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Releasing the Killer from the Kitchen? Ventilation and Air Pollution from Biomass Cooking

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Luciane Lenz, Gunther Bensch, Ryan Chartier, Moustapha Kane, Jörg Peters, and Marc Jeuland[1]

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Abstract

Household air pollution from biomass cooking is the most significant environmental health risk in the Global South. Interventions to address this risk mostly promote less-polluting stoves and clean fuels, but their diffusion proves difficult. This paper assesses the potentially complementary role of ventilation in reducing household air pollution. Using state-of-the-art measurements of kitchen concentrations of particulate matter (PM2.5) and personal exposure from 419 households in rural Senegal, we show that higher ventilation is strongly related to lower kitchen concentration, though absolute pollution levels remain high. This association is robust to controlling for a comprehensive set of potential confounders. Yet, these reductions in concentration do not translate into lower pollution exposure among cooks, probably due to avoidance behaviour. Our findings indicate that ventilation interventions may reduce smoke concentration nearly as good as many real-world clean stove interventions and can hence be an important complement to existing strategies. However, a more holistic approach is needed in order to reduce personal exposure in line with international health standards.

JEL-Codes: D12, O18, Q41, Q53

Keywords: Cookstoves; biomass burning; ventilation; particulate matter concentration; exposure; household air pollution

September 2022

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1. Introduction

One third of humanity primarily cooks with biomass, mostly wood and charcoal (IEA et al. 2022). The household air pollution resulting from combustion of such fuels is the leading environmental cause of mortality, inducing an estimated 3.8 million premature deaths per year globally (WHO 2016). Since the 2000s, policy interventions have promoted clean stoves and fuels such as gas and electricity, in order to combat household air pollution as well as forest degradation and relieve women from firewood collection (Köhlin et al. 2011; Shindell et al. 2012; Bailis et al. 2015; Bensch et al. 2021*a*). Yet, many countries are well off track in meeting Sustainable Development Goal 7, which requires universal access to clean cooking by 2030. The main transitional alternative to clean stoves and fuels are energy-efficient biomass cookstoves (EEBCs), which are not emission-free, but still reduce biomass consumption and, hence, time or monetary expenditures for fuel collection. Such EEBCs are more affordable than clean technologies, but supply and demand side challenges also slow their adoption and sustained use.[1] In rural Senegal for example, the site of this study, 96% of the population still used solid cooking fuels in 2020 (IEA et al. 2022), and poorer urban strata often still use biomass fuels as well (Rose et al. 2022).

This paper studies the role of improved kitchen ventilation in reducing household air pollution levels and exposures. Such a solution has recently emerged in policy and academic discussions as a potentially complementary approach to cleaner stoves and fuels, which dominate both discussions (see Fullerton et al. 2008, Langbein 2017, ESMAP 2020, and Simon et al. 2014). Rather than reducing the generation of kitchen pollution at its source, ventilation may reduce kitchen pollution levels in directing harmful emissions away from people, for example through improved kitchen air exchange. We examine the relationship between kitchen features and pollution concentrations, as well as cooks' personal exposure, using pooled data from two waves of state-of-the-art emission measurements and in-depth household surveys. Our sample includes 419 measurements of primary cooks' personal exposure, kitchen measurements and questionnaire-based data on cooking conditions, and 220 measurements of kitchen

[1] These challenges include underdeveloped supply chains (Lewis et al. 2015; Pattanayak et al. 2019), barriers to commercialization for stove developers (Bailis et al. 2009; Bensch et al. 2021*b*), misalignment of consumer preferences with available improved technologies, low valuation of these solutions (Mobarak et al. 2012; Jeuland et al. 2015 and 2020; Jeuland and Pattanayak 2012), liquidity constraints or affordability (Levine et al. 2018; Bensch and Peters 2020; Bensch et al. 2015), and poor durability (Hanna et al. 2016).

concentrations. The data were collected in the dry seasons of 2018 and 2019 in 15 rural Senegalese communities, where traditional cooking is predominant and ventilation conditions vary substantially. Our identification strategy relies on a cross-sectional comparison of different ventilation types and is hence prone to the typical concerns about selection biases. The strength of our approach, though, is in combining high-accuracy measurements with a comprehensive set of socio-economic and cooking-specific control variables in pre-specified regression analyses, that reduce measurement error and mitigate the risk of unobservables and data mining. We add to a thin literature on ventilation and household air pollution that mostly includes small samples and limited data to control for behavioural and other household-related confounders (Lenz et al. 2022). Given the lack of consensus on how to measure ventilation in the existing literature (see again Lenz et al. 2022), we furthermore present a conceptual framework that defines the different dimensions of kitchen ventilation and their operationalisation.

Our empirical analyses explore the role of four kitchen ventilation dimensions: kitchen air exchange (wall structure, roofing structure, kitchen openings), kitchen volume, kitchen separation and ventilation behaviour. Additionally, we generate two composite indicators of ventilation: a simple additive indicator, and an indicator based on data-driven classification methods, namely principal component analysis. We define four categories of ventilation intensity for each indicator, from *no*, over *poor* and *substantial* to *full* ventilation. The outcome measures are kitchen concentration and cooks' personal exposure to particulate matter of a diameter less than 2.5 micrometres ($PM_{2.5}$), the most harmful component of air pollution from use of firewood (WHO 2008). Due to its small size, $PM_{2.5}$ has a low likelihood of getting filtered by the upper respiratory tract and can hence penetrate deep into small body airways, lungs, and bloodstreams (Pope and Dockery 2006). We use sensor-measured 24-hour pollution averages and peak-level emissions, both based on real-time $PM_{2.5}$ data. We conduct a battery of robustness checks to investigate the stability of our main results.

We find that improved ventilation is associated with substantially lower kitchen concentration. According to our composite indicators, cooking in *fully* ventilated (primarily open air) or *substantially* ventilated kitchens (including at most three kitchen walls, for example), is associated with around 64-71% or 38-46% less kitchen concentration relative to *unventilated* kitchens (including e.g. only a door), respectively. This is not much less than the household air pollution reduction potentials associated with moving from traditional cooking to clean fuels, since also clean stove interventions do hardly replace all dirty stoves in a household (so-called stove stacking, see e.g. Pope et al. 2021 or Ruiz-Mercado and Masera 2015). It is important to note, though, that our measurements also show that the average kitchen concentration of 474 μg/m^3 $PM_{2.5}$ exceeds even the least stringent WHO (2021) interim air quality target of 35 μg/m^3 $PM_{2.5}$ by an order of magnitude. Average 24-hour personal exposure is substantially lower, but nevertheless high (136 μg/m^3 $PM_{2.5}$), and remains high even during non-cooking periods, suggesting exposure to higher levels of ambient air pollution. Moreover, personal exposure is not significantly associated with kitchen concentration and is lower – as a fraction of kitchen concentration – than commonly assumed in the literature. These discrepancies are most likely driven by cooking behaviour, and we find tentative supporting evidence using proxies for cooking behaviour.

Our findings inform the design of potential transitional measures to complement clean cooking access policies. First, policy might encourage greater ventilation in homes as a stand-alone intervention in settings where more open kitchens are climatically and culturally appropriate. Second, ventilation improvements could be tested as a complement to clean stoves and EEBCs in an effort to improve the cost-effectiveness of cooking interventions. Third, our finding that kitchen concentration is an inaccurate proxy for exposure in biomass-using households suggests that the interaction of stoves, fuels, housing conditions and cooking behaviours must not be ignored when tracking the success of clean cooking policies.

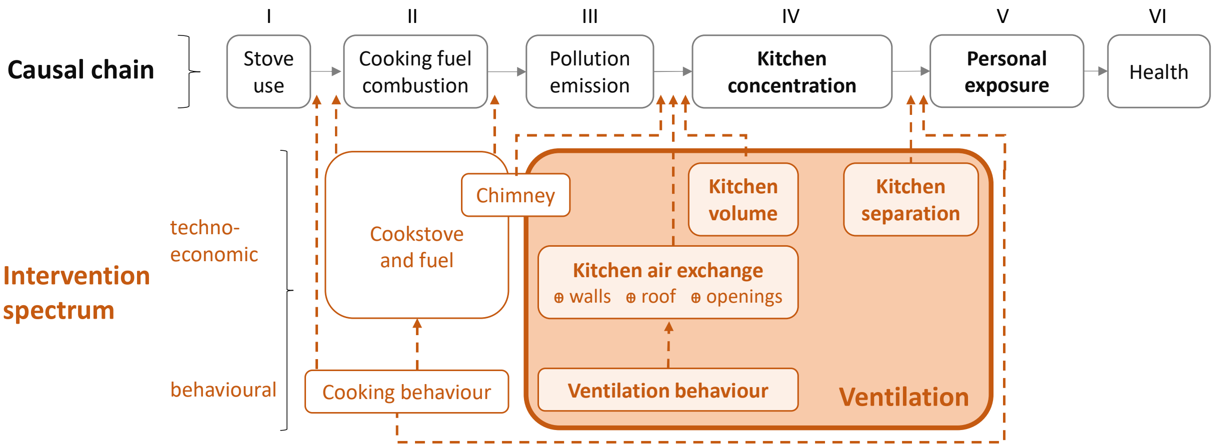
2. Conceptual framework

2.1. Ventilation as a cleaner-cooking intervention

The ultimate public health objective of clean cooking interventions is a reduction of health burdens related to cooking-induced pollution. Figure 1 illustrates a stylized causal chain linking cooking stove use to health outcomes, and locates a spectrum of techno-economic and behavioural interventions aiming to influence different elements in that causal chain.

Traditional stoves combust solid fuels inefficiently and thereby emit pollutants, such as fine particulates, carbon monoxide, nitrogen oxides, and volatile organic compounds. These all contribute to elevated kitchen concentration of pollutants, which is dispersed across the kitchen and beyond. The pollution a person is exposed, and hence inhales, defines personal exposure which then affects health.

Figure 1: Stylized causal chain and intervention spectrum



The specific hypothesis examined in this paper is that kitchen ventilation – represented by the four dimensions of ventilation in Figure 1 – can also alter kitchen concentrations and personal exposures, leading to an interference in the links III-IV and IV-V in the figure. Keeping emissions constant, pollution will be lower in a space with more kitchen air exchange, because particles move towards openings (Patel et al. 2017). More specifically, we consider the three kitchen air exchange sub-dimensions *wall structure*, *roof structure* and *kitchen openings*. A second dimension of kitchen ventilation is *kitchen volume*, i.e. the volume over which emissions can dilute. A third dimension is *ventilation behaviour*, which mainly refers to people's inclination to keep doors and windows open. Lastly, *kitchen separation* affects pollution dilution to parts of the house beyond the kitchen. Kitchen separation is therefore relevant for personal exposure only and, in contexts like ours, where pollution exposure is measured with cooks only, it is just relevant when pollution persists during non-cooking times. All these dimensions may interact and may be complementary with cookstove and fuel choices and cooking behaviour, which includes the choice of dishes cooked, the use of dry wood, and contact time, among others.[2] Figure 1 also identifies chimneys as technologies that pair an improved stove with a significant ventilation intervention, venting emissions directly to the outside.

[2] For example, Bensch and Peters (2015) present exploratory evidence that the dissemination of a portable improved stove (stove intervention) increased the likelihood of outdoor cooking (a ventilation-enhancing behaviour) and reduced the time that primary cooks spent near their stoves (an exposure-mitigating cooking behaviour).

Our empirical analysis does not consider health outcomes and hence ends at link IV-V. Importantly, existing evidence indicates that the concentration-response relationship between household air pollution and health impacts differs across diseases and may be highly nonlinear, implying that only very low pollution levels induce substantial health improvements (Ezzati and Kammen 2002; Burnett et al. 2014; Apte et al. 2015).[3]

Multiple contextual factors can alter the impact of kitchen ventilation on kitchen concentration and personal exposure. These include household wealth and cultural aspects. The installation of windows, for example, can be compromised by privacy or security concerns (Muindi et al. 2016; Lueker et al. 2020). The health status of household members is also important as it may determine whose and how much time is spent in the kitchen. In addition to these individual factors, which we seek to control for in our empirical analyses, the effectiveness of ventilation is conditioned on the quality of ambient air. Studies from urban areas have indeed shown that ventilation can worsen indoor air quality, if ambient air pollution or neighbours' emissions are high (Mönkkönen et al. 2005; Shibata et al. 2014). Finally, weather – including rain, winds and dust storms – can impact air quality via changes in ventilation behaviour (Kulshreshtha and Khare 2011; Nayek and Padhy 2017).

2.2. Kitchen ventilation indicators

The range of kitchen designs in rural Senegal covers many kitchen structures found in other developing countries. Kitchen volume is the only kitchen ventilation dimension that can be characterized using a continuous measure, which is m^3. For each kitchen ventilation dimension, we therefore create categorical indicators, using the following four categories: *no, poor, substantial,* and *full* ventilation (Table 1). These categories build on the Cooking Energy System concept proposed by the global Energising Development programme (GIZ 2017). With open-air kitchens included in the *full* ventilation category for all non-behavioural ventilation dimensions, *open air* is included as additional binary indicator in the analytical framework. The open-air indicator also has the advantage that it is included in some cross-country secondary datasets such as the Demographic Heath Survey (DHS).

[3] The small number of studies that address this link furthermore suggest that better ventilation can reduce the incidence of acute lower respiratory infections among children (Rehfuess et al. 2009; Buchner and Rehfuess 2015; Langbein 2017), reduce bronchitis (in Bolivia) and other respiratory problems (in Ghana) (Albalak et al. 1999; Boadi and Kuitunen 2006), and increases the rate of depressive symptoms (Zhang et al. 2017).

