000 to 64·3% (61·6–67·9) in 2018, signalling that household air pollution is still a crucial factor in under-5 LRTI deaths.[25]

District-level burden estimates further underscored the risk transition occurring in LMICs: the concentrations of particulate matter to which populations were exposed decreased, and were increasingly driven by ambient sources (figure 5). This transition generally decreased the share of LRTIs attributable to particulate air pollution (figure 1E). However, as experienced in China, India, and Nigeria, sharply rising outdoor pollution superseded clean cooking adoption and offset potential burden reductions (figure 5). In some countries, the prevalence of fatal LRTIs (figure 1G) fell without a corresponding decline in household air pollution: in Laos, for example, the rate of fatal LRTIs per 1000 children younger than 5 years fell 73·8% (95% UI 66·3–80·9) between 2000 and 2018, while solid-fuel use prevalence decreased by only 3·5% (1·0–6·9). In the 19 countries where under-5 LRTI death rates still exceed two per 1000 children, however, the proportion of LRTI deaths attributable to household air pollution ranged from 21·4% (12·8–30·0) in Lesotho to 60·9% (44·8–75·7) in Somalia, suggesting that reduction of household air pollution remains fundamental to the elimination of preventable child mortality.

Discussion
The results of our geospatial modelling study suggest that, despite progress since 2000, solid-fuel use continues to be widespread in LMICs, with uneven improvements driving regional and within-country inequalities. Our projections indicate that attaining the SDG target of universal access to clean cooking fuels by 2030 is improbable for many countries. Total particulate matter exposure fell between 2000 and 2018, but most people in LMICs continue to be exposed to PM$_{2.5}$ concentrations far above the interim air quality target of 35 μg/m³. The fraction of total PM$_{2.5}$ contributed by ambient air pollution rose, as growing outdoor concentrations in many geographies offset the health gains of cleaner cooking. The combination of a slow transition from solid-fuel use and displacement by ambient pollution sources supports a mandate for strengthening efforts to drive decreases in exposure to realise crucial health gains. The health effects of inaction are particularly relevant to vulnerable populations, such as children younger than 5 years, among whom more than a third of deaths from LRTIs are still attributable to air pollution.

