10-1-2020

Household and personal air pollution exposure measurements from 120 communities in eight countries: Results from the PURE-AIR study

Matthew Shupler
University of British Columbia, Vancouver, BC, Canada

Perry Hystad
Oregon State University, Corvallis, OR, USA.

Aaron Birch
University of British Columbia, Vancouver, BC, Canada

Daniel Miller-Lionberg
Access Sensors Technologies, Fort Collins, CO, USA.

Matthew Jeronimo
University of British Columbia, Vancouver, BC, Canada

See next page for additional authors

Recommended Citation
Shupler, M., Hystad, P., Birch, A., Miller-Lionberg, D., Jeronimo, M., Arku, R. E., Chu, Y. L., Khawaja, R., Iqbal, R., Kazmi, k. (2020). Household and personal air pollution exposure measurements from 120 communities in eight countries: Results from the PURE-AIR study. *The Lancet Planetary Health, 4*(10), e451-e462.
Available at: https://ecommons.aku.edu/pakistan_fhs_mc_chs_chs/809

HHS Public Access
Author manuscript
Lancet Planet Health. Author manuscript; available in PMC 2020 October 27.

Published in final edited form as:
Lancet Planet Health. 2020 October ; 4(10): e451–e462. doi:10.1016/S2542-5196(20)30197-2.

Household and personal air pollution exposure measurements from 120 communities in eight countries: results from the PURE-AIR study

Matthew Shupler,
School of Population and Public Health, University of British Columbia, Vancouver, BC, Canada; Department of Public Health and Policy, University of Liverpool, Liverpool, UK

Perry Hystad,
College of Public Health and Human Sciences, Oregon State University, Corvallis, OR, USA

Aaron Birch,
School of Population and Public Health, University of British Columbia, Vancouver, BC, Canada

Daniel Miller-Lionberg,
Access Sensors Technologies, Fort Collins, CO, USA

Matthew Jeronimo,
School of Population and Public Health, University of British Columbia, Vancouver, BC, Canada

Raphael E Arku,
School of Population and Public Health, University of British Columbia, Vancouver, BC, Canada; School of Public Health and Health Sciences, University of Massachusetts Amherst, Amherst, MA, USA

Yen Li Chu,
School of Population and Public Health, University of British Columbia, Vancouver, BC, Canada

Maha Mushtaha,

Correspondence to: Matthew Shupler, School of Population and Public Health, University of British Columbia, Vancouver, BC V6T 1Z3, Canada, mshupler@mail.ubc.ca.

Contributors

MS assisted with protocol development, led survey design, managed, cleaned, analysed, and interpreted all data, and wrote the first and final drafts of the Article. PH and MB designed and supervised the conduct of the PURE-Air study, supervised the data analysis and interpretation of the data, and reviewed and commented on all drafts and the final Article. AB led protocol development and assisted with study logistics. DM-L assisted with the monitoring equipment, data quality control and provided input on the final Article. MJ was in charge of laboratory analysis of the data. REA assisted with study design and reviewed and commented on the final Article. YLC assisted with data management and study logistics. SY designed and supervised the conduct of the PURE study and reviewed and commented on the final Article. MM and LH assisted with data management and study logistics. SR coordinated the worldwide study and reviewed and commented on the final Article. All other authors coordinated the study in their respective countries and commented on the final Article.

*Members of the PURE-AIR study are listed in the appendix

Declaration of interests

MB reports a grant from the Canadian Institutes of Health Research during the conduct of the study. PH reports a grant from the Canadian Institutes of Health Research and the National Institutes of Health Sciences during the conduct of the study. DM-L has a patent (US 10,488,305) issued to Access Sensor Technologies. All other authors declare no competing interests.

Data sharing

No additional data are available for this Article.

Population Health Research Institute, Hamilton Health Sciences, McMaster University, Hamilton, ON, Canada

Laura Heenan,
Population Health Research Institute, Hamilton Health Sciences, McMaster University, Hamilton, ON, Canada

Sumathy Rangarajan,
Population Health Research Institute, Hamilton Health Sciences, McMaster University, Hamilton, ON, Canada

Pamela Seron,
Universidad de La Frontera, Temuco, Chile

Fernando Lanas,
Universidad de La Frontera, Temuco, Chile

Fairuz Cazor,
Universidad de La Frontera, Temuco, Chile

Patricio Lopez-Jaramillo,
Universidad de Santander (UDES), Bucaramanga, Colombia

Paul A Camacho,
FOSCAL, Floridablanca, Colombia

Maritza Perez,
Universidad Militar Nueva Granada, Bogota, Colombia

Karen Yeates,
Pamoja Tunaweza Research Centre, Moshi, Tanzania; Department of Medicine, Queen's University, Kingston, ON, Canada

Nicola West,
Pamoja Tunaweza Research Centre, Moshi, Tanzania

Tatenda Ncube,
Department of Physiology, University of Zimbabwe, Harare, Zimbabwe

Brian Ncube,
Department of Physiology, University of Zimbabwe, Harare, Zimbabwe

Jephat Chifamba,
Department of Physiology, University of Zimbabwe, Harare, Zimbabwe

Rita Yusuf,
School of Life Sciences, Independent University, Dhaka, Bangladesh

Afreen Khan,
School of Life Sciences, Independent University, Dhaka, Bangladesh

Bo Hu,
Medical Research & Biometrics Center, National Center for Cardiovascular Diseases, Fuwai Hospital, Chinese Academy of Medical Sciences, Beijing, China

Xiaoyun Liu,
Medical Research & Biometrics Center, National Center for Cardiovascular Diseases, Fuwai Hospital, Chinese Academy of Medical Sciences, Beijing, China

Li Wei,
Medical Research & Biometrics Center, National Center for Cardiovascular Diseases, Fuwai Hospital, Chinese Academy of Medical Sciences, Beijing, China

Lap Ah Tse,
Jockey Club School of Public health and Primary Care, the Chinese University of Hong Kong, Hong Kong Special Administrative Region, China

Deepa Mohan,
Madras Diabetes Research Foundation, Chennai, India

Parthiban Kumar,
Madras Diabetes Research Foundation, Chennai, India

Rajeev Gupta,
Eternal Heart Care Centre & Research Institute, Jaipur, India

Indu Mohan,
Mahatma Gandhi Medical College, Jaipur, India

K G Jayachitra,
St John's Medical College & Research Institute, Bangalore, India

Prem K Mony,
St John's Medical College & Research Institute, Bangalore, India

Kamala Rammohan,
Health Action By People, Thiruvananthapuram and Medical College, Trivandrum, India

Sanjeev Nair,
Health Action By People, Thiruvananthapuram and Medical College, Trivandrum, India

P V M Lakshmi,
Post Graduate Institute of Medical Education and Research, Chandigarh, India

Vivek Sagar,
Post Graduate Institute of Medical Education and Research, Chandigarh, India

Rehman Khawaja,
Department of Community Health Science, Aga Khan University Hospital, Karachi, Pakistan

Romaina Iqbal,
Department of Community Health Science, Aga Khan University Hospital, Karachi, Pakistan

Khawar Kazmi,
Department of Community Health Science, Aga Khan University Hospital, Karachi, Pakistan

Salim Yusuf,
Population Health Research Institute, Hamilton Health Sciences, McMaster University, Hamilton, ON, Canada

Michael Brauer
School of Population and Public Health, University of British Columbia, Vancouver, BC, Canada

PURE-AIR study*

Summary

Background—Approximately 2·8 billion people are exposed to household air pollution from cooking with polluting fuels. Few monitoring studies have systematically measured health-damaging air pollutant (ie, fine particulate matter [$PM_{2·5}$] and black carbon) concentrations from a wide range of cooking fuels across diverse populations. This multinational study aimed to assess the magnitude of kitchen concentrations and personal exposures to $PM_{2·5}$ and black carbon in rural communities with a wide range of cooking environments.

Methods—As part of the Prospective Urban and Rural Epidemiological (PURE) cohort, the PURE-AIR study was done in 120 rural communities in eight countries (Bangladesh, Chile, China, Colombia, India, Pakistan, Tanzania, and Zimbabwe). Data were collected from 2541 households and from 998 individuals (442 men and 556 women). Gravimetric (or filter-based) 48 h kitchen and personal $PM_{2·5}$ measurements were collected. Light absorbance ($10^{-5}m^{-1}$) of the $PM_{2·5}$ filters, a proxy for black carbon concentrations, was calculated via an image-based reflectance method. Surveys of household characteristics and cooking patterns were collected before and after the 48 h monitoring period.

Findings—Monitoring of household air pollution for the PURE-AIR study was done from June, 2017, to September, 2019. A mean $PM_{2·5}$ kitchen concentration gradient emerged across primary cooking fuels: gas (45 μg/m^3 [95% CI 43–48]), electricity (53 μg/m^3 [47–60]), coal (68 μg/m^3 [61–77]), charcoal (92 μg/m^3 [58–146]), agricultural or crop waste (106 μg/m^3 [91–125]), wood (109 μg/m^3 [102–118]), animal dung (224 μg/m^3 [197–254]), and shrubs or grass (276 μg/m^3 [223–342]). Among households cooking primarily with wood, average $PM_{2·5}$ concentrations varied ten-fold (range: 40–380 μg/m^3). Fuel stacking was prevalent (981 [39%] of 2541 households); using wood as a primary cooking fuel with clean secondary cooking fuels (eg, gas) was associated with 50% lower $PM_{2·5}$ and black carbon concentrations than using only wood as a primary cooking fuel. Similar average $PM_{2·5}$ personal exposures between women (67 μg/m^3 [95% CI 62–72]) and men (62 [58–67]) were observed. Nearly equivalent average personal exposure to kitchen exposure ratios were observed for $PM_{2·5}$ (0·79 [95% 0·71–0·88] for men and 0·82 [0·74–0·91] for women) and black carbon (0·64 [0·45–0·92] for men and 0·68 [0·46–1·02] for women).