Table 1: Categorization of kitchen ventilation dimensions

	No ventilation	Poor ventilation	Substantial ventilation	Full ventilation
Wall structure	 *fully closed: impermeable with/without openings*	 *fully closed: permeable with/without openings*	 *semi-enclosed: one to three walls to the roof*	 *no walls*
Roof structure	 *solid roof*	 *Permeable*	 *permeable with openings*	 *no roof*
Kitchen openings	*no opening except for the door*	*small or medium-sized openings*	*significant openings*	*no walls, no roof or open air*
Kitchen volume	*less than 12.5m^3*	*12.5 to 25 m^3*	*more than 25 m^3*	*open air*
Kitchen separation	*inside main building*	*attached to main building*	*separated from main building*	*open air*
Ventilation behaviour	*frequency of opening doors and windows while cooking: never*	*rarely*	*often*	*always*
Open air		*non-open air*		*open air*

Note: Impermeable materials include e.g. concrete, bricks, and mud; permeable materials include e.g. bamboo, grass, and boards. Kitchen openings include hoods. Photographs taken during field work.

We further create composite indicators based on the single, one-dimensional ventilation indicators that refer to non-behavioural ventilation dimensions and that are relevant for both kitchen concentration and personal exposure. These are the first four single indicators in the Table 1 – walls, roof, openings, and volume. We consider two approaches from the literature on how to condense the information from multiple single indicators in a composite indicator. We call the first such composite indicator *aggregated ventilation*, as it simply sums up the four single indicators and implicitly applies an equal weighting to all four of them. Our second composite indicator abstains from imposing weights and instead leverages the correlation structure between the indicators using Principal Component Analysis (PCA, see Filmer and Pritchett 2001). To determine our *PCA ventilation* indicator, we combine the first two components derived by PCA, each weighted by the extent to which it explains the variation in the PCA. Both indicators are analysed as continuous measures ranging from 0 to 1 and as categorical measures, where the continuous score is split into quartiles. We additionally tested another data-driven composite indicator based on recursive partitioning techniques. Here, the categorization is informed by the data instead of adopting equal sample splits. Yet, this approach goes along with multiple problems in our setting, which is why we only discuss it in Annex A.

3. Empirical approach

3.1. Identification strategy and estimation framework

Our empirical work focuses on the relationship between ventilation variables and two outcome measures, kitchen concentration of $PM_{2.5}$, and personal exposure to that pollutant. To isolate the causal impact of ventilation on these measures, one would ideally vary ventilation randomly. In the absence of such a randomization, we use detailed individual-level data that allows controlling for many potential confounders, acknowledging that further confounders may remain uncontrolled. For example, households particularly vulnerable to household air pollution may preferentially invest in ventilation technology. The specification of variables used in the analysis is discussed in a pre-analysis plan for the larger impact evaluation study of which the analysis is a part (Peters and Jeuland 2017).

To test the association between kitchen ventilation and air pollution measures, we conduct Ordinary Least Squares (OLS) estimations with the following specification:

$$\log(Y_{i,j,t}) = \alpha + \beta_1 Ventilation_{i,j,t} + \mathbf{X}'_{i,j,t}\boldsymbol{\beta_2} + \delta W_t + \gamma_j + \epsilon_{i,j,t} \qquad (1),$$

where α is the intercept term, W is an indicator that is equal to 1 if the survey took place in t=2019 (and otherwise 0 for t=2018), γ_j are village fixed effects, and $\epsilon_{i,j,t}$ represents an error term specific to household i from village j for survey wave t. In the following, we explain in more detail the other three components of equation (1), the outcome $\log(Y_{i,j,t})$, the ventilation indicators $Ventilation_{i,j,t}$, and the set of control variables, $\mathbf{X}'_{i,j,t}$.

$\text{Log}(Y_{i,j,t})$ represents either of the two logged outcome measures of interest for household i,j and survey wave t: mean 24-hour $PM_{2.5}$ kitchen concentration and mean 24-hour cooks' personal exposure to $PM_{2.5}$. We log-transform pollution because its bivariate relationship with ventilation is not linear and to reduce the influence of extreme values. Kitchen concentration was measured at an approximate 1-meter vertical and horizontal distance from households' main stoves. For this measurement, we used one of two types of meters, gravimetric Micro Personal Exposure Monitors (MicroPEMs, RTI International, USA) and optical Indoor Air Pollution Meters (IAP Meters, Aprovecho, USA). For measurement of personal exposure, women agreed to wear the lightweight MicroPEMs at chest level to measure the fine particles they inhale from their breathing zone. Additionally, both the MicroPEM and IAP meters provide real-time pollution data, by registering $PM_{2.5}$ inflow in 30-second intervals via a light-scattering particle detector built into the devices. We order the real-time pollution measurements into percentiles of 24-hour pollution, from most polluting to least polluting and use these as outcome variables in a robustness test.

In equation (1), *Ventilation* describes an indicator for a household's kitchen ventilation, for which we evaluate the single and composite ventilation indicators introduced in Section 2 and listed in Table 2. Note that the present study does not test the indicator *ventilation behaviour* given that only around 25% of households have closable doors and virtually none have closable windows. Hence, this indicator is not applicable and can thus not be tested for the large majority of households in our sample.[4]

The last component of equation (1), $\mathbf{X}'_{i,j,t}$, represents a set of household, participant and measurement characteristics to control for potential confounders of the relationship between ventilation and pollution or exposure. First, we control for measures of wealth, including the occupation of the main cooks, a wealth index derived from asset ownership, and access to water and electricity infrastructure. Second, we control for ethnicity and some aspects of cooking behaviour. Third, we test whether our findings are robust to the inclusion of health status, which we exclude from our main specification due to concerns about reverse causality. Finally, we control for cooking time measured using Stove Use Monitors (SUMs) and the two ICS types that were randomized as part of the impact evaluation of which the analysis is a part, as well as technical factors specific to the kitchen concentration and personal exposure measurements.[5]

[4] Similarly, chimneys as a stove-ventilation combination are not found in the survey regions and therefore not included in our analysis.

[5] Two factors only included in the control set for kitchen concentration are the meter type and the share of cooking events next to monitored stove. Meanwhile, the personal exposure set includes three factors that are only relevant to exposure: the number of persons cooking during the measurement period, whether participants were secondary or main cooks during measurement, or neither, and the share of daytime hours spent wearing the MicroPEM.

Table 2: Definition of ventilation indicators

Indicator type	Indicator	Type of classification
Single	**Kitchen walls**	Categorical 1-4
	Kitchen roof	Categorical 1-4
	Kitchen openings	Categorical 1-4
	Kitchen volume	Continuous/ Categorical 1-4
	Kitchen separation	Categorical 1-4
	Open air	Categorical 0-1
Composite (walls + roof + openings + volume)	**Aggregated ventilation**	Continuous 0-1/ Categorical 1-4 (quartiles)
	PCA ventilation	Continuous 0-1/ Categorical 1-4 (quartiles)

Note: See Section 2.2 for the categorizations.

Given that our controls may not cover all relevant potential confounders, we investigate the role of unobservables and omitted variable bias in our estimates based on Oster (2019). The Oster method formalizes a well-known link, namely that smaller changes in coefficients paired with larger changes in R-squared after inclusion of controls eases concerns about omitted variable bias. The method estimates the ratio of selection on unobservables to selection on observables which would make the coefficient of interest equal to zero (delta). A delta higher than one signals that unobservables are more important than observables in explaining selection into ventilation. It is commonly interpreted as support for the model specification. The method requires definition of a maximum R-squared R_{max}, which Oster (2019) suggests setting to 1.3 times the observed R-squared. We apply this approach to specifications where it is technically possible, i.e., those that estimate a single coefficient for the ventilation indicator, which is the case for the three categorical and continuous indicators on a scale from zero to one.

3.2. Data collection

The household data used in our estimation framework was collected in 15 rural Senegalese villages during the dry season in early 2018 and early 2019. The study sample comprised two regions in northern and central Senegal characterized by typical Sahelian vegetation and scarce fuelwood. Villages located in these regions were eligible if they complied with two inclusion criteria. First, their total population was within the range of 600 to 1,600 typical for rural communities in the region, and second, they had not previously seen significant ICS promotion to ensure low initial penetration of improved biomass cooking technologies. The sample included 35 households per community, randomly sampled from household lists. For budgetary reasons, only 16 to 17 households per community could be included in the personal exposure measurements, among which around half were also selected for the kitchen concentration measurements. We applied stratified random sampling to maintain representativeness in the subsamples selected for these measurements. The stratification variable was an indicator variable for whether the household was above or below median kitchen ventilation as generated using PCA.[6] We invited households' primary cooks above age 15 to participate in the interview; in case this individual was unavailable, a secondary cook was enrolled instead. Only three households attrited due to absence of all household cooks at the time of the second round of interviews and measurements.

The pooled sample used in this paper includes 220 household-year observations with kitchen concentration measurements, and 418 household-year observations with cooks' personal exposure measurements. The samples are different, albeit with a good overlap (n=202, see Annex Table B.1), and use data from a total of 244 households. Note that, due to problems with data storage in the field, we have the percentile pollution data used in our robustness analyses for only a subset of 140 kitchen concentration data points and 344 personal exposure measurements. Dropout analyses using probit estimations show that the data loss is partly correlated with household characteristics, which makes controlling for household characteristics in the robustness analyses particularly important.

4. Summary statistics

4.1. Control variables

Survey participants were on average 32 years old, and spent on average 5.5 hours cooking per day, with 80% using a traditional or basic metal stove at the time of the surveys. There were 1.4 primary cooks among an average of 12 household members; in households with multiple cooks, the cooks typically take turns. Seventy-three percent of study participants identified as the primary cook, while 13% identified as a secondary cook. Households used a stove that was located next to our meter during roughly 90% of all cooking events. The MicroPEMs' built-in accelerometers suggest that cooks wore the device for personal exposure measurement on average during 70% of daytime hours (assuming eight hours of sleep). Ninety-four percent of

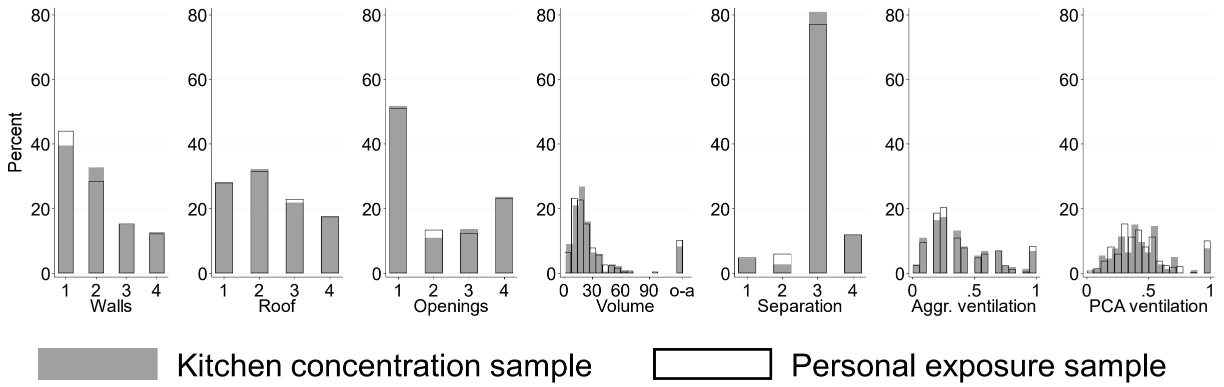
[6] The PCA used seven variables: kitchen volume and kitchen openings, cooking location, the number of primary cooks, a dummy for stove stacking, daily cooking time, and main fuel type. The PCA indicator used for stratification loads most strongly on kitchen location and openings.

participants categorized the day of measurement as a typical day. The kitchen concentration and personal exposure subsamples are very similar in terms of control variable statistics (Annex Table B.2), which is in line with expectation from the stratified randomization of measurements outlined in Section 3.2.

4.2. Ventilation indicators

The different kitchen ventilation categories are well represented across ventilation indicators in our sample (Figure 2). One exception is kitchen separation, with around 80% of households cooking in a detached kitchen. With around 12% of households cooking in open air, open-air cooking in our sample corresponds to what Langbein et al. (2017) find for entire rural Senegal using DHS data, which is lower than in rural areas of other developing countries (see again Langbein et al. 2017). Figure 2 furthermore shows that the two sub-samples with kitchen concentration and personal exposure measurements are similar with regards to their ventilation categorisation. High variability is found in kitchen structures within our two study regions, underscoring the need to consider ventilation heterogeneities.

Figure 2: Distribution of households across ventilation indicators



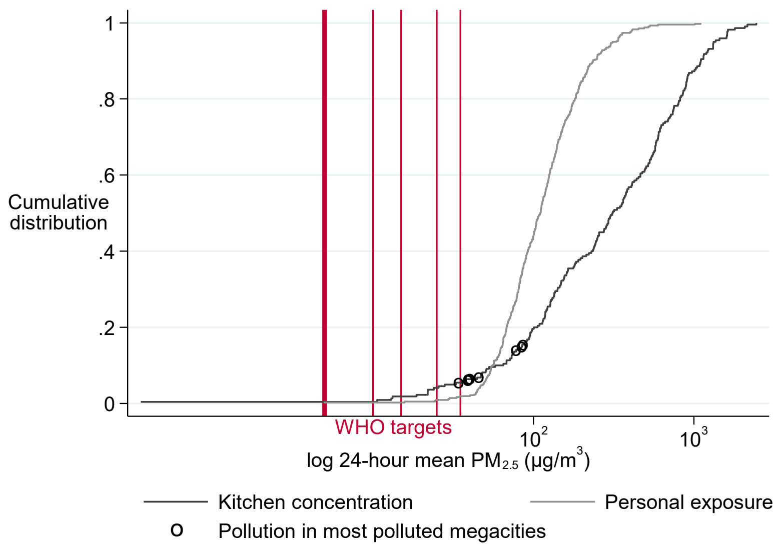
Note: The values for the categorical ventilation variables refer to: 1= No ventilation, 2= Poor ventilation, 3= Substantial ventilation, 4= full ventilation. o-a refers to open air, which corresponds to the binary open-air indicator. The three continuous indicators are all as well transformed to categorical quantile indicators.

Correlations among single ventilation indicators range from *rho*=0.4 to *rho*=0.5, with lower Spearman correlation coefficients of around 0.2 for kitchen volume, which is reassuring since a high correlation would suggest redundant indicators. Given their common variable base, the two composite ventilation indicators show a higher correlation of *rho*=0.8 (see Annex Table B.3). In our case, the first two components identified by PCA, which together form the basis of the *PCA ventilation* indicator, explain 58% and 21% of the variation in the PCA, respectively.