The inclusion of clean energy in multinational initiatives such as the Global Forum on Child Pneumonia,[26] climate change mitigation,[27] and a web of interlinked SDG targets[9] indicates that promotion of clean fuels will be crucial to the global development agenda in the coming decade. The energy-ladder hypothesis initially asserted that adoption of clean fuel sources was primarily driven by rising income, but subsequent research suggests that residential energy choices are influenced by a variety of complex socioeconomic forces, including community factors, agricultural practices, and dietary preferences.[14,28] Cooking is social, and campaigns to develop new energy markets by reducing prices and strengthening supply chains should be integrated with marketing and educational
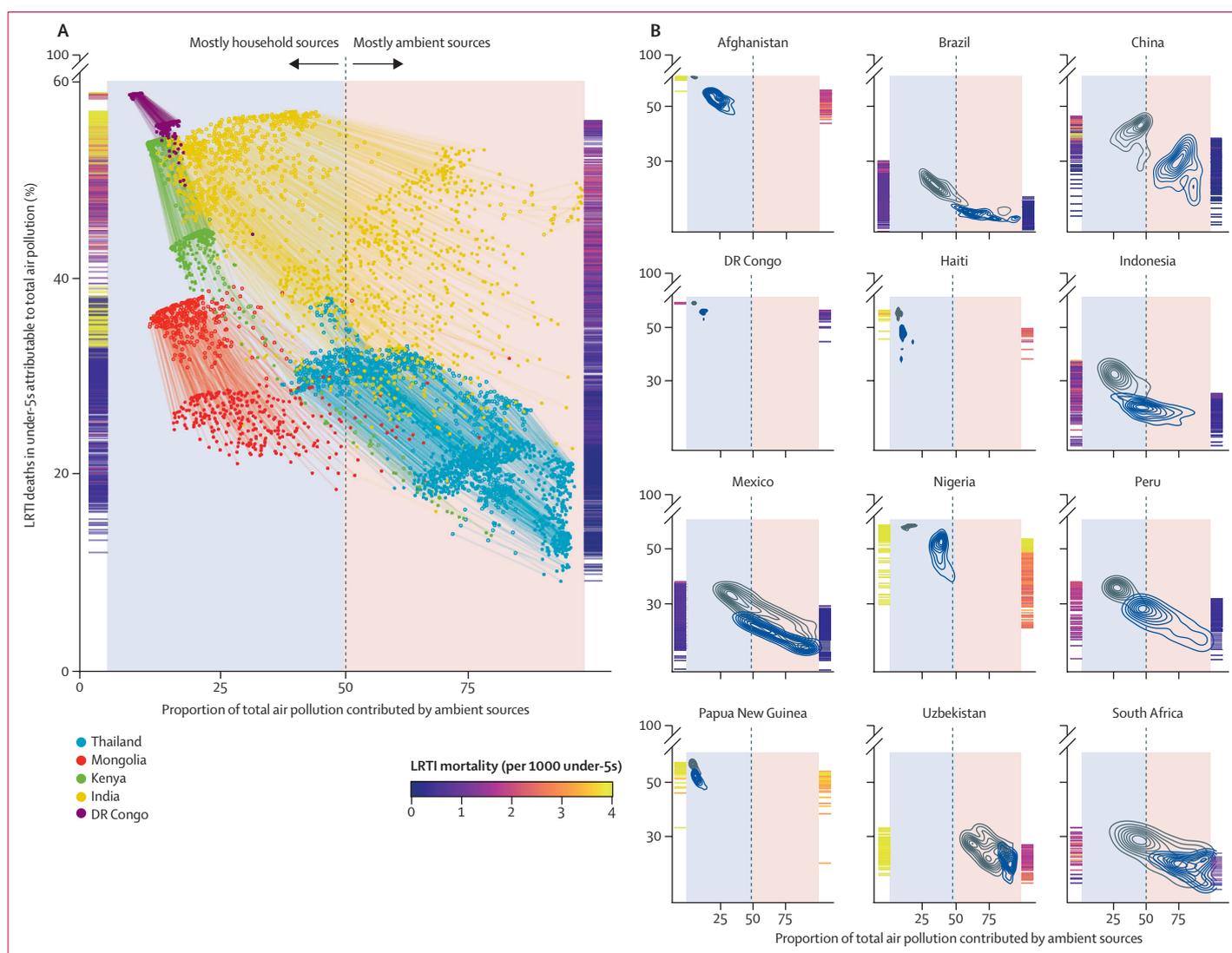
***Figure 5*: Air pollution risk transition, 2000–18**
(A) Trends in the proportion of LRTI deaths attributed to total air pollution at the second administrative unit (district) level in five low-income and middle-income countries. These countries were chosen to exemplify different stages of air-pollution risk transition (all other countries included in the study are illustrated in the appendix [p 63]). The y-axis rugs indicate the gradient of background LRTI mortality rates for 2000 (left) and 2018 (right), illustrating the correlation between LRTI rates and the fraction attributable to total ambient air pollution. The lines connect a district to its preceding timepoint across the series. (B) Countries with the highest LRTI mortality in 2000 for each Global Burden of Disease subregion. The grey contours represent district-level distributions in 2000, whereas the navy represents distributions in 2018. In Thailand and South Africa, for example, reductions in household air pollution have resulted in less than a quarter of LRTIs being attributable to air pollution, whereas in China and India, similar reductions have been counteracted by rising ambient air pollution concentrations, which means that a larger share of LRTI deaths in children younger than 5 years continue to be attributable to total air pollution. LRTI=lower respiratory tract infection.

outreach activities to build knowledge and change household norms.[29] Policies that include rural electrification and fuel subsidies have been efficacious, but our estimates support critiques that these campaigns need to be accelerated and redirected to target rural households that are continuing to fall behind in the adoption of clean cooking fuels.[30]