Interpretation—Using clean primary fuels substantially lowers kitchen $PM_{2·5}$ concentrations. Importantly, average kitchen and personal $PM_{2·5}$ measurements for all primary fuel types exceeded WHO's Interim Target-1 (35 μg/m^3 annual average), highlighting the need for comprehensive pollution mitigation strategies.

Introduction

Approximately 2·8 billion people used polluting fuels (eg, solid fuels such as wood and coal, and kerosene) for cooking or heating, or both, in 2018 and were exposed to health-damaging levels of household air pollution.[1] Exposure to elevated concentrations of fine particulate matter ($PM_{2·5}$) is associated with a range of adverse health effects.[2-6] The Global Burden of

Diseases, Injuries, and Risk Factors Study (GBD) 2018 estimated that 1·6 million deaths were attributable to $PM_{2·5}$ exposure from household air pollution in 2017.[7] Additionally, household air pollution contributes to outdoor air pollution[8] and black carbon, the second largest contributor to global warming.[9]

Few large-scale, systematic household air pollution measurement studies have included household concentrations and personal exposures of $PM_{2·5}$ and black carbon. A pooled model of 2208 measurements from 44 studies in 13 countries from 1996 to 2017[10] showed low precision in 24 h mean household $PM_{2·5}$ concentrations across primary fuel types: gas or electric (100 μg/m^3 [95% CI 40–270]), coal (320 μg/m^3 [120–840]), traditional wood (400 μg/m^3 [150–1040]), and animal dung (960 μg/m^3 [360–2500]).[11] Studies included in the model were typically done in few households (2–470 households; median 17) with diverse measurement methods.[10] For logistical and financial reasons, most household air pollution studies have only collected kitchen concentrations; studies that collected personal measurements have typically monitored female exposures (ie, the main household cook) only.[11] As the magnitudes of $PM_{2·5}$ and black carbon exposures remain imprecise, substantial uncertainties remain in our epidemiological understanding of household air pollution.[8] Large-scale household air pollution measurements in previously unmonitored communities will enable refined characterisation of exposure levels, which can improve future assessments of the effectiveness of household air pollution interventions (eg, the Household Air Pollution Intervention Tool [HAPIT][12]) in improving health outcomes, estimates of disease burden due to household air pollution, and polices to reduce household air pollution exposures.

A multinational household air pollution monitoring study was implemented in 120 rural communities in eight countries from the pre-existing Prospective Urban and Rural Epidemiological (PURE) study. Household air pollution monitoring included integrated 48 h measurements of $PM_{2·5}$ and black carbon alongside survey data on household and cooking characteristics that might influence household air pollution exposures, to provide important information on household and personal $PM_{2·5}$ and black carbon exposures, including variations across diverse populations, and a range of cooking environment factors (eg, primary and secondary fuels used, and stove type).

Methods

Study design

The PURE-AIR study is nested within the larger PURE cohort, which includes around 200 000 participants from 26 high-income, middle-income, and low-income countries.[13] In each country, participants were recruited from rural and urban communities clustered around urban centres (referred to as subnational regions) with access to laboratory equipment for processing of biological samples (for a list of subnational regions see the appendix p 9). Rural communities represent villages more than 50 km away from urban centres or without easy access to commuter transportation at baseline, but within a 45 min drive of a laboratory.[13] Door-to-door convenience sampling was done in all PURE communities. Within communities, recruited participants were representative of the age and sex distribution of adults aged 35–70 years. Evaluation studies have shown age, sex, education, and mortality distributions of PURE participants to generally represent national statistics.[14]

The PURE-AIR study was done in 120 rural communities in eight low-income and middle-income PURE countries (Bangladesh [16 communities], Chile [three], China [38], Colombia [18], India [32], Pakistan [six], Tanzania [five], and Zimbabwe [two]) where more than 10% of households used polluting fuels (wood, animal dung, agricultural waste, coal, charcoal, shrubs or grass, and kerosene) at baseline; these classifications were based on World Bank data during PURE study commencement (2003).[15] As a high amount of primary cooking fuel switching occurred between baseline assessment (which varied between countries; appendix p 2) and PURE-AIR monitoring,[16] communities were strategically selected for household air pollution monitoring to ensure a sufficient distribution of polluting fuel types among household samples. Although study recruitment included a higher proportion of households using clean primary fuels compared with baseline (appendix p 3), stratified sampling by community-level baseline primary cooking fuel use statistics (eg, 60% wood, 40% liquefied petroleum gas, hereafter referred to as gas) was maintained to ensure variations in polluting cooking fuel types.

Monitoring methods

Monitoring occurred from June, 2017, to September, 2019, by use of a standard protocol, as described elsewhere.[15] Briefly, $PM_{2·5}$ filter samples were collected with the ultrasonic personal Aerosol Sampler (UPAS; Access Sensor Technologies, Fort Collins, CO, USA) operated at a flow rate of 1·0 L/min and 50% duty cycle. The UPAS device was placed on a stand, approximately 1 m high and 1 m from the primary cookstove for 48 h kitchen monitoring. The 48 h sampling period was selected to capture potential day-to-day variation in household air pollution concentrations, while minimising monitoring costs and participant burden. In two regions of India and China, two 48 h kitchen samples were collected simultaneously in 26 households to evaluate variability in UPAS measurements. Previous laboratory evaluations and pilot studies[15,17,18] have shown high correlation ($r \geq 0·9$) between the UPAS and well established filter-based monitors. All filters (including 269 blank filters —approximately 10% of household samples) were weighed before and after the sampling period for $PM_{2·5}$ mass (method detection limit: 8·7 μg/m^3; analytical limit of detection 1·2 μg/m^3) with the same fully automated robotic balance system (Measurement Technology Laboratories, Bloomington, MN, USA) maintained in a temperature-controlled and humidity-controlled laboratory in Vancouver, BC, Canada (see appendix p 15 for details). Field blank filters were stored in research offices within the respective communities for the sampling duration, then packaged with sampled filters and shipped back to Canada for analysis. The absorption coefficient (light absorbance; $10^{-5}m^{-1}$) of the $PM_{2·5}$ filters weighed after sampling (method detection limit 0·47 $10^{-5}m^{-1}$), used as a proxy for black carbon concentrations,[19] was calculated via a low-cost and evaluated image-based reflectance method.[20] The image-based reflectance method was highly correlated (r^2=0·99) with elemental carbon concentrations on sampled filters (1 absorbance unit [$1\times10^{-5}m^{-1}$] is equivalent to 1·67 μg/m^3 elemental carbon).[20]

In a subset of households (696 [27%] of 2541), 48 h personal sampling was done (simultaneously with kitchen monitoring), with the UPAS worn in an armband (787 [79%] of 998 samples) or harness (211 [21%] of 998 samples) at participants' discretion. GPS data collected from the UPAS were used to evaluate the proportion of time participants spent away (>25 m radius) from their households during personal monitoring. Convenience sampling was used to select participants for personal monitoring; men and women from households selected for kitchen monitoring were sampled until the target sample size was achieved for each sex in the community (priority was given to paired male–female measurements from the same households). Before monitoring, a PURE-AIR survey was completed that contained the same cooking environment questions as a baseline PURE household survey, with additional questions on secondary fuel and stove type. After the 48 h monitoring period, another survey was completed on cooking and heating practices specific to the sampling period.[15] Log files of flow volume and run-time were transferred to a central project server and an R program code automatically scanned files every 24 h to detect potential errors (eg, flow rate <0·5 L/min, sample time <43 h). Erroneous files were brought to the attention of the field team for 48 h remonitoring of households or individuals, or both.

Statistical analysis

This descriptive analysis was focused on characterising multinational variations in concentrations and exposures by primary and secondary cooking fuel type. Household heating was also examined in six PURE-AIR subnational regions where heating fuel type varied among households using the same primary cooking fuel type. Seasonality, dichotomised as summer (April to September) or winter (October to March), and reversed for the southern hemisphere (ie, Chile, Tanzania, and Zimbabwe), was examined in subnational regions where more than 85% of samples were done in a single season, and via repeat measurements done approximately 6 months apart in 24 households in China (Beijing and Liaoning) and India (Chennai and Jaipur).

Descriptive statistics of measurements by primary cooking fuels used during monitoring are presented by key household characteristics (kitchen type, heating fuel, and fuel stacking), individual behaviours (cooking time, smoking status, and occupational exposure), and country or subnational region. All black carbon and $PM_{2 \cdot 5}$ measurements were log-transformed when generating summary statistics; geometric means (hereafter referred to as means) and 95% CIs were reported (significance was assessed via non-overlapping confidence intervals). Linear regression was used to characterise the relationship between $PM_{2 \cdot 5}$ and black carbon measurements for potential utility in estimating black carbon absorbance based on $PM_{2 \cdot 5}$ concentrations; Spearman's correlation coefficients (r) are reported. Male-to-female and personal-to-kitchen $PM_{2 \cdot 5}$ and black carbon ratios are presented for 227 households with paired male–female samples (n=454) to better compare sex-specific exposures. All analyses were done in R, version 3.4.4.