4.3. Kitchen concentration and personal exposures

Figure 3 plots the cumulative distribution of 24-hour air pollution measurements. The first result to note is that kitchen concentration surpasses the standards set by the WHO (2021) by a great deal, as does personal exposure. The five red lines represent the WHO guideline value for mean annual concentration of 5 μg/m³ and four less stringent interim target levels ranging from 10 to 35 μg/m³. The WHO's least demanding interim target 1, with mean annual concentration of 35 μg/m³, is met by only two percent of households for kitchen concentration and four percent for personal exposure when considering our 24-hour measurement results.[7] Figure 3 also illustrates that in at least 80 percent of households kitchen concentration surpasses annual averages of ambient pollution levels measured in the world's most polluted mega-cities (Krzyzanowski et al. 2014; IQAir 2022). Second, kitchen concentration is much higher than exposure, namely 312 versus 110 μg/m³ at the median. Third, both kitchen concentration and exposure vary greatly across households.

Figure 3: Cumulative distribution of 24-hour mean $PM_{2.5}$ kitchen concentration and personal exposure



Note: Red lines indicate the WHO guideline value and interim targets 4, 3, 2, and 1. Dots represent annual average $PM_{2.5}$ air quality values for the eight most polluted mega-cities with more than 10 million inhabitants, from Lahore, Pakistan to Beijing, China (IQAir 2022; UN 2022).

The non-linear concentration-response functions discussed in Section 2 suggest that daily peak pollution within a household also plays an important role in health outcomes. Table 3 shows mean pollution and pollution levels at two extreme points in the 24-hour pollution distribution, the 95th and 25th percentiles. The 95th percentile value reveals extremely elevated peak pollution

[7] This interim target 1 is associated with a mortality that the WHO projects to be 24% higher than under the WHO guideline value (WHO 2021).

that corresponds to the highest 5% of levels recorded during the day, i.e. the worst 1.2 hours. The 25th percentile, in contrast, can be interpreted as the background pollution level experienced during times without any cooking, given that cooking hours are limited during the day. Even this value surpasses the WHO interim target values in our setting with mostly detached kitchens, suggesting that secondary or ambient pollution sources contaminate the indoor and outdoor environment. Note that none of the survey areas were in heavy traffic areas or located close to industrial point sources of pollution, but that they do experience regular storms that can carry Saharan dust, especially in the dry season (Heft-Neal et al. 2020). Moreover, the burning of waste and agricultural residues is common in these communities, adding to the cooking smoke from neighbours that regularly permeates the air.

Table 3: Summary statistics of kitchen concentration and personal exposure

	Kitchen concentration		Personal exposure	
	mean (sd)	median	mean (sd)	median
$PM_{2.5}$: mean	474 (455)	312	136 (107)	110
$PM_{2.5}$: 95 pctl.	1839 (2204)	780	379 (556)	234
$PM_{2.5}$: 25 pctl.	30 (21)	25	33 (19)	29

Note: all values in µg/m³. pctl=percentile. The percentile values state that pollution is below that value during 95 (25) percent of the day or 22.8 (6) hours. See Annex Figure B.1 for various percentile averages.

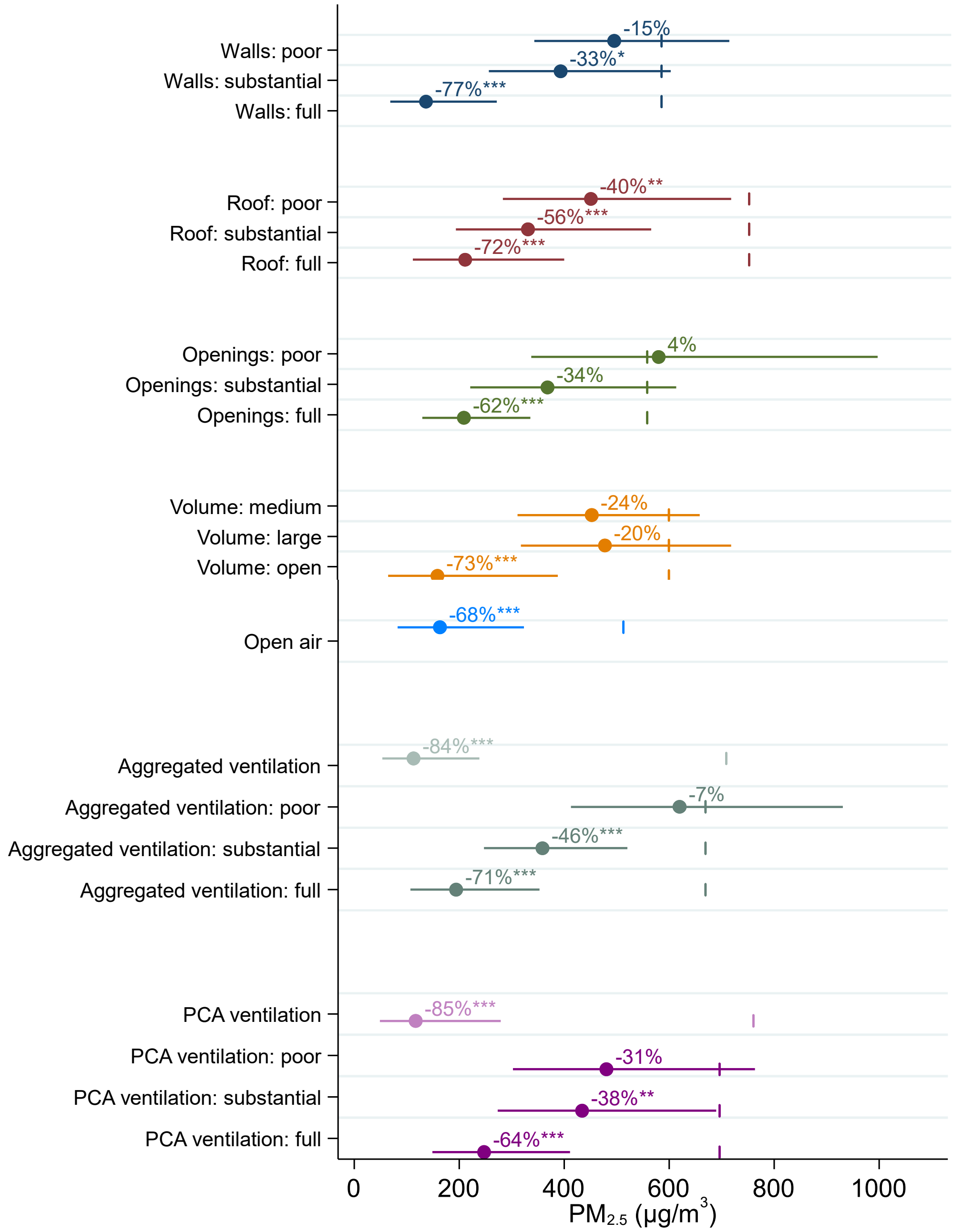
5. Relationship between ventilation and air pollution measures

5.1. Ventilation and kitchen concentration

Main results

Figure 4 graphically displays the coefficients for all single and composite ventilation indicators, both absolute and percentage changes, when switching from *unventilated* kitchens as the reference case to *poorly*, *substantially*, and *fully* ventilated kitchens. The coefficients are based on the model specification in equation (1). Across the different indicators, we find considerably lower kitchen concentrations in *fully* and *substantial*ly ventilated kitchens than in *unventilated* ones. Note that the *no ventilation* reference categories, which are presented by dashed vertical lines in the figure, are not the same across indicators. Percentage changes therefore cannot necessarily be directly compared across indicators and need to be considered in combination with the respective absolute level of the reference category.

Figure 4: Associations between kitchen concentration and ventilation indicators



*Note: The coefficient plot displays estimates for each ventilation indicator in the specifications where we regress the log of 24-hour average $PM_{2.5}$ kitchen concentration on the full set of control variables. The reference category, which is presented by dashed vertical lines, is the lowest category according to each indicator, i.e. most unventilated, closed, or smallest kitchen. Horizontal lines indicate the 95% confidence intervals. *** p<0.01, ** p<0.05, * p<0.1; N=211 in all estimations.*

Switching from *no* to *fully* ventilated kitchens is associated with a reduction of kitchen concentration by between 62 and 77%, depending on the indicator. This corresponds to absolute reductions in kitchen concentrations from 560 and 750 µg/m³ to between 140 and 250 µg/m³. The coefficient of switching from *no* to *poor* ventilation varies between +4% and -40%, and that of switching to *substantial* ventilation between -20% and -56%. These relationships are qualitatively robust across specifications. R-squared values of the OLS estimations suggest that at least 42% of variance across indicators can be explained by the full set of controls. The binary *open air* indicator as well captures important variation in ventilation and the continuously defined composite indicators for *aggregated ventilation* and *PCA ventilation* suggest a reduction of around 85% when switching from the extremes of *no* to *fully* ventilated kitchens. Regarding the categorical versions of the two composite indicators, the coefficients for the individual categories of *aggregated ventilation* are more differentiated than those for *PCA ventilation*. *PCA ventilation* exhibits the more precise estimates.

Further insight can be obtained from the covariate coefficients in the full specifications that underlie Figure 4 (Annex Table C.1 and Table C.2). Pollution levels are consistently and significantly lower when the dirtiest stove close to the meter is an LPG stove, when study participants are illiterate, cook for fewer people, or report that they smell neighbours' smoke relatively infrequently (less than weekly).[8] The latter may indicate that diffusion of secondary pollution into households' kitchens is higher among people with higher kitchen concentration. Somewhat unexpectedly, the improved and advanced biomass stoves assigned randomly in the related impact evaluation experiment did not significantly affect air pollution.

Sensitivity analyses

Figure 4 presented results separately for each ventilation indicator. We also estimated several models with multiple indicators, focusing especially on combinations that included kitchen volume as a continuous variable. Controlling for volume does add explanatory power to the models that include other ventilation indicators and some of the association between ventilation and pollution migrates to volume, but the association itself is not significant (Annex Table C.1 and Table C.2).[9] Moreover, one would expect that the role of volume for kitchen concentration increases as kitchens become less ventilated. Interacting volume and ventilation is suggestive of such a relationship, but the coefficients are imprecisely estimated. Overall, we tentatively conclude that increased kitchen volume is negatively related to kitchen concentration, and that this variable may be more important in less ventilated kitchens.

[8] Another significant difference is observed between the two measurement devices: the MicroPEM measured systematically higher concentrations than the IAP meters. This may be explained by the fact that the gravimetric data collection method captures smaller particles than the light-scattering nepelometer in the IAP meters and is considered a more precise measurement approach. In any case, we expect the difference to be in levels and hence not to bias our estimates.

[9] Alternatively, Annex Table C.3 excludes open-air cooking households and looks at the association between continuous volume and air pollution. The volume coefficient is marginally significant only in some specifications.

Our main analysis examined average 24-hour pollution. This measure masks considerable variation during the day as pollution levels drop at night, and peak episodes coincide with periods of cooking. We therefore also regress $PM_{2.5}$ percentiles on the composite indicators, and find that ventilation is significantly associated with periods of high pollution, but not with medium and low pollution levels (Figure C.1 in Annex). This is in line with expectations and increases confidence in our results.

In addition, we investigate the role of unobservables using the Oster method. Specifically, we compute Oster's delta for the three ventilation indicators to which it can be applied: the continuous *aggregated* and *PCA ventilation* indicators and the *open air* indicator. We find the delta to be extremely high for all indicators (Annex Table C.1 and Table C.2). To make the ventilation coefficient equal to zero, unobservables in our model would need to be at least 7 times more important, respectively, than what the other observables in our model explain. This seems unlikely, and further increases confidence in the results.

Next, to test whether the observed association is driven by households with *open air* kitchens, we estimate the model on a reduced sample that excludes these households, who comprise eight percent of the kitchen concentration sub-sample. *Aggregated* and *PCA ventilation* indicators decrease slightly in size, but remain large and significant, suggesting that the identified coefficient is not driven exclusively by households cooking outdoors (Annex Table C.4).

Finally, we did not control for the health of the primary cook in our main analysis, as health status is likely endogenous to air pollution in kitchens. In a separate estimation, we include a subjective indicator (self-reports of suffering from red or irritated eyes) and an objective indicator (normal blood pressure), to see whether our results hold if we include these potentially endogenous variables. Coefficient sizes of some ventilation indicators increase slightly but are otherwise robust to these changes. Self-reported experience of red or irritated eyes is significantly related to kitchen concentration, likely reflecting reverse causality (see Annex Table C.5).

5.2. Ventilation and cooks' personal exposures

In Figure 5, we observe no clear relationship between kitchen ventilation and cooks' personal exposure. Overall, coefficient sizes are small, significance is marginal at best, and statistically significant coefficients are not robust to different specifications and indicators. We further find that several other factors are significantly associated with personal exposures (Annex Table D.1

and Table D.2), most prominently whether those who wore the MicroPEMs were the households' primary cooks.

Figure 5: Associations between personal exposure and ventilation indicators

*Note: The coefficient plot displays estimates for each ventilation indicator in the specifications where we regress the log of 24-hour average personal exposure to $PM_{2.5}$ on the full set of control variables. The reference category, which is presented by dashed vertical lines, is the lowest category according to each indicator, i.e. most unventilated, closed, or smallest kitchen. Horizontal lines indicate the 95% confidence interval. We do not show estimates for kitchen separation given that very few households cook inside or in a space attached to the main building (see Figure 2). *** p<0.01, ** p<0.05, * p<0.1; N=414 in all estimations.*

Despite the much larger sample size, our multivariate analyses of cooks' exposure explain a much lower share of its variance of only around 26% than the analyses of kitchen concentration using essentially the same model specifications. Unobserved context-specific factors thus likely play a larger role for personal exposures. While these factors also include the pollution that cooks face during non-cooking activities and exposures during periods when the MicroPEM was not worn, behaviour likely drives personal exposure more strongly, and also more than kitchen concentration. Selective smoke avoidance could, for example, occur in that avoidance behaviour delivers benefits in less ventilated places, cancelling out the effect of poorer ventilation on exposures. Cooks may also have been sensitized to engage in smoke avoidance by our interviews and the very act of wearing devices.