Ambitious programmes, such as India's Pradhan Mantri Ujjwala Yojana, have substantially increased adoption of clean fuels, but beneficiaries struggle to sustain regular use.[12] Our estimates were derived from data for primary fuel type, and the widespread nature of

stacking (ie, parallel use of multiple fuel types[31]) supports the value of a more specific proxy for clean cooking than that used by us and in most household surveys. The Multi-Tier Framework surveys for some countries show that the extent of stacking depends on local context: for example, most urban households in Cambodia stack,[32] whereas more than 90% of households in Rwanda use one stove to meet their energy needs.[33] Air-monitoring data help to clarify the direction and magnitude of the bias introduced by exposure misclassification as a result of stove stacking: compared with households that exclusively use their primary fuel for cooking, households

that primarily use clean fuels but stack with a solid fuel have a much higher particulate matter differential than households who stack with a solid primary and clean secondary fuel, suggesting that primary fuel data underestimate the true burden of household air pollution.[34]

Ultimately, switching of primary fuel sources is an inadequate target for the reduction of household air pollution to levels that are acceptable for human health. While our analysis of primary fuel data shows the tremendous scale of residual solid-fuel use, it represents a narrow interpretation of SDG 7.1, and attainment of universal access to modern energy should incorporate solutions that acknowledge the contextual challenges of LMIC households (eg, power outages, fuel shortages, device malfunctions). Expanding the spatiotemporal coverage of nuanced surveys with more specific assessments of household energy behaviours would allow for future analyses to maintain our global scope while transitioning to more sophisticated indicators, like the Multi-Tier Framework data, to enable calculation of adequate proxies for total personal exposure to $PM_{2.5}$. Likewise, other indicators relevant to the immediate housing environment[35] should be integrated with these estimates to account for the synergistic effects they have on health outcomes.

Our study had several limitations. Although data[6] suggest that use of kerosene as a fuel for cooking has substantially diminished globally during the study period, our exclusion of kerosene in calculations of household air pollution probably underestimates the burden in countries where kerosene is still commonly used,[36] such as Equatorial Guinea, Djibouti, and urban areas in some Oceanian nations.[6] Furthermore, the lack of comprehensive data for fuels used for heating and lighting restricted our analyses to cooking. Solid-fuel use for heating especially contributes substantially to seasonal concentrations of $PM_{2.5}$ in LMICs with cooler climates.[37] Thus our burden estimates are probably too low in important cases, such as China[38] and South Africa.[39] Restricting our epidemiological case study to LRTI deaths in children younger than 5 years is an additional limitation, because LRTIs represent only a fraction of the deleterious health effects of air pollution. Aside from the robust evidence for effects on other child health endpoints, including adverse birth outcomes[40] and neurodevelopmental effects,[41] $PM_{2.5}$ pollution substantially affects adult health and is associated with chronic diseases like cardiovascular disease, chronic obstructive pulmonary disease, lung cancer, and diabetes.[7] Finally, the accuracy of our estimates is a function of the quality and volume of survey data available, and uncertainty is substantial in areas where data are missing or less reliable. Our projections are based on a simplified method for applying annual trends to estimates for 2018, and are dependent on countries maintaining this rate of progress. Accordingly, they do not reflect the potential effect of new technologies or investments in clean energy, nor do they capture how widespread economic and societal disruptions—such as those associated with the COVID-19 pandemic—could negatively affect immediate and long-term trajectories. Pandemic-related effects on pollution are likely to be multifaceted and nuanced across settings, and could vary in relation to a combination of public health measures taken against COVID-19.[42]

There have been notable triumphs in the push for global transition to clean cooking fuels, yet our estimates clearly show the breadth of residual exposure to household air pollution and the substantial challenges faced in addressing the relevant SDG targets before 2030. Unless global and national investments in clean energy access and adoption increase substantially this decade, household particulate concentrations will remain far above acceptable levels and the bold SDG ambitions for clean energy will remain unmet. Heterogeneity in reductions in the prevalence of solid-fuel use emphasises growing inequality in much of the world, and the changing relationship between solid-fuel use and ambient air pollution underscores the importance of continuing to push for universal access to clean fuels. Collectively, our results emphasise the need to support access to clean cooking fuels to achieve development goals and can help to inform the design of geospatially targeted campaigns that combat areas of enduring deprivation by proactively targeting inequality.

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Contributions for each author are listed in the appendix (pp 131–36). Members of the core research team (appendix p 131) had full access to and verified the underlying data used to generate estimates presented in this Article, and had final responsibility for the decision to submit for publication. All other authors had access to estimates and reviewed estimates as part of the research evaluation process, which included additional stages of formal review.

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Declaration of interests

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