Role of the funding source

The funders of the study had no role in study design, data collection, data analysis, data interpretation, or writing of the report. The corresponding author had full access to the study datasets and was responsible for the decision to submit for publication.

Results

Valid 48 h kitchen measurements were collected in more than 80% of attempts, leading to a final sample of 2541 households. GPS data obtained from the UPAS revealed that 45 (5%) of 998 participants did not travel for more than a 25 m radius away from their household during 48 h sampling (appendix p 34), suggesting potentially high compliance. Re-sampling occurred in 115 (5%) of 2541 households. Common monitoring issues were a depleted battery due to insufficient charging (154 [50%] of 308 errors), SD card tampering (68 [22%] of 308 errors), highly loaded filters (34 [11%] of 308 errors), and operating in extremely hot environments (nine [3%] of 308 errors). Duplicate 48 h kitchen samples from 25 households in India (n=11), China (n=9), and Pakistan (n=5) showed high agreement (r=0·8; p<0·0001; appendix p 24), with a median $PM_{2·5}$ concentration difference of 8·5 μg/m^3 (percentage difference 12·5%).

Polluting primary cooking fuels were used by 1436 (57%) households. Wood was the most prevalent primary cooking fuel in African, south Asian, and South American countries (figure 1). Open fires were most commonly used in Pakistan, Tanzania, Zimbabwe, and Colombia; mud stoves were most frequently used in India and Bangladesh; and manufactured chimney stoves were most prevalent in China and Chile. Fuel stacking (use of multiple fuels to meet cooking needs) occurred in 981 (39%) PURE-AIR households; the prevalence of stacking varied greatly, ranging from 1% (one of 132 households) in Karachi, Pakistan, to 88% (111 of 126 households) in Jiangsu, China (appendix p 5). Overall, 98% of households stacking fuels were in China, India, Colombia, and Chile; in India, the prevalence of stove stacking among PURE-AIR communities during 48 h monitoring (444 [55%] of 811 households) was around 20% higher than that of China (465 [37%] of 1244), Colombia (30 [39%] of 77), and Chile (27 [36%] of 75). 207 (24%) of869 households using gas as a primary fuel cooked with a polluting secondary fuel during the 48 h monitoring period. Participants using animal dung or shrubs or grass as primary fuels more frequently cooked outdoors, whereas participants using other primary fuels more commonly cooked indoors (table 1).

Self-reported average cooking time (primary fuel only) was approximately 2·3 h per day (table 1). Average daily cooking time was 0·7–1·1 h shorter among gas users (2·0 h per day) and electric stove users (1·6 h per day) than among wood stove users (2·7 h per day). Participants using animal dung cooked the longest, on average (4·8 h per day). 644 (25%) of 2541 households were heated with polluting fuels in open fires (299 [12%]), mud stoves (263 [10%]), or chimney stoves (82 [3%]) during the 48 h monitoring period.

998 personal samples (556 from female participants and 442 from male participants) were collected concurrently with kitchen monitoring. The average participant age was 60 years (range 38–84). On average, women spent almost three times as many hours per day in the kitchen as men (1·9 h versus 0·7 h; appendix p 12). 262 (47%) of 556 female participants reported their occupation as homemaker, compared with 44 (10%) male participants, and approximately a third of male participants (n=138) and female participants (n=139) self-reported exposure to “specific air pollution sources (eg, fires, industrial processes, traffic) at work” during the monitoring period (appendix p 12); we considered these participants as

having occupational air pollution exposures. 172 (39%) male participants smoked tobacco products during monitoring. Although only 13 (2%) female participants smoked, 195 (35%) reported exposure to second-hand smoke during the 48 h monitoring period.

Average 48 h household $PM_{2·5}$ kitchen concentrations in households using wood as a primary cooking fuel (109 μg/m^3 [95% CI 102–118]) were twice as high as concentrations from households using gas (45 μg/m^3 [43–48]) or electric (53 μg/m^3 [47–60]) cooking fuels (figure 2). Average $PM_{2·5}$ concentrations from the most polluting fuels were higher than those from gas and electric fuels (animal dung, four times higher: 224 μg/m^3 [95% CI 197–254]; shrubs or grass, five times higher: 276 μg/m^3 [223–342]). Longer self-reported average daily cooking times were associated with increasing average $PM_{2·5}$ kitchen concentrations in a dose-response manner among all polluting fuel types (table 2). 1915 (75%) of 2541 kitchen $PM_{2·5}$ measurements, including 694 (63%) of 1105 measurements within households using clean fuels, were above the WHO Interim Target-1 (35 μg/m^3 annual average).

Average $PM_{2·5}$ kitchen concentrations remained substantially higher in households cooking with wood than in those using gas when stratifying by season (summer or winter) in PURE-AIR subnational regions where sampling spanned both seasons (appendix p 21). Seasonal differences in $PM_{2·5}$ concentrations in some PURE-AIR subnational regions were likely to be partly due to household heating; heating via polluting fuels in mud stoves or open fires substantially increased average 48 h $PM_{2·5}$ kitchen concentrations in the winter compared with summer among households primarily cooking with gas in Chennai, India (53 μg/m^3 [95% CI 47–59] *vs* 32 μg/m^3 [26–38]) and Liaoning, China (152 μg/m^3 [70–330] *vs* 39 μg/m^3 [29–52]; appendix p 21).

Black carbon and $PM_{2·5}$ kitchen concentrations were highly correlated (r=0·88; p<0·0001); an increasing black carbon kitchen level gradient among polluting primary fuel types was also observed (figure 2). The average absorbance among households using clean primary fuels was less than half that of households using biomass primary fuel types (except for charcoal). However, minimal differences in black carbon concentrations existed between households using gas or electricity and coal or charcoal as primary fuels, despite a nearly two-fold variation in $PM_{2·5}$ concentrations.

There was considerable between-country variation in household $PM_{2·5}$ concentrations (intra-class correlation $[ICC]_{country}$=0·61) and black carbon absorbance ($ICC_{country}$=0·59) within the same primary cooking fuel type (appendix p 31). For example, among households cooking with wood, average $PM_{2·5}$ concentrations from chimney stoves in China (50 μg/m^3 [95% CI 45–55]) were half as high as those from mud stoves used in India (105 μg/m^3 [96–116]). Average $PM_{2·5}$ concentrations in households cooking with wood open fires in Bangladesh and Pakistan (383 μg/m^3 [95% CI 339–435]) and African countries (318 μg/m^3 [266–381]) were approximately three to four times higher than in households using mud stoves in India. Average $PM_{2·5}$ concentrations in households using gas fuels in South America (20 μg/m^3 [95% CI 17–23]) were half as high as in households using gas fuels in China (46 μg/m^3 [43–49]) and India (50 μg/m^3 [46–54]; table 2). Similarly, average black carbon kitchen concentrations in households cooking with wood in South America

($2·1×10^{-5}m^{-1}$ [95% CI 1·7–2·6]) and China ($3·1×10^{-5}m^{-1}$ [2·8–3·5]) were 33–50% lower than in households using wood in India ($6·6×10^{-5}m^{-1}$ [5·9–7·4]). Average black carbon concentrations in households cooking with wood in Africa ($13·3×10^{-5}m^{-1}$ [95% CI 11·1–15·8]) and in Pakistan and Bangladesh ($25·0×10^{-5}m^{-1}$ [21·6–28·8]) were two to four times higher than in households cooking with wood in India (appendix p 25). Thus, among households primarily cooking with wood, a ten-fold variation existed between countries in average 48 h measurements of $PM_{2·5}$ (95% CI 40–380 μg/m^3; table 2) and black carbon ($2·1–25·0×10^{-5}m^{-1}$; appendix p 25). A similar country-level pattern in average kitchen absorbance levels existed among households using gas fuels; black carbon levels in China ($2·1×10^{-5}m^{-1}$ [95% CI 2·0–2·3]) and India ($2·7×10^{-5}m^{-1}$ [2·5–3·0]) were twice as high as in South American countries ($1·1×10^{-5}m^{-1}$ [0·9–1·3]).

Among households using wood as a primary cooking fuel, use of gas as a secondary cooking fuel resulted in nearly 50% lower average $PM_{2·5}$ concentrations (78 μg/m^3 [95% CI 70–87]; table 2) and 50% lower average black carbon kitchen concentrations ($4·3×10^{-5}m^{-1}$ [95% CI 3·8–4·9]; appendix p 25) than use of only wood for cooking (146 μg/m^3 [132–162] and $8·3×10^{-5}m^{-1}$ [7·5–9·3]). Using animal dung as a secondary fuel with gas as a primary fuel was associated with approximately three times higher average $PM_{2·5}$ concentrations (142 μg/m^3 [95% CI 96–211]) and black carbon concentrations ($6·5×10^{-5}m^{-1}$ [95% CI 4·5–9·3]) than using only gas for cooking (44 μg/m^3 [42–48] and $2·1×10^{-5}m^{-1}$ [1·9–2·3]; table 2; appendix p 25).