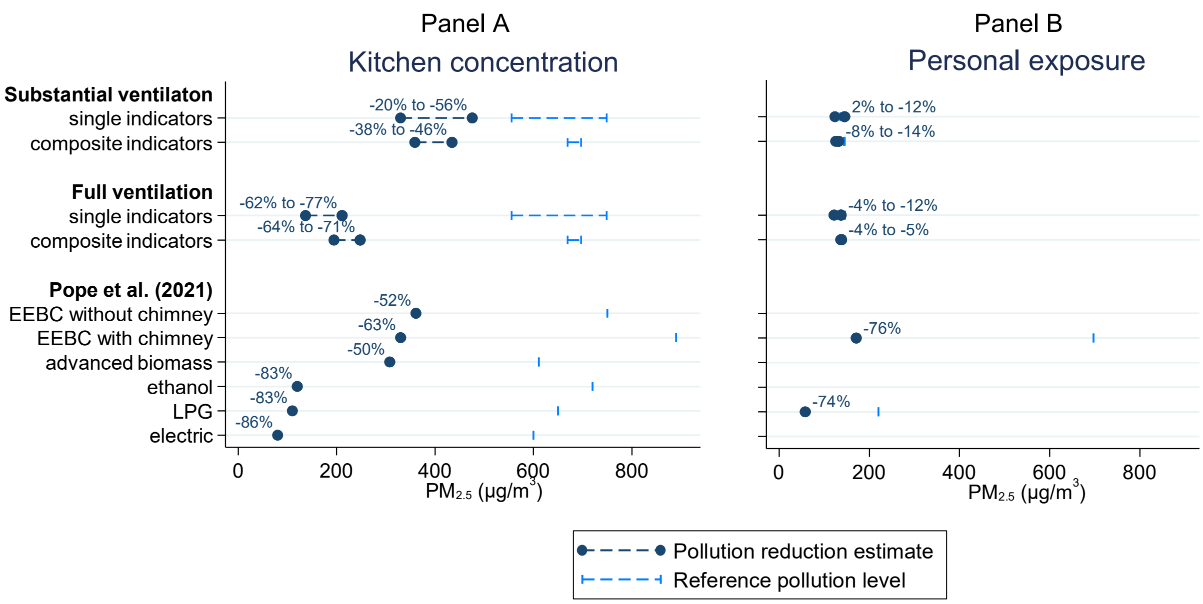
We observe such behavioural responses only imperfectly and thus cannot rigorously test for them, but three additional pieces of evidence suggest that that they may be at play. First, and consistent with selective responses, median personal-to-kitchen pollution ratios increase with kitchen ventilation: households with increasingly open kitchens, as measured from poor to full for *aggregated ventilation*, have median ratios of 0.25, 0.24, 0.38, and 0.62, respectively. Second, we find mixed evidence when assessing the relationship between two proxies for behavioural smoke avoidance and other relevant variables. In particular, the relationship between better ventilated kitchens and self-reports of avoidance behaviour as well as the share of cooking time spent off the stove is mostly insignificant, but rather negative when including the full set of control variables (Annex Table D.3). Third, Figure 5 suggests that some of our ventilation indicators, most notably wall ventilation, are non-linearly related to personal exposure, which either reflects large confidence intervals, or selective smoke avoidance behaviour. Similarly, cooks may respond differently depending on their baseline health. Introducing health proxies to the estimation, does not confirm this hypothesis, however (Annex Table D.4). Lastly, we check whether controlling for kitchen concentration affects personal exposure results (Annex Table D.1 and Table D.2). We see a positive kitchen concentration coefficient that is robust across indicators, but that the coefficients of the ventilation indicators are neither strongly nor systematically affected by addition of this control.

5.3. Contextualization of results

To put the pollution reduction potentials found in this study in perspective, we first compare kitchen concentration reduction estimates to those of stove and fuel interventions as determined in a recent meta-analysis (Pope et al. 2021). In that analysis of evidence from 39 studies on EEBCs, EEBCs without and with chimneys lowered $PM_{2.5}$ kitchen concentration compared to traditional stoves by 52% and 63%, respectively. The same meta-analysis used 18 studies to estimate a decrease in $PM_{2.5}$ kitchen concentration of 83-86% from the adoption of clean fuel stoves (LPG, electricity and ethanol). This finding is in line with previous research that shows that fuel and stove stacking is often prevalent among poor households (Ruiz-Mercado and Masera 2015). Panel A of Figure 6 provides a graphical comparison of those results and our results for *substantial* and *full* ventilation across the different indicators. Both relative and absolute changes again have to be considered to make meaningful comparisons.

Effect sizes for EEBCs correspond roughly to the coefficient estimates we find in switching from *no* kitchen ventilation to *substantial* ventilation, and the effect sizes for clean fuels are only slightly higher than what we find for *fully* ventilated kitchens. One could also interpret our coefficient sizes for *substantial* and *full* ventilation as equivalent to doing 20% to 56% and 62% to 77% of cooking on a fully *clean* stove with zero emissions, keeping everything else constant. Other research suggests that stove stacking is indeed prevalent, with 20% to 80% of cooking being done on improved stoves among households who own them (Jeuland et al. 2018).

Figure 6: Reduction potentials compared to those from stove and fuel interventions



Note: Advanced biomass stoves refer to stoves fueled with biomass and with fans to aid combustion or to stoves that use gasification.

Panel B of Figure 6 makes obvious that there is a considerable discrepancy between our estimates and those of the – relatively fewer – studies that look at personal exposure. The figure suggests that the difference is partly driven by the reference pollution level. For example, the reference pollution level for the studies on EEBC with chimneys covered by Pope et al. (2021), which all come from Latin America and South Asia, is five times higher than the reference pollution levels of *no* ventilation households in our sample. At the same time, half the studies find reference pollution levels similar to those in our study.

The results on kitchen concentration and personal exposure furthermore imply a low correlation between the two outcomes. One measure to express this relationship is the median ratio between the two, that is, the personal-to-kitchen $PM_{2.5}$ pollution ratio. We find a ratio of 0.37 in our sub-sample of households that participated in both measurements (*n*=202). This is much lower than the spatially uniform value of 0.74 applied for women by the leading epidemiological research program on global health risks, the Global Burden of Disease Study (Shupler et al. 2020). The multi-country study by Shupler et al. (2020) helps to contextualize this discrepancy: these authors find similar levels with median ratios between 0.33 to 0.44 in countries with similar cooking conditions to those in Senegal, namely Bangladesh, Pakistan, and Zimbabwe. Countries studied by Shupler et al. (2020) with clearly different shares of clean fuel and/ or chimney woodfuel stove usage – China, India, Chile, and Columbia – have considerably higher ratios, ranging between 0.88 and 1.33. The same picture emerges when looking at correlation coefficient between kitchen concentration and personal exposure, which we find to amount to 0.26 (Pearson's *r*), or alternatively 0.34 (Spearman's *rho*).[10] In the countries studied by Shupler et al. (2020), Spearman correlation coefficients range between 0.15 and 0.36 for those countries with similar cooking conditions and between 0.31 and 0.79 for countries with different shares of clean fuel and/ or chimney woodfuel stove usage.[11]

6. Conclusion and policy implication

This paper examined the potential of better ventilated kitchens to complement current clean cooking programs by comparing kitchen concentration levels and exposure levels in kitchens with different ventilation levels. We conducted a non-experimental and hence correlative

[10] The ratio is only somewhat higher for peak pollution, while the correlation tends to be lower (for example, the values are 0.48 and 0.16/ 0.24 at the 90th percentile, respectively, reflecting the 2.4 most polluted hours).

[11] This is also consistent with data from Pope et al. (2021) who find higher ratios for households with clean stoves (around 0.7-0.8) than with traditional stoves (around 0.5). Higher ventilation through chimneys installed in the kitchens would likely show lower personal-to-kitchen ratios, as also evidenced in a study from Sri Lanka (Chartier et al. 2017). For an eighth country studied by Shupler et al. (2020), Tanzania, the authors provide no values due to low sample size. We further screened the *Global database of household air pollution measurements* (WHO 2018) to retrieve additional values for comparison. However, merely four studies report either a ratio or correlation for PM, which are all hardly comparable, as one studies children (and finds a lower correlation coefficient) and three are from samples with chimney stoves (and find somewhat higher ratios or correlations ranging between 0.4 and 0.6).

analysis, but using state-of-the-art $PM_{2.5}$ measurements combined with in-depth survey data from a household sample that is large compared to the few previous field studies on household air pollution. This setup helps to minimize measurement error and to control for a large number of potential confounders. In terms of transferability of results, our sample is plausibly representative of rural and poor households in arid and dusty regions of West Africa. We, first, find kitchen concentration of $PM_{2.5}$ to greatly exceed the WHO guideline value. This holds true even beyond cooking times, indicating that ambient air pollution is already above WHO standards. Our results show that kitchen concentration has a large, highly significant, and robust inverse relationship with kitchen ventilation. No similar relationship is found between kitchen ventilation and personal exposure. This provides tentative evidence that cooking behaviour is important for the relationship between pollution levels and exposures: cooks seem to evade the smoke, for example by leaving the kitchen during peak emission phases. In combination, our findings suggest that the crucial question of people's exposure to harmful smoke is co-determined by cooking fuels, stoves, cooking behaviour and kitchen ventilation, echoing arguments that have already been made long ago by Smith et al. (1983). The narrow focus in the policy debate on cooking fuels and stoves seems partly misleading, which leads us to draw a number of conclusions on pollution and ventilation measurement and potential policy responses to household air pollution.

Regarding measurement, our study provides a blueprint on how to conceptualize and operationalize ventilation as part of the cooking environment, both using one- and multi-dimensional indicators for ventilation. More can be done to systematize aspects of ventilation and cooking behaviour, and to understand the influence of ambient air pollution, which is well above the WHO guideline value in our setting. Some of the discrepancies between our findings and those of previous studies may be driven by different procedures, protocols, and measurement devices, which calls for more standardized approaches. At the same time, the variation across studies also hints at the context dependence of cooking-related emissions. In line with studies from similar contexts, we find much lower personal-to-kitchen pollution ratios than the global default applied by the Global Burden of Disease Study to estimate the burden of disease from traditional cooking. We therefore recommend replacing this global default with a differentiated set of values that account, at a minimum, for fuels and the cleanliness of the stoves. In addition, we caution against overinterpreting these values and, likewise, technology-based cookstove classifications, since such factors and classifications miss to reflect the important role of ventilation and cooking behaviour.

A more holistic view of cooking environments that explicitly considers kitchen ventilation could also improve intervention planning and policy-making. This begins with the design of cookstove interventions, where currently a number of EEBC models are being promoted that are bricked into the kitchen and, hence, non-portable and which may push households to cook in spaces with lower ventilation (see Hanna et al. 2016 and Grimm and Peters 2012). Ventilation can also be integrated into transitional interventions that complement clean cooking access policies, for example by raising awareness about the benefits of better ventilation. Some ventilation improvements are very cheap and may be cost-effective if adapted to the local context, such as the regular opening of doors and windows, or simple housing modifications to add openings. Furthermore, low-cost EEBC combined with, or targeted to, households with highly ventilated kitchens may be particularly effective as a transitional solution. Such a strategy may also be more cost-effective than clean technology promotion, especially in remote rural areas where the supply chain for clean options is interrupted (for similar claims see Langbein et al. 2017 and Teune et al. 2020).

The absence of evidence on reductions in personal exposure from improved ventilation, however, cautions against asserting that ventilation alone will trigger reductions in personal exposure that are sufficient to mitigate the negative health impacts of household air pollution. Only exclusive use of clean stoves has the potential to fully eliminate this pollution. In light of substantial challenges with providing universal access to clean stoves, we pragmatically recommend that kitchen ventilation conditions be considered more systematically by researchers and policy-makers seeking to understand and overcome the myriad burdens of traditional cooking.

References

Albalak, R., Frisancho, A. R., & Keeler, G. J. (1999). Domestic biomass fuel combustion and chronic bronchitis in two rural Bolivian villages. *Thorax*, *54*(11), 1004-1008.

Apte, J. S., Marshall, J. D., Cohen, A. J., & Brauer, M. (2015). Addressing global mortality from ambient $PM_{2.5}$. *Environmental Science & Technology*, *49*(13), 8057-8066.

Bailis, R., Cowan, A., Berrueta, V., & Masera, O. (2009). Arresting the killer in the kitchen: the promises and pitfalls of commercializing improved cookstoves. *World Development*, *37*(10), 1694-1705.

Bailis, R., Drigo, R., Ghilardi, A., & Masera, O. (2015). The carbon footprint of traditional woodfuels. *Nature Climate Change*, *5*(3), 266-272.

Bensch, G., Grimm, M., & Peters, J. (2015). Why do households forego high returns from technology adoption? Evidence from improved cooking stoves in Burkina Faso. *Journal of Economic Behavior & Organization*, *116*, 187-205.

Bensch, G., Jeuland, M., & Peters, J. (2021*a*). Efficient biomass cooking in Africa for climate change mitigation and development. *One Earth, 4*(6), 879-890.

Bensch, G., Kluve, J., & Stöterau, J. (2021*b*). The market-based dissemination of energy-access technologies as a business model for rural entrepreneurs: Evidence from Kenya. *Resource and Energy Economics*, *66*, 101248.

Bensch, G., & Peters, J. (2020). One-Off Subsidies and Long-Run Adoption—Experimental Evidence on Improved Cooking Stoves in Senegal. *American Journal of Agricultural Economics*, *102*(1), 72-90.

Bensch, G., & Peters, J. (2015). The intensive margin of technology adoption–Experimental evidence on improved cooking stoves in rural Senegal. *Journal of Health Economics*, *42*, 44-63.

Boadi, K. O., & Kuitunen, M. (2006). Factors affecting the choice of cooking fuel, cooking place and respiratory health in the Accra metropolitan area, Ghana. *Journal of Biosocial Science*, *38*(3), 403.

Buchner, H., & Rehfuess, E. A. (2015). Cooking and season as risk factors for acute lower respiratory infections in African children: a cross-sectional multi-country analysis. *PloS One*, *10*(6), e0128933.

Burnett, R. T., Pope III, C. A., Ezzati, M., Olives, C., Lim, S. S., Mehta, S., ... & Cohen, A. (2014). An integrated risk function for estimating the global burden of disease attributable to ambient fine particulate matter exposure. *Environmental Health Perspectives*, *122*(4), 397-403.

Chartier, R., Phillips, M., Mosquin, P., Elledge, M., Bronstein, K., Nandasena, S., ... & Rodes, C. (2017). A comparative study of human exposures to household air pollution from commonly used cookstoves in Sri Lanka. *Indoor Air*, *27*(1), 147-159.

ESMAP, Energy Sector Management Assistance Program (2020). *The State of Access to Modern Energy Cooking Services.* World Bank, Washington DC.

Ezzati, M., & Kammen, D. M. (2002). The health impacts of exposure to indoor air pollution from solid fuels in developing countries: knowledge, gaps, and data needs. *Environmental Health Perspectives*, *110*(11), 1057-1068.

Filmer, D., & Pritchett, L. H. (2001). Estimating wealth effects without expenditure data—or tears: an application to educational enrollments in states of India. *Demography*, *38*(1), 115-132.

Fullerton, D. G., Bruce, N., & Gordon, S. B. (2008). Indoor air pollution from biomass fuel smoke is a major health concern in the developing world. *Transactions of the Royal Society of Tropical Medicine and Hygiene*, *102*(9), 843-851.

GIZ, Deutsche Gesellschaft für Internationale Zusammenarbeit (2017). EnDev's proxy-indicator approach for assessing the quality of a Cooking Energy System. Available at https://endev.info/wp-content/uploads/2020/11/EnDev_Cooking_Energy_System_CES_concept.pdf.

Grimm, M., & Peters, J. (2012). Improved cooking stoves that end up in smoke? *RWI Positionen* 52.

Hanna, R., Duflo, E., & Greenstone, M. (2016). Up in smoke: the influence of household behavior on the long-run impact of improved cooking stoves. *American Economic Journal: Economic Policy*, *8*(1), 80-114.

Heft-Neal, S., Burney, J., Bendavid, E., Voss, K. K., & Burke, M. (2020). Dust pollution from the Sahara and African infant mortality. *Nature Sustainability*, *3*(10), 863-871.

IEA, IRENA, UNSD, World Bank, & WHO (2022). *Tracking SDG 7: The Energy Progress Report*. World Bank, Washington DC.

IQAir (2022). 2021 World Air Quality Report. Region & City PM2.5 Ranking. Available at https://www.iqair.com/world-most-polluted-cities/world-air-quality-report-2021-en.pdf.

Jeuland, M., & Pattanayak, S. K. (2012). Benefits and costs of improved cookstoves: assessing the implications of variability in health, forest and climate impacts. *PloS One*, *7*(2), e30338.

Jeuland, M., Pattanayak, S. K., & Bluffstone, R. (2015). The economics of household air pollution. *Annual Review of Resource Economics*, *7*(1), 81-108.

Jeuland, M., Pattanayak, S. K., Tan Soo, J. S., & Usmani, F. (2020). Preferences and the effectiveness of behavior-change interventions: Evidence from adoption of improved cookstoves in India. *Journal of the Association of Environmental and Resource Economists*, *7*(2), 305-343.

Jeuland, M., Soo, J. S. T., & Shindell, D. (2018). The need for policies to reduce the costs of cleaner cooking in low income settings: Implications from systematic analysis of costs and benefits. *Energy Policy*, 121, 275-285.

Köhlin, G., Sills, E.O., Pattanayak, S.K., & Wilfong, C. (2011). Energy, gender and development: what are the linkages? Where is the evidence? *The World Bank Policy Research Working Paper, 5800*.

Krzyzanowski, M., Apte, J. S., Bonjour, S. P., Brauer, M., Cohen, A. J., & Prüss-Ustun, A. M. (2014). Air pollution in the mega-cities. *Current Environmental Health Reports*, *1*(3), 185-191.

Kulshreshtha, P., & Khare, M. (2011). Indoor exploratory analysis of gaseous pollutants and respirable particulate matter at residential homes of Delhi, India. *Atmospheric Pollution Research*, *2*(3), 337-350.

Langbein J. (2017). Firewood, smoke and respiratory diseases in developing countries—the neglected role of outdoor cooking. *PloS One*, *12*(6), e0178631.

Langbein, J., Peters, J., & Vance, C. (2017). Outdoor cooking prevalence in developing countries and its implication for clean cooking policies. *Environmental Research Letters*, *12*(11), 115008.

Lenz, L., Bensch, G., Eßer, J., & Jeuland, M. (2022). Kitchen ventilation and air pollution from biomass cooking – A systematic review. *Mimeo*.

Levine, D. I., Beltramo, T., Blalock, G., Cotterman, C., & Simons, A. M. (2018). What impedes efficient adoption of products? Evidence from randomized sales offers for fuel-efficient cookstoves in Uganda. *Journal of the European Economic Association*, *16*(6), 1850-1880.

Lewis, J. J., Bhojvaid, V., Brooks, N., Das, I., Jeuland, M., Patange, O., & Pattanayak, S. K. (2015). Piloting improved cookstoves in India. *Journal of Health Communication*, *20*(sup1), 28-42.

Lueker, J., Bardhan, R., Sarkar, A., & Norford, L. (2020). Indoor air quality among Mumbai's resettled populations: Comparing Dharavi slum to nearby rehabilitation sites. *Building and Environment*, *167*, 106419.

Mobarak, A. M., Dwivedi, P., Bailis, R., Hildemann, L., & Miller, G. (2012). Low demand for nontraditional cookstove technologies. *Proceedings of the National Academy of Sciences*, *109*(27), 10815-10820.

Mönkkönen, P., Pai, P., Maynard, A., Lehtinen, K. E., Hämeri, K., Rechkemmer, P., ... & Kulmala, M. (2005). Fine particle number and mass concentration measurements in urban Indian households. *Science of the Total Environment*, *347*(1-3), 131-147.

Muindi, K., Kimani-Murage, E., Egondi, T., Rocklov, J., & Ng, N. (2016). Household air pollution: sources and exposure levels to fine particulate matter in Nairobi slums. *Toxics*, *4*(3), 12.

Nayek, S., & Padhy, P. K. (2017). Daily personal exposure of women cooks to respirable particulate matters during cooking with solid bio-fuels in a rural community of West Bengal, India. *Aerosol and Air Quality Research*, *17*(1), 245-252.

Oster, E. (2019). Unobservable selection and coefficient stability: Theory and evidence. *Journal of Business & Economic Statistics*, *37*(2), 187-204.

Patel, S., Li, J., Pandey, A., Pervez, S., Chakrabarty, R. K., & Biswas, P. (2017). Spatio-temporal measurement of indoor particulate matter concentrations using a wireless network of low-cost sensors in households using solid fuels. *Environmental Research*, *152*, 59-65.

Pattanayak, S. K., Jeuland, M., Lewis, J. J., Usmani, F., Brooks, N., Bhojvaid, V., ... & Ramanathan, V. (2019). Experimental evidence on promotion of electric and improved biomass cookstoves. *Proceedings of the National Academy of Sciences*, *116*(27), 13282-13287.

Peters, J., & Jeuland, M. (2017). Evaluating the effectiveness of household energy interventions in rural Senegal using experimental and quasi-experimental methods. *Registry for International Development for Impact Evaluations (RIDIE)*. Available at: 10.23846/ridie120

Pope III, C. A., & Dockery, D. W. (2006). Health effects of fine particulate air pollution: lines that connect. *Journal of the Air & Waste Management Association*, *56*(6), 709-742.

Pope D., Johnson M., Fleeman N., Jagoe K., Duarte R., Maden M., Ludolph R., Bruce N., Shupler M., Adair-Rohani H., Lewis J. (2021). Are cleaner cooking solutions clean enough? A systematic review and meta-analysis of particulate and carbon monoxide concentrations and exposures. *Environmental Research Letters*, *16*(8), 083002.

Rehfuess, E. A., Tzala, L., Best, N., Briggs, D. J., & Joffe, M. (2009). Solid fuel use and cooking practices as a major risk factor for ALRI mortality among African children. *Journal of Epidemiology & Community Health*, *63*(11), 887-892.

Rose, J., Bensch, G., Munyehirwe, A. and Peters, J. (2022). The forgotten coal: Charcoal demand in sub-Saharan Africa. *World Development Perspectives*, *25*, 100401.

Ruiz-Mercado, I. & Masera, O. (2015). Patterns of stove use in the context of fuel-device stacking: Rationale and implications. *EcoHealth* *12*(1), 42–56.

Shibata, T., Wilson, J. L., Watson, L. M., LeDuc, A., Meng, C., La Ane, R., ... & Maidin, A. (2014). Childhood acute respiratory infections and household environment in an eastern Indonesian urban setting. *International Journal of Environmental Research and Public Health*, *11*(12), 12190-12203.

Shindell, D., Kuylenstierna, J.C., Vignati, E., van Dingenen, R., Amann, M., Klimont, Z., Anenberg, S.C., Muller, N., Janssens-Maenhout, G., & Raes, F. (2012). Simultaneously mitigating near-term climate change and improving human health and food security. *Science, 335*, 183-189.

Shupler, M., Hystad, P., Birch, A., Miller-Lionberg, D., Jeronimo, M., Arku, R. E., ... & Seron, P. (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.

Simon, G. L., Bailis, R., Baumgartner, J., Hyman, J., & Laurent, A. (2014). Current debates and future research needs in the clean cookstove sector. *Energy for Sustainable Development*, *20*, 49-57.

Smith, K. R., Aggarwal, A. L., & Dave, R. M. (1983). Air pollution and rural biomass fuels in developing countries: a pilot village study in India and implications for research and policy. *Atmospheric Environment*, *17*(11), 2343-2362.

Teune, B., Ha, H. T., Salinas, D., McLean, K., & Bailis, R. (2020). Low-cost interventions to reduce emissions and fuel consumption in open wood fires in rural communities. *Energy for Sustainable Development*, *58*, 119-128.

UN, United Nations (2022), World Urbanization Prospects 2018. Available at https://population.un.org/wup/DataQuery/.

WHO, World Health Organization (2021). *WHO global air quality guidelines.* World Health Organization, Geneva.

WHO, World Health Organization (2018). *Global database of household air pollution measurements*. Available at https://www.who.int/data/gho/data/themes/air-pollution/hap-measurement-db.

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

WHO, World Health Organization (2008). *Evaluating household energy and health interventions: A catalogue of methods.* World Health Organization, Geneva.

Zhang, X., Zhang, X., & Chen, X. (2017). Happiness in the air: How does a dirty sky affect mental health and subjective well-being? *Journal of Environmental Economics and Management*, *85*, 81-94.

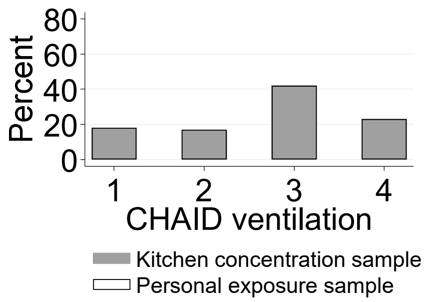
Annex

Annex A: The composite *CHAID ventilation* indicator

We also tested a third composite indicator that differs in two further ways from the two presented in the main text: first, it brings in outcome and control variable information, and, second, the categorization is not based on equal sample splits but is rather informed by the data. It relies on an algorithm that recursively searches through alternative potential splits of the four single ventilation indicators to uncover an optimal "decision tree" that explains the dependent variable. For the dependent variable, we use predicted kitchen concentration, such that the categorization explains the outcome variable conditional on the control variables. We call this indicator *CHAID ventilation* according to the name of the recursive partitioning technique Chi-square automated interaction detection (CHAID) on which it is based, which was originally proposed by Kass (1980).

We set the CHAID algorithm to create a four-category indicator for the data to make it comparable to the other composite indicators. The CHAID algorithm requires to categorize the outcome variable into quantiles (*nq*) and allows to set two minimum requirements, the minimum number of observations allowed in a terminal cluster or "node" (*mn*) and the minimum number of observations across all levels of an optimally merged splitting variable (*ms*). With our sample, CHAID splits the data into four categories when setting these three values to *nq*=5, *mn*=35 and *ms*=50. The resulting four categories of *CHAID ventilation* are depicted in Figure A.1 and include the following categories of the single kitchen ventilation indicators: *category 1 (no ventilation)*: walls{ no }, roof{ no }, openings{ no to substantial }; *category 2 (poor ventilation)*: like category 1, but with roof{ poor to full }; *category 3 (substantial ventilation)*: walls{ poor to full }, openings{ no to substantial }; *category 4 (full ventilation)*: openings{ full }.

Figure A.1: Distribution of households across indicator categories



However, this indicator comes with a number of shortcomings in our study context. First, since we fit the CHAID indicator to kitchen concentration, for which we have data only from a sub-sample, this indicator is available for this sub-sample only. Second, the study sample is anyway rather small for the data-driven nature of the underlying algorithm. This affected our methodology in that we did not split the sample into training data and validation data but used the entire available sample for both training and validation. Furthermore, the algorithm could only find splits in the data when not using the entire set of control variables, but excluding the measurement controls. Third, we also find indications that the indicator suffers from overfitting: in the analysis where we regress $PM_{2.5}$ percentiles on the composite indicators, we find a reverse relationship for poorly ventilated households according to *CHAID ventilation*. (Figure C.1 in Annex). Hence, while *CHAID ventilation* is fitted to the households' mean kitchen concentration, this comes at the cost of it being unfit for disaggregated pollution data.

These shortcomings may be overcome with even larger study samples so that the *CHAID ventilation* indicator may be an option for multi-dimensional ventilation measurement in other settings. However, in light of these shortcomings we abstain from showing results for this indicator in the present study.