No significant difference was observed between average 48 h personal $PM_{2·5}$ exposures between female (67 μg/m^3 [95% CI 62–72]) and male (62 μg/m^3 [58–67]) participants. This finding held at a country level, except among PURE communities in Bangladesh and Pakistan, where female $PM_{2·5}$ and black carbon exposures were significantly higher than male exposures (table 3; appendix p 26). In PURE communities within China and South American countries, average female $PM_{2·5}$ exposures were 2–8 μg/m^3 lower than male exposures (table 3).

Female participants cooking with gas as a primary fuel had 30 μg/m^3 lower average $PM_{2·5}$ exposures than female participants using wood as a primary fuel (48 μg/m^3 [95% CI 43–54] *vs* 78 μg/m^3 [68–89]; figure 3). Although average black carbon exposures were generally lower among participants using clean fuels than among those using polluting fuels, male participants living in households cooking with wood as a primary fuel had slightly lower average black carbon exposures than did those living in households primarily using electric stoves (figure 3).

Behavioural factors substantially affected personal exposure measurements. Average 48 h $PM_{2·5}$ concentrations of both men and women were approximately 20 μg/m^3 higher among those exposed to air pollution sources during work than in those reporting no occupational exposure (table 3). Average male and female black carbon exposure concentrations did not differ significantly between those reporting exposure and those reporting no exposure to occupational air pollution sources (appendix p 26). Younger participants (aged 43–60 years) had higher $PM_{2·5}$ and black carbon exposures than older participants (aged 61–84 years). Male participants smoking tobacco products during the 48 h monitoring period had marginally higher (12 μg/m^3) average $PM_{2·5}$ exposures than male participants who did not smoke. Male and female participants who reported exposure to second-hand smoke (regardless of smoking status) had substantially higher (approximately 20 μg/m^3) average $PM_{2·5}$ and black carbon exposures than male and female participants who did not have exposure to second-hand smoke.

Mean male-to-kitchen and female-to-kitchen ratios from 227 households with paired male–female samples (n=454) were nearly equivalent for $PM_{2·5}$ (0·79 [95% CI 0·71–0·88]) and 0·82 [0·74–0·91]) and black carbon (0·64 [0·45–0·92] and 0·68 [0·46–1·02]; appendix p 19). Female-to-kitchen and male-to-kitchen $PM_{2·5}$ and black carbon exposure ratios were near or above 1 for most primary fuels (except for wood and shrubs or grass; range 0·4–0·7). The median male-to-female exposure ratio was 1·0 for both $PM_{2·5}$ and black carbon (range 0·9–1·1) across all primary fuel types. However, at a country level, male-to-female $PM_{2·5}$ ratios were greater than male-to- female ratios for black carbon in Chile, Colombia, and Pakistan; the reverse was true in China and India (appendix p 19).

Personal exposures were moderately correlated with kitchen $PM_{2·5}$ concentrations (r=0·69; p<0·0001) and black carbon absorbance (r=0·63; p<0·0001; appendix p 30). When stratifying by sex, the correlation between female exposures and kitchen concentrations was higher than that of male exposures for both $PM_{2·5}$ (r=0·71 [p<0·0001] *vs* r=0·65 [p<0·0001]) and black carbon (r=0·67 [p<0·0001] *vs* r=0·57 [p<0·0001]). The correlation between average black carbon and $PM_{2·5}$ kitchen concentrations and personal exposures was modified by kitchen type in a monotonically decreasing manner (eg, among $PM_{2·5}$ kitchen concentrations and female exposures: r=0·80 [p<0·0001] in single-room indoor kitchens, r=0·66 [p<0·0001] in multi-room indoor kitchens and r=0·46 [p<0·0001] in outdoor kitchens; appendix p 23). A sensitivity analysis examining $PM_{2·5}$ exposures by UPAS wearing location (armband or harness) revealed no significant differences in exposures (appendix p 14).

Discussion

The PURE-AIR study included $PM_{2·5}$ and black carbon measurements related to household air pollution for 2541 households and 998 individuals in 120 diverse, rural communities within eight countries. Clear gradients in $PM_{2·5}$ and black carbon kitchen concentrations were observed across primary cooking fuels; households using clean primary fuels had approximately two to five times lower average $PM_{2·5}$ and black carbon kitchen concentrations than households using polluting primary fuels. Fuel stacking occurred in 981 (39%) households, and using clean secondary fuels was associated with 50% lower $PM_{2·5}$ and black carbon concentrations. The use of clean primary cooking fuels also resulted in lower personal $PM_{2·5}$ and black carbon exposures than the use of polluting fuels. Participants using gas as a primary fuel cooked for an average of 0·7 h per day less than participants using wood, suggesting that gas stoves can offer cumulative time savings.[23,24]

Stove characteristics and secondary fuel type affected measured $PM_{2·5}$ and black carbon concentrations; among countries using different wood stoves (eg, chimney stoves in China, mud stoves in India, and open fires in Bangladesh, Pakistan, and African countries), there was a ten-fold variation in average $PM_{2·5}$ kitchen concentrations (approximately 40–380 μg/m^3; table 3) and black carbon absorbance ($2·1–25·0×10^{-5}m^{-1}$; appendix p 25). This analysis showed that using polluting secondary cooking fuels (eg, animal dung) in conjunction with gas as a primary fuel could potentially increase average 48 h $PM_{2·5}$ and black carbon kitchen levels by 300%, from 44 μg/m^3 to 142 μg/m^3 (table 3) and from $2·1×10^{-5}m^{-1}$ to $6·5×10^{-5}m^{-1}$ (appendix p 25). Conversely, using a clean secondary fuel with a primary wood stove could decrease $PM_{2·5}$ and black carbon kitchen concentrations by 50%. Accounting for fuel stacking and stove type in addition to primary cooking fuel type in household air pollution risk assessments is therefore important for reducing potential $PM_{2·5}$ exposure misclassification.[25]

Despite female participants spending an average of 1·2 h per day longer in the kitchen than male participants (appendix p 12), median $PM_{2·5}$ and black carbon personal-to-kitchen exposure ratios were identical for male and female participants (0·89 *vs* 0·86). The $PM_{2·5}$ ratio in the PURE-AIR study is higher than previous median $PM_{2·5}$ personal to kitchen ratios (0·74 for women *vs* 0·45 for men)[8,26] used in GBD 2017.[7] Higher median $PM_{2·5}$ and black carbon personal-to-kitchen ratios in the PURE-AIR study were driven by PURE communities in four countries (China, India, Chile, and Columbia) where personal-to-kitchen ratios were generally higher than 0·9 (appendix p 19). In the four other countries (Bangladesh, Pakistan, Tanzania, and Zimbabwe), median $PM_{2·5}$ and black carbon personal-to-kitchen ratios in PURE communities were lower than 0·5.

Greater homogeneity among black carbon and $PM_{2·5}$ exposures between sexes among PURE communities in some countries is probably not attributable to increased smoking rates among male participants, as minimal differences existed in average $PM_{2·5}$ concentrations among male and female non-smokers in households using gas as a primary fuel. Minor differences in average $PM_{2·5}$ exposures by sex deviate from findings of previous household air pollution studies; in GBD 2017 and the HAPIT,[7,12] a male-to-female exposure ratio of 0·6 is the default,[8] whereas the median $PM_{2·5}$ male-to-female exposure ratio in PURE-AIR was 1·0. $PM_{2·5}$ and black carbon concentrations for one sex could serve as a viable household air pollution exposure proxy for the other in some settings. The health burden related to household air pollution in men might also be underestimated when assuming average male $PM_{2·5}$ and black carbon exposures are consistently lower than female exposures across all low-income and middle-income countries. From the perspective of $PM_{2·5}$ and black carbon exposures, these findings can have substantial global health implications by extending the framing of household air pollution beyond an issue primarily affecting women who are usually the primary household cook.

Across all polluting primary fuels, slightly higher $PM_{2·5}$ personal-to-kitchen exposure ratios compared to black carbon exposure ratios (appendix p 19) suggest that sources other than biomass combustion probably contributed to $PM_{2·5}$ exposures. The potential contribution of ambient pollution to $PM_{2·5}$ exposures is further demonstrated by an increase of approximately 20 μg/m^3 in average $PM_{2·5}$ exposures among male and female participants reporting exposure to air pollution sources during work compared to participants who did not (table 3), with minimal differences in black carbon concentrations between the two groups (appendix p 26).

The relationship between $PM_{2·5}$ and black carbon kitchen concentrations varied between countries. PURE-AIR communities in which polluting fuel combustion probably had the largest contribution to overall concentrations (kitchens with the highest black carbon fraction of $PM_{2·5}$) included those in northern India, Pakistan, and Bangladesh (appendix p 28). Outdoor kitchens had a higher black carbon fraction of $PM_{2·5}$ than indoor kitchens in Tanzania and two regions in India (appendix p 29), and the average kitchen absorbance levels from gas fuels in China ($2·1\times10^{-5}m^{-1}$ [95% CI 2·0–2·3]) and India ($2·7\times10^{-5}m^{-1}$ [2·5–3·0]) were twice as high as those from gas fuels in South American countries ($1·1\times10^{-5}m^{-1}$ [0·9–1·3]; appendix p 25), possibly due to ambient sources of black carbon such as agricultural field burning. Furthermore, black carbon female-to-kitchen ratios among those using electric or gas stoves were higher than $PM_{2·5}$ female-to-kitchen ratios in China, implying that ambient black carbon sources affected exposures. China accounts for the highest crop straw production globally,[27] and around 25% of crop residue in India was burned in agricultural fields in 2017.[28] Average male black carbon exposures from households in which coal and wood were the primary cooking fuels were lower than average male black carbon exposures from households where electric stoves were primarily used, which do not emit black carbon (appendix p 26), indicating male exposure to other black carbon sources, especially in India and China.