Reference

Kass, G. V. (1980). An exploratory technique for investigating large quantities of categorical data. *Applied Statistics*, *29*(2), 119-127.

Annex B: Descriptives

Table B.1: Sample sizes, by measurement and year

	Year 1	Year 2	Total
Kitchen concentration only	2	16	18
Personal exposure only	114	102	216
Kitchen concentration and personal exposure	125	77	202
Total	241	195	436

Note: We have a slightly larger sample from year 1, due to misfunctioning meters in year 2.

Table B.2: Household, cooking, and measurement controls, by measurement sub-sample

	Kitchen concentration mean (sd)	**Personal exposure** mean (sd)
(i) Study participant and household characteristics		
Age of Participant	32.43 (11.40)	32.62 (10.55)
Participant is homemaker	0.59	0.57
Participant is literate	0.17	0.19
HH is primarily Wolof	0.72	0.72
HH size	11.87 (5.90)	12.14 (6.44)
HH has a private tap	0.68	0.66
HH has modern electricity	0.58	0.57
HH's normalized wealth index	-0.04 (1.05)	0.02 (1.07)
Participant has normal blood pressure	0.45	0.41
Participant has red eyes at least sometimes	0.19	0.18
(ii) Cooking characteristics		
Dirtiest stove=traditional stove	0.75	0.64
Dirtiest stove=basic metal stove	0.09	0.09
Dirtiest stove=fuelwood ICS	0.14	0.17
Dirtiest stove=LPG stove	0.03	0.10
Share of cooking on open-fire stove	0.67	0.68
Total cooking duration	332.57 (126.44)	337.55 (122.71)
Person-caterings per day	31.94 (20.16)	34.25 (24.16)
Treatment group: control	0.70	0.71
Treatment group: simple ICS	0.14	0.14
Treatment group: advanced ICS	0.16	0.16
(iii) Cooking behaviour		
Regularly burning agricultural waste at home	0.33	0.34
Participant reports to avoid kitchen smoke	0.84	0.80
Smell neighbours' smoke weekly (secondary exposure to air pollution)	0.35	0.31
(iv) Measurement controls		
Endline	0.42	0.43
Meter is MicroPEM	0.80	
Share of cooking events with meter installed	0.90	
Number of main cooks		1.39 (0.72)
Participant was main cook		0.73
Participant was secondary cook		0.14
Meter daytime wearing (in %)		0.70 (0.19)
Observations	220	418

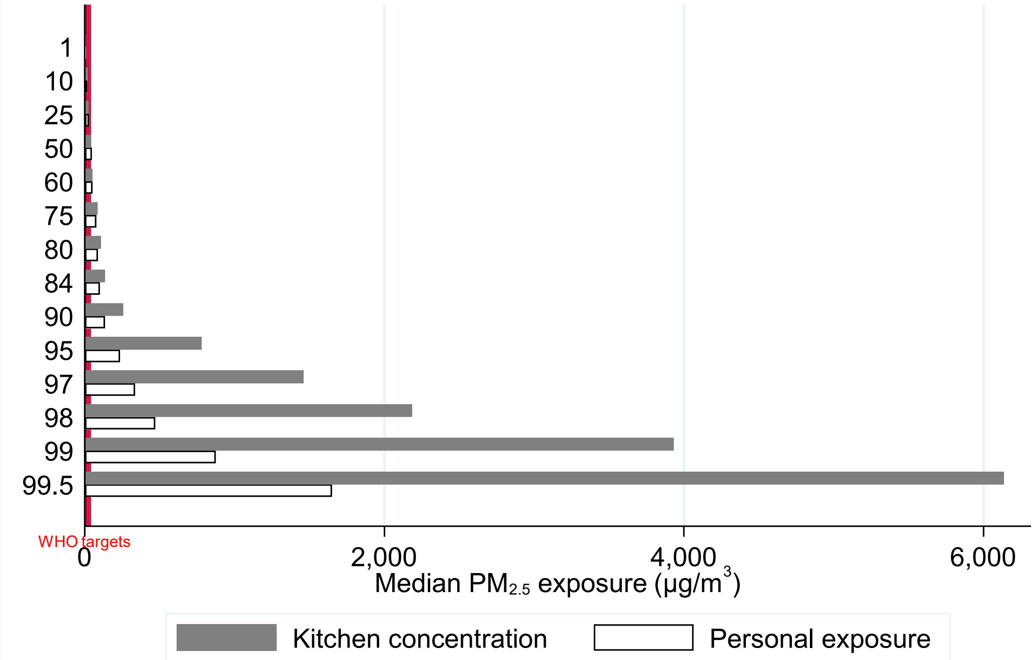
*Note: sd = standard deviation; * p < 0.05, ** p < 0.01, *** p < 0.001. Normal blood pressure is defined as (SYS<120 and DIA<80), as opposed to elevated pressure or hypertension stages, following the definition of the American Heart Association from 2017. The wealth index is generated via Principal Component Analysis using 19 variables, among others land holding, device ownership and livestock ownership. The index is normalized to a mean of zero and a standard deviation of 1. The dirtiest stove refers to stoves observed to be located close (<3m) to the meter for kitchen concentration measurement, and to the self-reported dirtiest stove used for personal exposure measurement.*

Table B.3: Spearman monotone dependence between ventilation indicators

	Kitchen walls	Kitchen roof	Kitchen openings	Kitchen volume	Kitchen separation	Aggregated ventilation	PCA ventilation
Kitchen roof	0.45	1.00					
Kitchen openings	0.44	0.53	1.00				
Kitchen volume	0.24	0.17	0.23	1.00			
Kitchen separation	0.39	0.52	0.42	0.34	1.00		
Aggregated ventilation	0.71	0.76	0.79	0.49	0.49	1.00	
PCA ventilation	0.62	0.55	0.46	0.72	0.45	0.80	1.00
CHAID ventilation	0.75	0.70	0.62	0.21	0.45	0.82	0.61

Note: Light-shaded cells refer to correlations among single ventilation indicators and darker-shaded cells to correlations among composite ventilation indicators. Medium-shaded cells represent correlations between single and composite ventilation indicators. The composite indicator CHAID ventilation is discussed in Annex A.

Figure B.1: Median kitchen concentration and personal exposure ($PM_{2.5}$), by percentiles

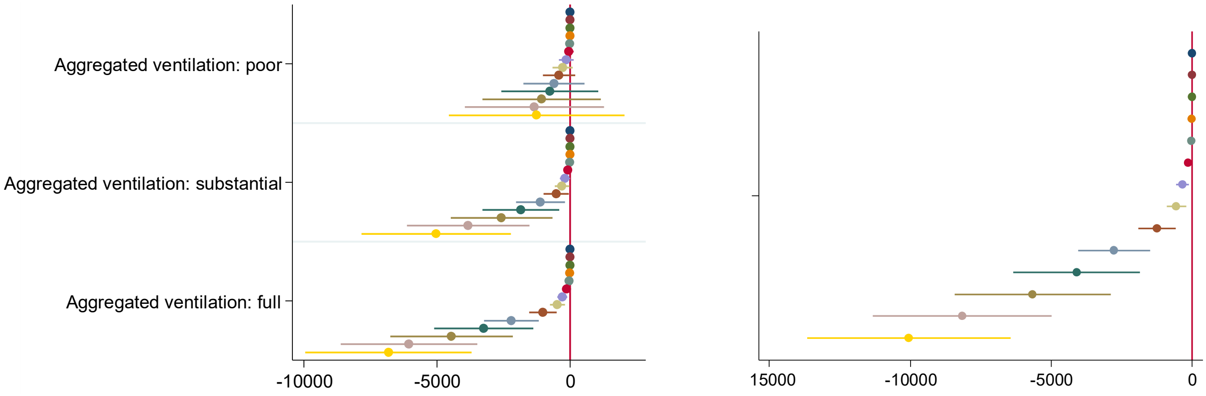


Note: Percentiles on the y-axis, with smaller intervals at higher pollution levels. The 95th percentile value, for example, states that during 95 percent of the day or 22.8 hours, pollution is below that value.

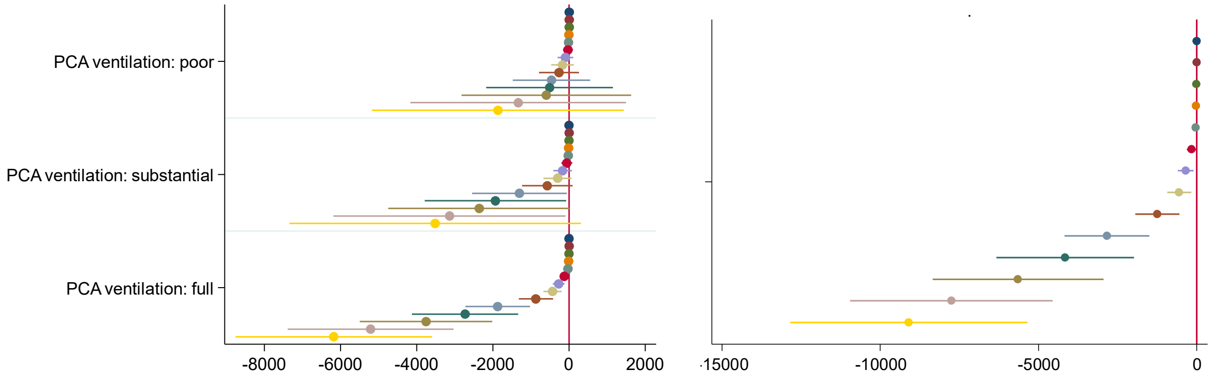
Annex C: Estimation results on kitchen concentration

Figure C.1: Ventilation and percentile absolute kitchen concentration ($PM_{2.5}$)

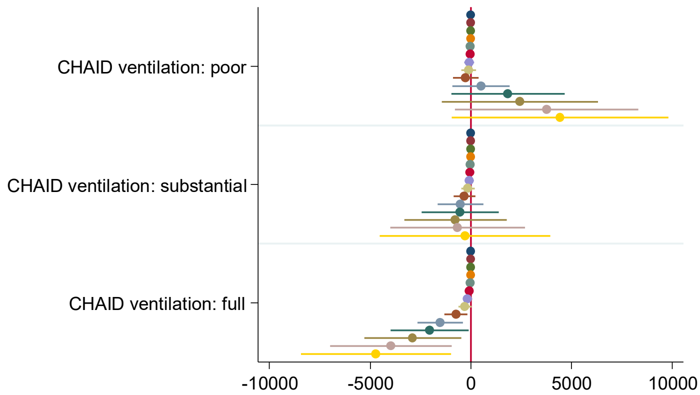
Panel A: Aggregated Ventilation



Panel B: PCA Ventilation



Panel C: CHAID Ventilation



Note: Graphs show coefficients and their 95% confidence intervals retrieved from our default OLS regression with the full set of controls, where each panel presents a different composite ventilation indicator. The percentiles depicted are the 14 percentiles shown in Figure B.1, which range – from top to bottom – from the 1st to 95.5th percentile.

Table C.1: Ventilation and kitchen concentration ($PM_{2.5}$): single ventilation indicators

PANEL A

	coeff *(se)* (1)	*coeff* *(se)* (2)	*coeff* *(se)* (3)	*coeff* *(se)* (4)	*coeff* *(se)* (5)	*coeff* *(se)* (6)	*coeff* *(se)* (7)	*coeff* *(se)* (8)	*coeff* *(se)* (9)	*coeff* *(se)* (10)
Walls: poor	-0.21	-0.22	-0.18	-0.17	-0.17					
	(0.20)	(0.20)	(0.17)	(0.18)	(0.18)					
Walls: substantial	-0.58***	-0.57**	-0.64***	-0.45**	-0.40*					
	(0.21)	(0.22)	(0.22)	(0.21)	(0.22)					
Walls: full	-1.24***	-0.87**	-1.28***	-1.27***	-1.45***					
	(0.35)	(0.37)	(0.34)	(0.33)	(0.35)					
Roof: poor						-0.30	-0.26	-0.35	-0.39	-0.51**
						(0.25)	(0.25)	(0.23)	(0.25)	(0.23)
Roof: substantial						-0.46	-0.45	-0.56**	-0.62**	-0.82***
						(0.30)	(0.30)	(0.26)	(0.28)	(0.27)
Roof: full						-1.10***	-0.78***	-1.19***	-1.06***	-1.27***
						(0.32)	(0.29)	(0.31)	(0.33)	(0.32)
Endline	-0.19	-0.22*	-0.24*	-0.17	-0.17	-0.22	-0.25*	-0.25*	-0.21	0.03
	(0.13)	(0.13)	(0.13)	(0.18)	(0.18)	(0.13)	(0.13)	(0.13)	(0.13)	(0.22)
Volume: medium		-0.19					-0.19			
		(0.21)					(0.22)			
Volume: large		-0.17					-0.16			
		(0.23)					(0.24)			
Volume: open		-0.68					-0.85*			
		(0.53)					(0.46)			
Share of cooking events with measurement			0.22	0.40	0.41			0.25	0.46	0.67*
			(0.26)	(0.26)	(0.34)			(0.28)	(0.30)	(0.35)
MicroPEM			0.88***	0.91***	0.88***			0.89***	0.93***	0.96***
			(0.22)	(0.20)	(0.18)			(0.21)	(0.20)	(0.19)
Participant's age				-0.00	-0.00				0.00	0.00
				(0.01)	(0.01)				(0.01)	(0.01)
Participant is homemaker				0.35*	0.22				0.37*	0.26
				(0.19)	(0.18)				(0.19)	(0.17)
Participant is literate				0.47**	0.47**				0.54**	0.53***
				(0.22)	(0.18)				(0.21)	(0.17)
HH is primarily Wolof (d)				0.07	0.09				0.04	0.03
				(0.23)	(0.22)				(0.22)	(0.21)
HH size (#)				0.04*	0.03				0.04**	0.03
				(0.02)	(0.02)				(0.02)	(0.02)
HH has a private tap (d)				0.27	0.35*				0.16	0.22
				(0.19)	(0.18)				(0.18)	(0.17)
HH has modern electricity (d)				0.03	-0.03				0.06	-0.02
				(0.31)	(0.31)				(0.31)	(0.31)
HH's normalized wealth index				0.06	0.10				0.01	0.06
				(0.12)	(0.11)				(0.13)	(0.12)
Basic metal stove					0.48					0.27
					(0.41)					(0.46)
Improved woodfuel stove					-0.08					-0.06
					(0.31)					(0.33)
LPG stove					-1.20***					-1.49***
					(0.45)					(0.51)
Share of cooking on OFS					0.25					0.19
					(0.31)					(0.30)
Total cooking duration					-0.00					-0.00**
					(0.00)					(0.00)
Simple treatment stove					0.26					0.13
					(0.33)					(0.30)
Advanced treatment stove					0.15					0.09
					(0.28)					(0.27)
Person-caterings per day					0.01**					0.01***
					(0.00)					(0.00)
Burn agricultural waste at home (d)					-0.26*					-0.18
					(0.15)					(0.14)
Participant avoids kitchen smoke					0.09					-0.05
					(0.23)					(0.24)
Smell neighbours' smoke weekly (d)					0.45***					0.48***
					(0.16)					(0.16)
Constant	5.79***	5.88***	4.95***	3.55***	3.35***	5.86***	5.96***	5.04***	3.49***	3.44***
	(0.27)	(0.28)	(0.42)	(0.64)	(0.70)	(0.35)	(0.37)	(0.43)	(0.57)	(0.65)
Community and year	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Observations	220	220	219	212	211	220	220	219	212	211
Mean(Y) reference cat.	582.7	582.7	582.7	586.9	586.9	637.8	637.8	638.3	641.7	641.7
R-squared	0.21	0.22	0.29	0.37	0.46	0.19	0.21	0.28	0.35	0.44