Average $PM_{2·5}$ concentrations and exposures were above the WHO Interim Target-1 (35 $\mu g/m^3$ annual average) across all primary fuel types, including clean fuels. Kitchen concentrations from gas and electric stoves were two to four times higher in some western Chinese provinces (Liaoning and Shaanxi) than in eastern Chinese provinces (Jiangsu; appendix p 8), suggesting high ambient air pollution levels in China. Ambient air pollution might be partly driven by community-level use of polluting fuels[29] as biomass stove emissions can disperse and infiltrate neighbouring homes.[30] Therefore, meeting WHO Air Quality Guidelines will require community-level transition to clean cooking fuels, and potentially emission reductions from other ambient pollution sources.[31]

The measured $PM_{2·5}$ concentrations associated with each primary fuel type were considerably lower than estimates from a global $PM_{2·5}$ modelling study based on the WHO global household air pollution database, where modelled concentrations were as follows: 104 $\mu g/m^3$ (95% CI 39–273) for gas and electricity, 319 $\mu g/m^3$ (119–838) for coal, and 958 $\mu g/m^3$ (359–2520) for animal dung.[11] Substantially lower PURE-AIR measurements might result from inclusion of studies done before 2000 in the WHO global household air pollution database, when household air pollution levels were likely to be higher in many low-income and middle-income countries, and also the demography of PURE households, which generally had a less than 1 h commute to research laboratories and might represent less rural communities with higher socioeconomic levels than communities sampled in previous household air pollution studies. As PURE-AIR included communities originally recruited for a study not focused on household air pollution, the findings might be more representative of rural exposures than studies focused on household air pollution that generally selectively recruit from communities with a high prevalence of household air pollution. These recent measurements might also represent broader trends in lower exposures due to increasing use of cleaner cooking fuels[16] or reductions in family size, or both.

The PURE-AIR study leveraged the research capacity of the multinational PURE study, remote field-staff training, easy to use air samplers, real-time quality control measures, and a rapid, low-cost image-based reflectance method (proxy for black carbon concentrations) to enable scale up of $PM_{2·5}$ and black carbon absorbance measurements to 120 communities in eight countries in a 2-year period. All PURE-AIR monitoring followed a harmonised protocol, minimising potential biases associated with pooling measurements across studies with different designs, measurement periods, monitoring equipment, and analytical methods. Although laboratory testing indicated a small coefficient of variation (5%) among duplicate UPAS measurements,[18] a non-negligible difference in kitchen concentrations (8·5 $\mu g/m^3$) among collocated UPAS monitors warrants further field testing, although this was possibly due to low sample sizes and poorly mixed kitchen environments. Wearing compliance of the UPAS during 48 h personal sampling was not included in this analysis (and is not commonly reported in the literature). GPS recorded by the UPAS revealed that 45 (5%) participants did not spend time away from their household during 48 h sampling (appendix p 34), which potentially signals high compliance with personal monitoring.

The PURE-AIR study was restricted to rural PURE communities with more than 10% polluting fuel use at baseline; the communities are not nationally representative of rural populations in each country. Given the pace of urbanisation during the 10–15-year follow-up period, some communities defined as rural according to baseline criteria might now be considered peri-urban.[16] As we were not able to collect information on participant refusals, personal measurements might not be representative of PURE-AIR participants within each community.

Although 48 h monitoring is less sensitive to individual cooking events than a 24 h monitoring period, it might not represent longer-term exposures. Although repeat seasonal measurements were not done in all PURE-AIR communities because of logistical constraints, repeat seasonal measurements in 26 households in India and China, as well as a sensitivity analysis within eight PURE-AIR subnational regions (appendix p 21), revealed increases in kitchen concentrations in winter months compared to summer months in several countries (India, China, and Chile) with gas and wood as primary cooking fuels. As such, PURE-AIR measurements might not reflect annual average levels in some locations, but do provide multinational data on the range of concentrations by cooking fuel types.

PURE-AIR surveys did not include questions about polluting fuels used for lighting (eg, kerosene), which might have an important role in household air pollution, especially black carbon. Analysis of household heating was restricted as most households in each community did not heat their homes or used similar heating methods during the sampling period. However, among households in one subnational region in India and China, cooking with gas but using wood for heating (cooking in mud stoves in India and open fires in China), a significant increase in average kitchen concentrations relative to households with no heating was detected. Because of logistical constraints, outdoor air pollution concentrations were not monitored.

In conclusion, the PURE-AIR study illustrates potential global health and climate co-benefits of using clean cooking fuels, through reduced $PM_{2·5}$ and black carbon concentrations. Although using clean primary fuels substantially lowered $PM_{2 \cdot 5}$ kitchen concentrations, 75% of all kitchen measurements, including 63% among households using clean fuels, were above the WHO Interim Target-1, suggesting that mitigation of ambient air pollution sources is needed to maximise the benefits to health and the climate. PURE-AIR measurements can be informative to global health stakeholders interested in characterising the health and climate impacts of household air pollution in future risk assessments.

Supplementary Material

Refer to Web version on PubMed Central for supplementary material.

Acknowledgments

We acknowledge the field teams in all PURE-AIR countries who did the household air pollution monitoring and administered the surveys. Without their extensive efforts, this study would not be possible. We thank Ann Dion and Quinn Stewart for overseeing filter weighing and management. The PURE-AIR study is funded by the Canadian Institutes of Health Research (grant #136893) and by the Office of The Director, National Institutes of Health (NIH; Award Number DP5OD019850). The content is solely the responsibility of the authors and does not necessarily represent the official views of the Canadian Institutes of Health Research or the NIH. The PURE study is an investigator-initiated study that is funded by the Population Health Research Institute, the Canadian Institutes of Health Research, Heart and Stroke Foundation of Ontario, support from Canadian Institutes of Health Research's Strategy for Patient Oriented Research (SPOR), through the Ontario SPOR Support Unit, as well as the Ontario Ministry of Health and Long-Term Care and through unrestricted grants from several pharmaceutical companies (with major contributions from AstraZeneca [Canada], Sanofi-Aventis [France and Canada], Boehringer Ingelheim [Germany and Canada], Servier, and GlaxoSmithKline), and additional contributions from Novartis and King Pharma and from various national or local organisations in participating countries. Further details about the funding and participating countries and institutions, and on collaborating staff, are shown at the end of the appendix.

Funding Canadian Institutes for Health Research, National Institutes of Health.

References

1. International Bank for Reconstruction and Development, World Bank Group. Tracking SDG7: the energy progress report 2018. 6 25, 2018 https://www.seforall.org/publications/tracking-sdg7 (accessed Aug 17, 2020).
2. Amegah AK, Quansah R, Jaakkola JJK. Household air pollution from solid fuel use and risk of adverse pregnancy outcomes: a systematic review and meta-analysis of the empirical evidence. PLoS One 2014; 9: e113920. [PubMed: 25463771]
3. Dherani M, Pope D, Mascarenhas M, Smith KR, Weber M, Bruce N. Indoor air pollution from unprocessed solid fuel use and pneumonia risk in children aged under five years: a systematic review and meta-analysis. Bull World Health Organ 2008; 86: 390–98C. [PubMed: 18545742]
4. Kurmi OP, Arya PH, Lam K-BH, Sorahan T, Ayres JG. Lung cancer risk and solid fuel smoke exposure: a systematic review and meta-analysis. Eur Respir J 2012; 40: 1228–37 [PubMed: 22653775]
5. Kurmi OP, Semple S, Simkhada P, Smith WCS, Ayres JG. COPD and chronic bronchitis risk of indoor air pollution from solid fuel: a systematic review and meta-analysis. Thorax 2010; 65: 221–28. [PubMed: 20335290]
6. Onakomaiya D, Gyamfi J, Iwelunmor J, et al. Implementation of clean cookstove interventions and its effects on blood pressure in low-income and middle-income countries: systematic review. BMJ Open 2019; 9: e026517.
7. Stanaway JD, Afshin A, Gakidou E, et al. Global, regional, and national comparative risk assessment of 84 behavioural, environmental and occupational, and metabolic risks or clusters of risks for 195 countries and territories, 1990–2017: a systematic analysis for the Global Burden of Disease Study 2017. Lancet 2018; 392: 1923–94. [PubMed: 30496105]

8. Smith KR, Bruce N, Balakrishnan K, et al. Millions dead: how do we know and what does it mean? Methods used in the comparative risk assessment of household air pollution. Annu Rev Public Health 2014; 35: 185–206. [PubMed: 24641558]

9. Bond TC, Sun H. Can reducing black carbon emissions counteract global warming? Environ Sci Technol 2005; 39: 5921–26. [PubMed: 16173547]

10. Shupler M, Balakrishnan K, Ghosh S, et al. Global household air pollution database: kitchen concentrations and personal exposures of particulate matter and carbon monoxide. Data Brief 2018; 21: 1292–95. [PubMed: 30456246]

11. Shupler M, Godwin W, Frostad J, Gustafson P, Arku RE, Brauer M. Global estimation of exposure to fine particulate matter ($PM_{2·5}$) from household air pollution. Environ Int 2018; 120: 354–63. [PubMed: 30119008]

12. Pillarisetti A, Mehta S, Smith KR. HAPIT, the household air pollution intervention tool, to evaluate the health benefits and cost-effectiveness of clean cooking interventions In: Thomas EA, ed. Broken pumps and promises. Cham, Switzerland: Springer International Publishing, 2016: 147–69.

13. Teo K, Chow CK, Vaz M, Rangarajan S, Yusuf S. The Prospective Urban Rural Epidemiology (PURE) study: examining the impact of societal influences on chronic noncommunicable diseases in low-, middle-, and high-income countries. Am Heart J 2009; 158: 1–7e1. [PubMed: 19540385]

14. Corsi DJ, Subramanian SV, Chow CK, et al. Prospective Urban Rural Epidemiology (PURE) study: baseline characteristics of the household sample and comparative analyses with national data in 17 countries. Am Heart J 2013; 166: 636–46.e4. [PubMed: 24093842]

15. Arku RE, Birch A, Shupler M, Yusuf S, Hystad P, Brauer M. Characterizing exposure to household air pollution within the Prospective Urban Rural Epidemiology (PURE) study. Environ Int 2018; 114: 307–17. [PubMed: 29567495]

16. Shupler M, Hystad P, Gustafson P, et al. Household, community, sub-national and country-level predictors of primary cooking fuel switching in nine countries from the PURE study. Environ Res Lett 2019; 14: 085006.

17. Pillarisetti A, Carter E, Rajkumar S, et al. Measuring personal exposure to fine particulate matter ($PM_{2·5}$) among rural Honduran women: a field evaluation of the Ultrasonic Personal Aerosol Sampler (UPAS). Environ Int 2019; 123: 50–53. [PubMed: 30496981]

18. Volckens J, Quinn C, Leith D, Mehaffy J, Henry CS, Miller-Lionberg D. Development and evaluation of an ultrasonic personal aerosol sampler. Indoor Air 2016; 27: 409–16. [PubMed: 27354176]

19. Cyrys J, Heinrich J, Hoek G, et al. Comparison between different traffic-related particle indicators: elemental carbon (EC), $PM_{2·5}$ mass, and absorbance. J Expo Anal Environ Epidemiol 2003; 13: 134–43. [PubMed: 12679793]

20. Jeronimo M, Stewart Q, Weakley AT, et al. Analysis of black carbon on filters by image-based reflectance. Atmos Environ 2020; 223: 117300.

21. WHO. Harmonized survey questions for monitoring household energy use and SDG indicators 71.1 and 71.2. 11, 2019 https://www.who.int/airpollution/household/1_Harmonized_household_energy_survey_questions-list_format_final_Nov2019.pdf?ua=1 (accessed Aug 28, 2020).

22. Lear SA, Teo K, Gasevic D, et al. The association between ownership of common household devices and obesity and diabetes in high, middle and low income countries. CMAJ 2014; 186: 258–66. [PubMed: 24516093]

23. Brooks N, Bhojvaid V, Jeuland MA, Lewis JJ, Patange O, Pattanayak SK. How much do alternative cookstoves reduce biomass fuel use? Evidence from North India. Resour Energy Econ 2016; 43: 153–71.

24. WHO. Burning opportunity: clean household energy for health, sustainable development, and wellbeing of women and children. Geneva: World Health Organization, 2016.

25. Ruiz-Mercado I, Masera O. Patterns of stove use in the context of fuel-device stacking: rationale and implications. EcoHealth 2015; 12: 42–56. [PubMed: 25724593]

26. Balakrishnan K, Ghosh S, Ganguli B, et al. State and national household concentrations of $PM_{2·5}$ from solid cookfuel use: results from measurements and modeling in India for estimation of the global burden of disease. Environ Health 2013; 12: 77. [PubMed: 24020494]

27. Zhang L, Liu Y, Hao L. Contributions of open crop straw burning emissions to $PM_{2·5}$ concentrations in China. Environ Res Lett 2016; 11: 014014.

28. Ravindra K, Singh T, Mor S. Emissions of air pollutants from primary crop residue burning in India and their mitigation strategies for cleaner emissions. J Clean Prod 2019; 208: 261–73.

29. Lacey FG, Henze DK, Lee CJ, van Donkelaar A, Martin RV. Transient climate and ambient health impacts due to national solid fuel cookstove emissions. Proc Natl Acad Sci USA 2017; 114: 1269–74. [PubMed: 28115698]

30. Weaver AM, Gurley ES, Crabtree-Ide C, et al. Air pollution dispersion from biomass stoves to neighboring homes in Mirpur, Dhaka, Bangladesh. BMC Public Health 2019; 19: 425. [PubMed: 31014315]

31. Pope D, Bruce N, Dherani M, Jagoe K, Rehfuess E. Real-life effectiveness of 'improved' stoves and clean fuels in reducing $PM_{2·5}$ and CO: systematic review and meta-analysis. Environ Int 2017; 101: 7–18. [PubMed: 28285622]

Research in context

Evidence before this study

An estimated 2·8 billion people cooked with polluting fuels (eg, wood, coal, animal dung, and kerosene) in 2018. Evidence from household air pollution measurement studies demonstrates that cooking with polluting fuels is associated with higher concentrations of fine particulate matter ($PM_{2·5}$) mass and black carbon (two important indicators of health and climate impacts), compared to clean cooking fuels (gas and electricity). An existing global modelling study that pooled $PM_{2·5}$ kitchen and personal measurements (n=2208) from 44 published measurement studies available in the WHO global database of household air pollution measurements showed large variations in mean $PM_{2·5}$ concentrations and female exposures across primary fuel types and geographical locations. These existing household air pollution measurement studies were generally done among small populations in few communities, and most individual monitoring data were collected from women who are more commonly the primary household cook than men. Compared to $PM_{2·5}$, relatively little measurement data are available for household concentrations of black carbon. The magnitude of $PM_{2·5}$ and black carbon household exposures therefore remains unclear.

Added value of this study

The PURE-AIR study is among the largest and most diverse exposure assessments of $PM_{2·5}$ and black carbon related to household air pollution, with measurements from 120 rural communities in eight countries (Bangladesh, Chile, China, Colombia, India, Pakistan, Tanzania, and Zimbabwe). The PURE-AIR study more than doubles the number of $PM_{2·5}$ measurements available in the WHO global household air pollution database. By collecting information on both primary and secondary cooking fuels, the impact of multiple fuel combinations (ie, fuel stacking) on $PM_{2·5}$ and black carbon kitchen concentrations was also assessed. Personal monitoring of both sexes in this study provides unique information about household air pollution exposures among men, who have often been considered to be at lower risk of $PM_{2·5}$ and black carbon exposure from cooking than women. PURE-AIR measurements provide extensive information about the contribution of household cooking to overall exposures in different countries and the role of different cooking fuel types on emissions of air pollutants that contribute to global warming.

Implications of all the available evidence

The PURE-AIR study provides important new information about variations in $PM_{2·5}$ and black carbon kitchen concentrations and household air pollution exposures on a multinational scale. These measurements can be used to inform risk assessments and policy scenarios targeting household air pollution and can be integrated with health studies to further understand the relationship between exposure to household air pollution and adverse health effects.

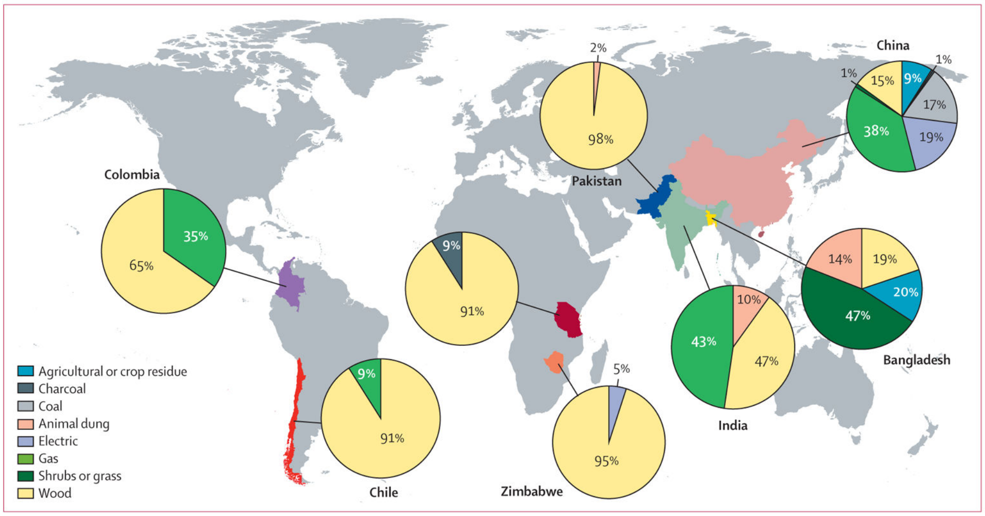

Figure 1:

Primary fuel proportions sampled from each country in the PURE-AIR study

Author Manuscript

Author Manuscript

Author Manuscript

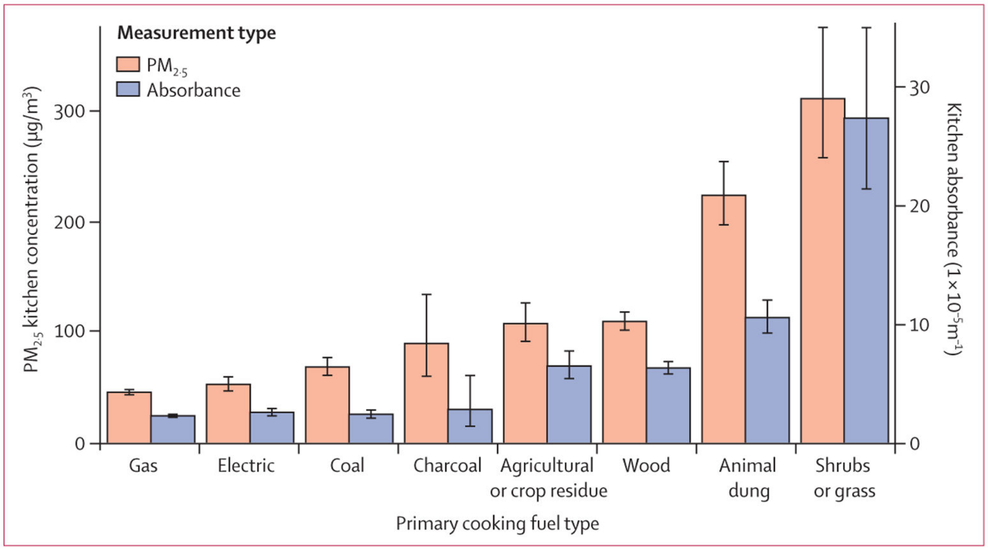

Figure 2:

Summary of $PM_{2\cdot5}$ kitchen concentrations (μg/m^3) and absorbance levels ($1\times10^{-5}m^{-1}$) by primary fuel type

Error bars are 95% CIs. Point estimates are geometric means.

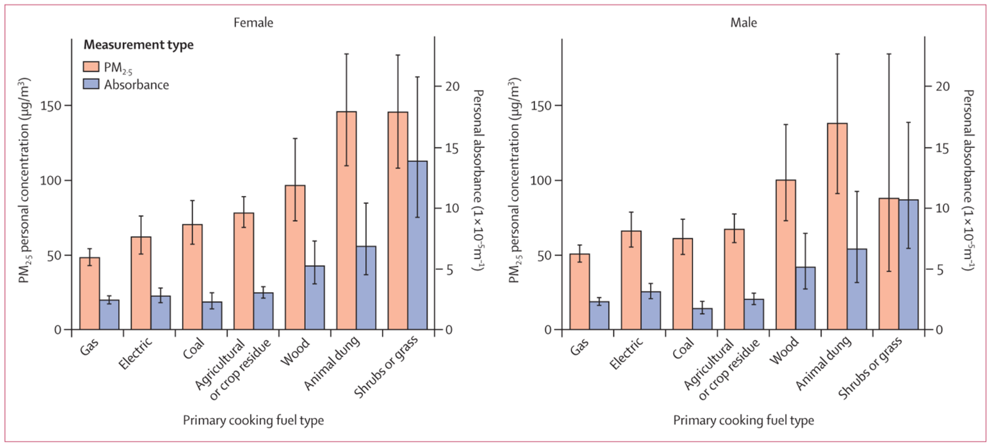

Figure 3:
Summary of $PM_{2·5}$ personal exposures (μg/m^3) and absorbance levels ($1\times10^{-5}m^{-1}$) by sex and primary fuel type

Error bars are 95% CIs. Point estimates are geometric means.

Table 1:

Characteristics of households included in the PURE-AIR study by primary cooking fuel type

	All households	Gas	Electric	Coal	Charcoal	Agricultural or crop residue	Wood	Animal dung	Shrubs or grass
Households (%)	2541	869 (34%)	236 (9%)	209 (8%)	8 (0%)	144 (6%)	903 (36%)	103 (4%)	69 (3%)
Country or region (%)									
China	1244 (49%)	478 (55%)	232 (98%)	208 (99%)	6 (75%)	117 (81%)	191 (21%)	2 (2%)	10 (14%)
India	811 (32%)	342 (40%)	1 (1%)	1 (1%)	0	2 (1%)	383 (42%)	80 (78%)	0
Other south Asia (Bangladesh and Pakistan)	258 (10%)	1 (0%)	0	0	0	25 (17%)	152 (17%)	21 (20%)	59 (86%)
South America (Chile and Colombia)	152 (6%)	47 (5%)	0	0	0	0	105 (12%)	0	0
Africa (Tanzania and Zimbabwe)	78 (3%)	1 (0%)	3 (1%)	0	2 (25%)	0	72 (8%)	0	0
Fuel stacking (%)	981 (39%)	338 (39%)	60 (25%)	38 (18%)	0	83 (58%)	375 (42%)	79 (77%)	8 (12%)
Secondary fuel (%)									
None	1570 (61%)	523 (60%)	183 (78%)	175 (84%)	8 (100%)	62 (43%)	528 (59%)	24 (23%)	61 (88%)
Gas	409 (16%)	..	27 (11%)	0	0	20 (14%)	283 (31%)	75 (73%)	2 (3%)
Electric	314 (12%)	139 (16%)	..	33 (16%)	0	54 (38%)	77 (9%)	0	6 (9%)
Coal	17 (1%)	3 (1%)	7 (3%)	..	0	3 (2%)	2 (0%)	0	0
Charcoal	0	2 (0%)	0	0	..	1 (1%)	1 (0%)	0	0
Agricultural or crop residue	23 (1%)	17 (2%)	2 (1%)	0	0	..	2 (0%)	1 (1%)	0
Wood	198 (8%)	177 (20%)	17 (7%)	0	0	1 (1%)	..	2 (2%)	0
Animal dung	14 (1%)	8 (1%)	0	0	0	0	6 (1%)	..	0
Shrubs or grass	0	0	0	0	0	0	3 (0%)	1 (1%)	..
Kitchen type (%)*									
Inside (no separate room)	118 (5%)	96 (11%)	1 (1%)	1 (1%)	0	1 (1%)	19 (2%)	0	0
Inside (separate room)	1882 (74%)	726 (84%)	227 (97%)	203 (97%)	7 (88%)	115 (80%)	526 (58%)	56 (54%)	22 (32%)
Porch or veranda	83 (4%)	12 (1%)	5 (2%)	4 (2%)	1 (12%)	5 (3%)	36 (4%)	14 (14%)	11 (16%)
Outside (open air)	433 (17%)	24 (3%)	0	0	0	21 (15%)	314 (35%)	33 (32%)	36 (52%)
Mean cooking time (primary fuel only; h per day)	2·3 (1·4)	2·0 (1·1)	1·6 (0·7)	1·4 (1·0)	1·7 (0·9)	1·9 (1·8)	2·7 (1·2)	4·8 (1·8)	2·3 (0·8)
Kitchen ventilation									
Chimney	842 (33%)	155 (18%)	115 (49%)	192 (92%)	5 (63%)	99 (69%)	211 (23%)	55 (53%)	10 (14%)
Window	1904 (75%)	785 (90%)	213 (90%)	190 (91%)	7 (88%)	114 (79%)	521 (58%)	56 (54%)	18 (26%)
Heating fuel type† (%)									

	All households	Gas	Electric	Coal	Charcoal	Agricultural or crop residue	Wood	Animal dung	Shrubs or grass
No heating	1692 (67%)	574 (66%)	152 (64%)	177 (85%)	5 (63%)	49 (34%)	567 (62%)	101 (98%)	67 (98%)
Electric or gas	195 (8%)	148 (17%)	31 (13%)	1 (0%)	0	9 (6%)	4 (1%)	1 (1%)	1 (1%)
Mud stove	261 (10%)	35 (4%)	23 (10%)	14 (7%)	0	76 (53%)	113 (13%)	0	1 (1%)
Open fire	300 (12%)	106 (12%)	26 (11%)	16 (8%)	3 (38%)	9 (6%)	138 (15%)	1 (1%)	0
Chimney stove	82 (3%)	3 (1%)	0	0	0	0	79 (9%)	0	0
Smoking in home (%)	708 (28%)	235 (27%)	99 (42%)	63 (30%)	2 (25%)	41 (28%)	193 (21%)	44 (43%)	31 (45%)
Household asset index‡ (%)									
Tertile 1 (lowest)	1322 (52%)	309 (36%)	154 (65%)	165 (79%)	5 (63%)	95 (66%)	536 (59%)	28 (27%)	27 (39%)
Tertile 2	815 (32%)	349 (40%)	64 (27%)	31 (15%)	2 (25%)	32 (22%)	269 (30%)	42 (41%)	24 (35%)
Tertile 3 (highest)	316 (12%)	180 (21%)	15 (6%)	12 (6%)	1 (12%)	13 (9%)	73 (8%)	8 (8%)	14 (20%)
Education level§ (%)									
None	607 (24%)	104 (12%)	20 (8%)	40 (19%)	1 (12%)	18 (13%)	348 (39%)	47 (46%)	29 (42%)
Primary	809 (32%)	240 (28%)	90 (38%)	107 (51%)	2 (25%)	25 (17%)	305 (34%)	24 (23%)	16 (23%)
Secondary	996 (39%)	466 (54%)	120 (51%)	54 (26%)	5 (63%)	89 (62%)	218 (24%)	24 (23%)	20 (29%)
Trade or university	82 (3%)	44 (5%)	1 (0%)	5 (2%)	0	6 (4%)	19 (2%)	4 (4%)	3 (4%)

Data are n (%) or mean (SD).