PANEL B

	coeff (se) (1)	coeff (se) (2)	coeff (se) (3)	coeff (se) (4)	coeff (se) (5)	coeff (se) (6)	coeff (se) (7)	coeff (se) (8)	coeff (se) (9)
Openings: poor	0.50**	0.52**	0.41*	0.12	0.04				
	(0.23)	(0.24)	(0.23)	(0.26)	(0.27)				
Openings: substantial	-0.18	-0.15	-0.31	-0.36	-0.41				
	(0.27)	(0.27)	(0.28)	(0.25)	(0.26)				
Openings: full	-0.93***	-0.72***	-1.02***	-0.94***	-0.98***				
	(0.25)	(0.21)	(0.24)	(0.24)	(0.24)				
Volume: medium		-0.20				-0.23	-0.23	-0.38*	-0.28
		(0.22)				(0.22)	(0.20)	(0.20)	(0.19)
Volume: large		-0.13				-0.20	-0.10	-0.24	-0.23
		(0.23)				(0.23)	(0.22)	(0.21)	(0.21)
Volume: open		-0.73				-1.29***	-1.29***	-1.23***	-1.32***
		(0.44)				(0.47)	(0.47)	(0.46)	(0.45)
Endline	-0.12	-0.16	-0.15	-0.14	0.05	-0.27**	-0.31**	-0.26*	-0.11
	(0.14)	(0.14)	(0.14)	(0.15)	(0.23)	(0.13)	(0.13)	(0.14)	(0.23)
Share of cooking events with measurement			0.28	0.45	0.62*		0.16	0.43	0.47
			(0.27)	(0.29)	(0.34)		(0.27)	(0.30)	(0.37)
MicroPEM			0.88***	0.92***	0.93***		0.86***	0.90***	0.88***
			(0.21)	(0.20)	(0.19)		(0.22)	(0.20)	(0.18)
Participant's age				0.00	0.00			0.00	0.00
				(0.01)	(0.01)			(0.01)	(0.01)
Participant is homemaker				0.36**	0.26			0.35*	0.22
				(0.18)	(0.17)			(0.18)	(0.17)
Participant is literate				0.51**	0.51***			0.61***	0.62***
				(0.21)	(0.18)			(0.22)	(0.18)
HH is primarily Wolof (d)				0.19	0.20			0.14	0.12
				(0.21)	(0.21)			(0.24)	(0.23)
HH size (#)				0.04*	0.02			0.04*	0.02
				(0.02)	(0.03)			(0.02)	(0.03)
HH has a private tap (d)				0.14	0.20			0.22	0.31
				(0.17)	(0.17)			(0.19)	(0.19)
HH has modern electricity (d)				0.08	0.01			-0.03	-0.09
				(0.31)	(0.32)			(0.33)	(0.33)
HH's normalized wealth index				0.06	0.13			0.09	0.15
				(0.12)	(0.11)			(0.13)	(0.12)
Basic metal stove					0.26				0.48
					(0.40)				(0.43)
Improved woodfuel stove					-0.14				0.07
					(0.31)				(0.34)
LPG stove					-1.44***				-1.21**
					(0.47)				(0.47)
Share of cooking on OFS					0.17				0.30
					(0.30)				(0.33)
Total cooking duration					-0.00				-0.00
					(0.00)				(0.00)
Simple treatment stove					0.13				0.20
					(0.31)				(0.34)
Advanced treatment stove					0.08				0.16
					(0.27)				(0.28)
Person-caterings per day					0.01*				0.01**
					(0.00)				(0.00)
Burn agricultural waste at home (d)					-0.16				-0.19
					(0.14)				(0.14)
Participant avoids kitchen smoke					-0.02				0.07
					(0.23)				(0.23)
Smell neighbours' smoke weekly (d)					0.39**				0.46***
					(0.16)				(0.16)
Constant	5.77***	5.84***	4.93***	3.56***	3.41***	5.54***	4.74***	3.28***	2.98***
	(0.37)	(0.35)	(0.48)	(0.64)	(0.69)	(0.27)	(0.41)	(0.59)	(0.68)
Community and year	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Observations	220	220	219	212	211	220	219	212	211
Mean(Y) reference cat.	543.2	543.2	542.7	543.2	543.2	507.2	507.2	515.2	515.2
R-squared	0.23	0.25	0.31	0.37	0.44	0.18	0.26	0.34	0.42

PANEL C

	coeff (se) (1)	coeff (se) (2)	coeff (se) (3)	coeff (se) (4)	coeff (se) (5)
Open air	-0.99***	-0.58*	-1.03***	-1.03***	-1.14***
	(0.33)	(0.33)	(0.33)	(0.33)	(0.34)
Volume: medium		-0.20			
		(0.22)			
Volume: large		-0.19			
		(0.23)			
Volume: open		-0.77			
		(0.53)			
Endline	-0.20	-0.24*	-0.24*	-0.21	-0.12
	(0.14)	(0.13)	(0.14)	(0.14)	(0.21)
Share of cooking events with measurement			0.14	0.36	0.43
			(0.27)	(0.28)	(0.35)
MicroPEM			0.86***	0.89***	0.88***
			(0.22)	(0.20)	(0.19)
Participant's age				-0.00	-0.00
				(0.01)	(0.01)
Participant is homemaker				0.37**	0.24
				(0.19)	(0.17)
Participant is literate				0.56**	0.56***
				(0.23)	(0.20)
HH is primarily Wolof (d)				0.11	0.12
				(0.23)	(0.22)
HH size (#)				0.04	0.02
				(0.02)	(0.02)
HH has a private tap (d)				0.29	0.36*
				(0.20)	(0.19)
HH has modern electricity (d)				-0.02	-0.06
				(0.33)	(0.32)
HH's normalized wealth index				0.09	0.14
				(0.12)	(0.11)
Basic metal stove					0.50
					(0.40)
Improved woodfuel stove					-0.02
					(0.32)
LPG stove					-1.13**
					(0.48)
Share of cooking on OFS					0.25
					(0.31)
Total cooking duration					-0.00
					(0.00)
Simple treatment stove					0.34
					(0.33)
Advanced treatment stove					0.24
					(0.27)
Person-caterings per day					0.01**
					(0.00)
Burn agricultural waste at home (d)					-0.25*
					(0.14)
Participant avoids kitchen smoke					0.07
					(0.23)
Smell neighbours' smoke weekly (d)					0.43***
					(0.16)
Constant	5.46***	5.57***	4.69***	3.32***	3.14***
	(0.29)	(0.29)	(0.45)	(0.62)	(0.70)
Community and year	Yes	Yes	Yes	Yes	Yes
Observations	220	220	219	212	211
Mean(Y) reference cat.	503.5	503.5	503.0	505.6	505.6
R-squared	0.18	0.19	0.26	0.35	0.43
delta					16.63

*Notes: The dependent variable is log of 24-hour average $PM_{2.5}$ kitchen concentration. Standard errors are clustered at the household level and displayed in parentheses. The reference category of all variables of interest is their lowest category, i.e. most closed/smallest kitchen. *** p<0.01, ** p<0.05, * p<0.1*

Table C.2: Ventilation and kitchen concentration ($PM_{2.5}$): composite ventilation indicators

PANEL A

	coeff (se) (1)	coeff (se) (2)	coeff (se) (3)	coeff (se) (4)	coeff (se) (5)	coeff (se) (6)	coeff (se) (7)	coeff (se) (8)	coeff (se) (9)	coeff (se) (10)
Aggregated ventilation	-1.70***	-1.67***	-1.81***	-1.65***	-1.83***					
	(0.41)	(0.47)	(0.38)	(0.37)	(0.38)					
Aggregated ventilation: poor						0.12	0.08	0.00	0.05	-0.08
						(0.25)	(0.25)	(0.21)	(0.21)	(0.21)
Aggregated ventilation: substantial						-0.47**	-0.52**	-0.56***	-0.53***	-0.62***
						(0.21)	(0.24)	(0.19)	(0.19)	(0.19)
Aggregated ventilation: full						-1.14***	-0.93***	-1.22***	-1.11***	-1.24***
						(0.30)	(0.26)	(0.28)	(0.29)	(0.30)
Endline	-0.19	-0.19	-0.23*	-0.20	0.06	-0.17	-0.20	-0.21	-0.17	0.07
	(0.13)	(0.13)	(0.13)	(0.13)	(0.22)	(0.13)	(0.13)	(0.13)	(0.13)	(0.22)
Volume: medium		-0.03					-0.10			
		(0.21)					(0.21)			
Volume: large		0.16					0.10			
		(0.24)					(0.24)			
Volume: open		-0.10					-0.57			
		(0.53)					(0.45)			
Share of cooking events with measurement			0.19	0.40	0.50			0.24	0.45*	0.55*
			(0.25)	(0.26)	(0.32)			(0.26)	(0.27)	(0.33)
MicroPEM			0.91***	0.94***	0.95***			0.87***	0.91***	0.91***
			(0.21)	(0.20)	(0.18)			(0.21)	(0.19)	(0.18)
Participant's age				-0.00	0.00				-0.00	-0.00
				(0.01)	(0.01)				(0.01)	(0.01)
Participant is homemaker				0.35*	0.23				0.38**	0.27
				(0.18)	(0.16)				(0.19)	(0.18)
Participant is literate				0.52**	0.48***				0.54**	0.50***
				(0.21)	(0.17)				(0.21)	(0.18)
HH is primarily Wolof (d)				0.08	0.07				0.06	0.05
				(0.22)	(0.21)				(0.22)	(0.22)
HH size (#)				0.04*	0.03				0.04*	0.03
				(0.02)	(0.02)				(0.02)	(0.02)
HH has a private tap (d)				0.18	0.25				0.18	0.24
				(0.17)	(0.16)				(0.18)	(0.17)
HH has modern electricity (d)				0.05	-0.04				0.06	-0.03
				(0.30)	(0.29)				(0.31)	(0.30)
HH's normalized wealth index				0.05	0.11				0.07	0.13
				(0.11)	(0.10)				(0.12)	(0.11)
Basic metal stove					0.27					0.23
					(0.40)					(0.40)
Improved woodfuel stove					-0.08					-0.14
					(0.31)					(0.31)
LPG stove					-1.49***					-1.52***
					(0.46)					(0.47)
Share of cooking on OFS					0.27					0.18
					(0.29)					(0.30)
Total cooking duration					-0.00*					-0.00
					(0.00)					(0.00)
Simple treatment stove					0.13					0.16
					(0.30)					(0.29)
Advanced treatment stove					0.07					0.02
					(0.26)					(0.27)
Person-caterings per day					0.01**					0.01*
					(0.00)					(0.00)
Burn agricultural waste at home (d)					-0.17					-0.15
					(0.13)					(0.13)
Participant avoids kitchen smoke					-0.06					-0.11
					(0.23)					(0.23)
Smell neighbours' smoke weekly (d)					0.49***					0.44***
					(0.15)					(0.15)
Constant	6.22***	6.21***	5.42***	3.92***	3.78***	5.92***	5.97***	5.12***	3.63***	3.65***
	(0.36)	(0.36)	(0.46)	(0.61)	(0.68)	(0.32)	(0.32)	(0.44)	(0.61)	(0.67)
Community	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Observations	220	220	219	212	211	220	220	219	212	211
Mean(Y) reference cat.	.	.	.	.	.	617.0	617.0	617.0	625.5	625.5
R-squared	0.23	0.23	0.32	0.39	0.47	0.23	0.24	0.31	0.39	0.46
delta					7.4					