* Kitchen type is a derived variable that was coded to match groupings reported in the WHO harmonised survey for monitoring household energy use.[21] Participants who reported cooking indoors and having at least two rooms in the home were categorised as cooking indoors "in a separate room". Those reporting having one room in the home were categorised as indoor cooking with "no separate room". Participants who reported cooking inside with their kitchen being "partially open to the outside" were categorised as cooking on a "porch or veranda". Those who reported cooking outdoors were assumed to cook "in open air". No questions were asked in PURE surveys about whether the indoor kitchen was attached or detached from the main household.

† Percentages for heating fuel type do not add up to 100% due to non-response (0%).

‡ Household asset index was ranked at a national level and grouped into country-stratified tertiles.[22] Percentages for household asset index do not add up to 100% due to non-response (3%).

§ Highest education level in the household (baseline). Percentages for education level do not add up to 100% due to non-response (2%).

Table 2:

Summary of average 48 h $PM_{2 \cdot 5}$ kitchen concentrations by primary fuel type

	Gas (n=869)	Electric (n=236)	Coal (n=209)	Charcoal (n=8)	Agricultural or crop residue (n=144)	Wood (n=903)	Animal dung (n=103)	Shrubs or grass (n=69)
Kitchen $PM_{2 \cdot 5}$ ($\mu g/m^3$)								
Total	45 (43–48)	53 (47–60)	68 (61–77)	92 (58–146)	106 (91–125)	109 (102–118)	224 (197–254)	276 (223–342)
Country or region								
China	46 (43–49)	53 (47–60)	68 (61–77)	78 (48–127)	89 (74–106)	50 (45–55)	85 (40–182)	65 (43–100)
India	50 (46–54)	..	..	..	140 (17–1126)	105 (96–116)	209 (181–242)	..
Other south Asia (Bangladesh and Pakistan)	..	..	..	..	244 (200–298)	383 (339–435)	317 (259–388)	352 (296–420)
South America (Chile and Colombia)	20 (17–23)	..	..	..	..	41 (34–49)	..	..
Africa (Tanzania and Zimbabwe)	..	26 (14–47)	..	136 (126–147)	..	318 (266–381)	..	..
Secondary fuel								
None	44 (42–48)	54 (46–62)	71 (62–81)	92 (58–146)	122 (95–171)	146 (132–162)	287 (210–346)	324 (265–397)
Gas	..	70 (57–86)	..	..	70 (50–99)	78 (70–87)	206 (177–238)	210 (121–251)
Electric	45 (41–51)	..	56 (46–67)	..	102 (83–125)	46 (39–56)	..	62 (39–97)
Coal	139 (74–261)	47 (30–75)	..	..	134 (79–227)	..	..	..
Charcoal	191 (71–514)	..	..	..	..	..	..	..
Agricultural or crop waste	41 (31–53)	80 (73–87)	..	..	..	304 (200–463)	..	..
Wood	45 (40–50)	30 (22–38)	..	..	..	..	..	..
Animal dung	142 (96–211)	..	..	..	..	168 (111–256)	..	..
Shrubs or grass	..	..	..	..	..	284 (143–564)	..	..
Cooking time during monitoring (primary fuel only; h per day)								
0·0–1·0	47 (41–54)	70 (56–87)	69 (58–83)	65 (38–110)	104 (67–160)	76 (60–97)	..	162 (86–306)
1·1–2·0	44 (41–47)	48 (41–57)	69 (58–83)	93 (38–228)	94 (77–115)	97 (85–110)	266 (197–358)	225 (142–357)
2·1–3·0	47 (42–53)	53 (41–68)	78 (56–107)	136 (126–147)	181 (135–241)	101 (89–113)	245 (180–335)	311 (229–421)
≥3·1	48 (40–58)	98 (30–329)	51 (38–68)	..	188 (69–514)	150 (127–175)	219 (189–255)	372 (265–524)

Data are geometric means (95% CI).

Table 3:

Summary of average 48 h $PM_{2 \cdot 5}$ personal exposures by primary fuel type

	All households		Gas		Electric		Coal		Agricultural or crop waste		Wood		Animal dung		Shrubs or grass	
	Male (n=442)	**Female (n=556)**	**Male (n=l68)**	**Female (n=194)**	**Male (n=57)**	**Female (n=59)**	**Male (n=34)**	**Female (n=37)**	**Male (n=25)**	**Female (n=29)**	**Male (n=142)**	**Female (n=201)**	**Male (n=7)**	**Female (n=17)**	**Male (n=9)**	**Female (n=19)**
Total	62 (58–67)	67 (62–72)	51 (45–56)	48 (43–54)	66 (55–78)	62 (50–76)	61 (52–78)	71 (57–86)	100 (73–138)	97 (73–128)	68 (59–78)	78 (69–89)	138 (91–210)	146 (110–194)	88 (39–199)	147 (109–197)
Country or region																
China	57 (52–62)	55 (50–61)	50 (43–59)	47 (38–56)	66 (55–78)	61 (49–75)	61 (52–78)	71 (58–88)	93 (64–136)	94 (68–129)	44 (37–54)	45 (36–54)	..	..	37 (3–405)	64 (32–128)
India	66 (57–77)	70 (62–80)	53 (45–63)	56 (48–64)	..	..	..	..	..	..	82 (64–107)	89 (74–114)	178 (132–240)	150 (105–216)	..	..
Other south Asia (Bangladesh and Pakistan)	103 (83–119)	158 (125–179)	..	..	..	..	..	..	147 (137–157)	148 (110–198)	90 (67–111)	148 (100–182)	73 (34–159)	147 (81–269)	135 (110–165)	183 (146–229)
South America (Chile and Colombia)	40 (30–51)	32 (25–38)	40 (28–53)	23 (18–28)	..	..	..	..	..	..	40 (25–64)	39 (28–50)	..	..	..	..
Africa (Tanzania and Zimbabwe)	114 (79–166)	146 (112–141)	..	..	..	85 (51–140)	..	..	..	..	120 (80–179)	153 (116–202)	..	..	..	..
Age, years																
43–60	71 (62–82)	79 (71–88)	61 (51–74)	52 (44–62)	60 (42–85)	65 (45–93)	57 (37–87)	76 (56–102)	100 (56–181)	122 (74–200)	83 (63–110)	86 (71–103)	131 (91–187)	159 (110–231)	153 (128–182)	190 (144–251)
61–84	57 (50–63)	54 (47–63)	47 (40–56)	49 (39–62)	82 (56–119)	55 (32–96)	63 (48–82)	58 (37–92)	100 (68–147)	92 (66–127)	62 (51–75)	65 (50–84)	184 (126–268)	119 (70–203)	67 (20–219)	94 (50–174)
Occupational air pollution exposure*																
Yes	75 (65–86)	82 (71–96)	63 (51–77)	53 (40–70)	81 (44–152)	62 (50–78)	50 (43–58)	71 (57–88)	100 (73–138)	97 (73–128)	78 (63–97)	96 (80–117)	236 (142–394)	95 (62–145)	132 (104–169)	148 (126–174)
No	57 (52–62)	63 (57–69)	46 (40–53)	47 (41–54)	63 (52–77)	56 (23–136)	64 (52–80)	..	..	..	58 (48–70)	66 (55–79)	112 (73–171)	175 (124–246)	53 (9–325)	146 (97–219)

	All households		Gas		Electric		Coal		Agricultural or crop waste		Wood		Animal dung		Shrubs or grass	
	Male (n=442)	**Female (n=556)**	**Male (n=l68)**	**Female (n=194)**	**Male (n=57)**	**Female (n=59)**	**Male (n=34)**	**Female (n=37)**	**Male (n=25)**	**Female (n=29)**	**Male (n=142)**	**Female (n=201)**	**Male (n=7)**	**Female (n=17)**	**Male (n=9)**	**Female (n=19)**
Smoker																
Yes	70 (62–79)	91 (58–141)	63 (52–77)	74 (33–164)	72 (54–96)	..	75 (52–109)	..	104 (57–188)	..	68 (54–85)	105 (46–244)	138 (107–178)	..	164 (135–199)	..
No	58 (52–63)	67 (62–72)	44 (38–50)	47 (42–54)	58 (47–72)	62 (50–76)	61 (48–77)	71 (57–86)	98 (66–144)	97 (73–128)	67 (55–81)	78 (68–89)	138 (76–252)	146 (110–194)	74 (26–205)	147 (109–197)
Second-hand smoke exposure																
Yes	72 (64–81)	79 (70–90)	59 (48–71)	66 (52–83)	69 (50–93)	76 (55–105)	81 (55–121)	66 (48–91)	100 (60–164)	102 (64–164)	78 (63–96)	78 (111–168)	137 (110–165)	191 (118–197)	135 (110–165)	153 (118–197)
No	54 (49–60)	61 (55–67)	45 (39–51)	42 (36–48)	62 (51–76)	53 (40–70)	60 (47–76)	72 (55–93)	101 (71–144)	93 (65–134)	57 (46–71)	79 (66–94)	140 (48–407)	131 (91–188)	37 (3–405)	135 (53–346)

Data are geometric mean (95% CI) in units of $\mu g/m^3$.

*Occupational air pollution represents participants who self-reported being exposed to specific air pollution sources (eg, fires, industrial processes, and traffic) while at work during the 48 h monitoring period.