PANEL B

	coeff *(se)* (1)	*coeff* *(se)* (2)	*coeff* *(se)* (3)	*coeff* *(se)* (4)	*coeff* *(se)* (5)	*coeff* *(se)* (6)	*coeff* *(se)* (7)	*coeff* *(se)* (8)	*coeff* *(se)* (9)	*coeff* *(se)* (10)
PCA ventilation	-1.72***	-1.99**	-1.75***	-1.67***	-1.87***					
	(0.48)	(0.76)	(0.46)	(0.46)	(0.44)					
Quartile PCA ventilation: poor						-0.29	-0.41	-0.24	-0.32	-0.37
						(0.25)	(0.27)	(0.23)	(0.24)	(0.23)
Quartile PCA ventilation: substantial						-0.36	-0.62*	-0.24	-0.46*	-0.47**
						(0.27)	(0.35)	(0.26)	(0.23)	(0.23)
Quartile PCA ventilation: full						-0.97***	-0.97***	-1.02***	-0.96***	-1.03***
						(0.27)	(0.32)	(0.25)	(0.26)	(0.26)
Endline	-0.23*	-0.23*	-0.27**	-0.23*	-0.05	-0.20	-0.24*	-0.25*	-0.21	-0.02
	(0.13)	(0.13)	(0.13)	(0.14)	(0.22)	(0.14)	(0.13)	(0.14)	(0.14)	(0.22)
Volume: medium		0.17					0.16			
		(0.24)					(0.24)			
Volume: large		0.39					0.40			
		(0.32)					(0.34)			
Volume: open		0.18					-0.48			
		(0.71)					(0.52)			
Share of cooking events with measurement			0.17	0.39	0.45			0.18	0.44	0.53
			(0.26)	(0.28)	(0.34)			(0.28)	(0.30)	(0.37)
MicroPEM			0.85***	0.90***	0.90***			0.91***	0.93***	0.92***
			(0.22)	(0.20)	(0.18)			(0.22)	(0.21)	(0.19)
Participant's age				0.00	0.00				0.00	-0.00
				(0.01)	(0.01)				(0.01)	(0.01)
Participant is homemaker				0.35*	0.22				0.33*	0.21
				(0.18)	(0.17)				(0.19)	(0.17)
Participant is literate				0.58***	0.56***				0.53**	0.51***
				(0.21)	(0.17)				(0.22)	(0.18)
HH is primarily Wolof (d)				0.02	0.01				0.03	0.03
				(0.23)	(0.22)				(0.22)	(0.22)
HH size (#)				0.04*	0.03				0.04*	0.03
				(0.02)	(0.02)				(0.02)	(0.02)
HH has a private tap (d)				0.21	0.28*				0.15	0.21
				(0.18)	(0.17)				(0.18)	(0.17)
HH has modern electricity (d)				0.00	-0.06				0.05	-0.00
				(0.30)	(0.30)				(0.31)	(0.31)
HH's normalized wealth index				0.09	0.15				0.11	0.16
				(0.11)	(0.10)				(0.11)	(0.10)
Basic metal stove					0.40					0.30
					(0.40)					(0.40)
Improved woodfuel stove					-0.07					-0.15
					(0.32)					(0.33)
LPG stove					-1.36***					-1.38***
					(0.49)					(0.47)
Share of cooking on OFS					0.30					0.21
					(0.32)					(0.33)
Total cooking duration					-0.00					-0.00
					(0.00)					(0.00)
Simple treatment stove					0.23					0.19
					(0.32)					(0.31)
Advanced treatment stove					0.17					0.13
					(0.27)					(0.27)
Person-caterings per day					0.01**					0.01**
					(0.00)					(0.00)
Burn agricultural waste at home (d)					-0.19					-0.16
					(0.14)					(0.15)
Participant avoids kitchen smoke					0.02					0.05
					(0.22)					(0.23)
Smell neighbours' smoke weekly (d)					0.47***					0.43***
					(0.15)					(0.15)
Constant	6.13***	6.16***	5.35***	3.91***	3.74***	5.80***	5.83***	4.96***	3.59***	3.40***
	(0.35)	(0.37)	(0.47)	(0.61)	(0.68)	(0.28)	(0.27)	(0.43)	(0.59)	(0.66)
Community	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Observations	220	220	219	212	211	220	220	219	212	211
Mean(Y) reference cat.	.	.	.	.	.	571.4	571.4	571.4	573.2	573.2
R-squared	0.21	0.21	0.28	0.37	0.45	0.19	0.22	0.28	0.35	0.43
delta					-157.9					

PANEL C

	coeff (se) (1)	coeff (se) (2)	coeff (se) (3)	coeff (se) (4)	coeff (se) (5)
CHAID ventilation: poor	0.00	-0.02	-0.12	-0.14	-0.24
	(0.29)	(0.29)	(0.26)	(0.29)	(0.29)
CHAID ventilation: substantial	-0.42	-0.41	-0.50**	-0.40	-0.56**
	(0.26)	(0.27)	(0.25)	(0.26)	(0.26)
CHAID ventilation: full	-1.16***	-0.95***	-1.27***	-1.11***	-1.24***
	(0.28)	(0.25)	(0.27)	(0.29)	(0.28)
Endline	-0.06	-0.11	-0.12	-0.13	0.09
	(0.15)	(0.14)	(0.15)	(0.14)	(0.24)
Volume: medium		-0.20			
		(0.22)			
Volume: large		-0.13			
		(0.23)			
Volume: open		-0.75*			
		(0.43)			
Share of cooking events with measurement			0.30	0.45	0.65*
			(0.29)	(0.30)	(0.34)
MicroPEM			0.84***	0.91***	0.94***
			(0.22)	(0.20)	(0.18)
Participant's age				0.00	0.00
				(0.01)	(0.01)
Participant is homemaker				0.33*	0.22
				(0.18)	(0.18)
Participant is literate				0.49**	0.48***
				(0.21)	(0.17)
HH is primarily Wolof (d)				0.07	0.04
				(0.22)	(0.21)
HH size (#)				0.04**	0.03
				(0.02)	(0.02)
HH has a private tap (d)				0.11	0.17
				(0.17)	(0.16)
HH has modern electricity (d)				0.12	0.06
				(0.31)	(0.31)
HH's normalized wealth index				0.04	0.08
				(0.13)	(0.12)
Basic metal stove					0.12
					(0.43)
Improved woodfuel stove					-0.14
					(0.30)
LPG stove					-1.43***
					(0.42)
Share of cooking on OFS					0.21
					(0.29)
Total cooking duration					-0.00*
					(0.00)
Simple treatment stove					0.17
					(0.31)
Advanced treatment stove					0.04
					(0.28)
Person-caterings per day					0.01**
					(0.00)
Burn agricultural waste at home (d)					-0.15
					(0.14)
Participant avoids kitchen smoke					-0.02
					(0.23)
Smell neighbours' smoke weekly (d)					0.40**
					(0.15)
Constant	5.93***	6.03***	5.16***	3.67***	3.49***
	(0.39)	(0.41)	(0.50)	(0.61)	(0.67)
Community	Yes	Yes	Yes	Yes	Yes
Observations	211	211	211	211	211
Mean(Y) reference cat.	642.6	642.6	642.6	642.6	642.6
R-squared	0.22	0.24	0.29	0.36	0.44

*Notes: The dependent variable is log of 24-hour average $PM_{2.5}$ kitchen concentration. Standard errors are clustered at the household level and displayed in parentheses. The reference category of all variables of interest is their lowest category, i.e. most closed/smallest kitchen. In order to derive percentage changes presented in the main text, coefficients are transformed with the formula (exp(coef)-1)*100. *** p<0.01, ** p<0.05, * p<0.1*

Table C.3: Kitchen volume and kitchen concentration ($PM_{2.5}$), closed-kitchen subsample and continuous kitchen volume definition

	coeff *(se)* (1)	*coeff* *(se)* (2)	*coeff* *(se)* (3)	*coeff* *(se)* (4)	*coeff* *(se)* (5)
Kitchen volume (#)	-0.01	-0.00	-0.01	-0.01	0.00
	(0.01)	(0.00)	(0.00)	(0.00)	(0.01)
Aggregated ventilation: poor					-0.05
					(0.21)
Aggregated ventilation: substantial					-0.65***
					(0.20)
Aggregated ventilation: full					-0.70**
					(0.27)
Constant	5.54***	4.64***	3.22***	3.00***	3.40***
	(0.34)	(0.49)	(0.59)	(0.68)	(0.65)
Community and year	Yes	Yes	Yes	Yes	Yes
Measurement	No	Yes	Yes	Yes	Yes
Cook and household	No	No	Yes	Yes	Yes
Cooking behaviour	No	No	No	Yes	Yes
Observations	192	191	185	184	184
R-squared	0.17	0.26	0.36	0.45	0.50

*Notes: The dependent variable is log of 24-hour average $PM_{2.5}$ kitchen concentration. Standard errors are clustered at the household level and displayed in parentheses. The reference category of all variables of interest is their lowest category, i.e. most closed/smallest kitchen; *** p<0.01, ** p<0.05, * p<0.1*

Table C.4: Ventilation and kitchen concentration ($PM_{2.5}$), closed-kitchen subsample

	coeff *(se)* (1)	*coeff* *(se)* (2)	*coeff* *(se)* (3)	*coeff* *(se)* (4)	*coeff* *(se)* (5)	*coeff* *(se)* (6)	*coeff* *(se)* (7)	*coeff* *(se)* (8)	*coeff* *(se)* (9)	*coeff* *(se)* (10)
Aggregated ventilation:	0.14	0.13	0.02	0.07	-0.03					
poor	(0.25)	(0.26)	(0.21)	(0.22)	(0.20)					
Aggregated ventilation:	-0.48**	-0.50**	-0.55***	-0.55***	-0.63***					
substantial	(0.21)	(0.24)	(0.19)	(0.19)	(0.19)					
Aggregated ventilation:	-0.77***	-0.79***	-0.86***	-0.61***	-0.70***					
full	(0.23)	(0.26)	(0.21)	(0.23)	(0.26)					
Quartile PCA						-0.34	-0.43	-0.30	-0.34	-0.39*
ventilation: poor						(0.25)	(0.27)	(0.23)	(0.23)	(0.23)
Quartile PCA						-0.49*	-0.70*	-0.37	-0.58**	-0.59**
ventilation: substantial						(0.26)	(0.36)	(0.24)	(0.24)	(0.23)
Quartile PCA						-0.68***	-0.89***	-0.76***	-0.61***	-0.64***
ventilation: full						(0.24)	(0.33)	(0.21)	(0.23)	(0.23)
Constant	5.81***	5.86***	4.94***	3.43***	3.48***	5.70***	5.73***	4.84***	3.37***	3.21***
	(0.35)	(0.35)	(0.46)	(0.53)	(0.65)	(0.31)	(0.30)	(0.45)	(0.56)	(0.65)
Community and year	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Kitchen volume	No	Yes	No	No	No	No	Yes	No	No	No
Measurement	No	No	Yes	Yes	Yes	No	No	Yes	Yes	Yes
Cook and household	No	No	No	Yes	Yes	No	No	No	Yes	Yes
Cooking behaviour	No	No	No	No	Yes	No	No	No	No	Yes
Observations	193	193	192	186	185	193	193	192	186	185
Mean(Y) reference cat.	617.0	617.0	617.0	625.5	625.5	571.4	571.4	571.4	573.2	573.2
R-squared	0.23	0.23	0.32	0.41	0.50	0.20	0.20	0.29	0.39	0.48

*Notes: The dependent variable is log of 24-hour average $PM_{2.5}$ kitchen concentration. Standard errors are clustered at the household level and displayed in parentheses. The reference category of all variables of interest is their lowest category, i.e. most closed/smallest kitchen. *** p<0.01, ** p<0.05, * p<0.1*

Table C.5: Ventilation and kitchen concentration ($PM_{2.5}$), with health covariates

	coeff	*coeff*	*coeff*	*coeff*	*coeff*	*coeff*	*coeff*	*coeff*	*coeff*	*coeff*
	(se)	*(se)*	*(se)*	*(se)*	*(se)*	*(se)*	*(se)*	*(se)*	*(se)*	*(se)*
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)
Walls: poor	-0.21									
	(0.18)									
Walls: substantial	-0.48**									
	(0.21)									
Walls: full	-1.39***									
	(0.35)									
Roof: poor		-0.48**								
		(0.24)								
Roof: substantial		-0.74***								
		(0.27)								
Roof: full		-1.18***								
		(0.32)								
Openings: poor			0.06							
			(0.27)							
Openings: substantial			-0.47*							
			(0.26)							
Openings: full			-0.93***							
			(0.23)							
Volume: medium				-0.28						
				(0.19)						
Volume: large				-0.25						
				(0.20)						
Volume: open				-1.26***						
				(0.45)						
Open air					-1.07***					
					(0.34)					
Aggregated ventilation						-1.77***				
						(0.37)				
Aggregated ventilation: poor							-0.08			
							(0.21)			
Aggregated ventilation: substantial							-0.65***			
							(0.19)			
Aggregated ventilation: full							-1.17***			
							(0.30)			
PCA ventilation								-1.80***		
								(0.44)		
Quartile PCA ventilation: poor									-0.37	
									(0.23)	
Quartile PCA ventilation: substantial									-0.47**	
									(0.23)	
Quartile PCA ventilation: full									-0.98***	
									(0.25)	
CHAID ventilation: poor										-0.15
										(0.29)
CHAID ventilation: substantial										-0.58**
										(0.26)
CHAID ventilation: full										-1.17***
										(0.28)
Participant has normal blood pressure	0.15	0.19	0.19	0.18	0.16	0.12	0.14	0.12	0.14	0.26
	(0.16)	(0.16)	(0.16)	(0.17)	(0.16)	(0.16)	(0.17)	(0.16)	(0.17)	(0.16)
Participant has red eyes at least sometimes	0.41**	0.31*	0.42**	0.42**	0.38**	0.41**	0.42**	0.43**	0.41**	0.39**
	(0.16)	(0.18)	(0.16)	0.18	(0.16)	(0.16)	(0.17)	(0.16)	(0.17)	(0.18)
Constant	3.25***	3.25***	3.26***	2.84***	3.00***	3.64***	3.50***	3.60***	3.25***	3.32***
	(0.73)	(0.67)	(0.71)	(0.70)	(0.72)	(0.71)	(0.71)	(0.71)	(0.70)	(0.69)
Community and year	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Measurement	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Cook and household	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Cooking behaviour	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Observations	211	211	211	211	211	211	211	211	211	211
Mean(Y) reference cat.	586.9	641.7	543.2	515.2	508.1	.	625.5	.	573.2	642.6
R-squared	0.47	0.45	0.46	0.43	0.45	0.49	0.48	0.47	0.45	0.46

*Notes: The dependent variable is log of 24-hour average $PM_{2.5}$ kitchen concentration. Standard errors are clustered at the household level and displayed in parentheses. The reference category of all variables of interest is their lowest category, i.e. most closed/smallest kitchen. *** p<0.01, ** p<0.05, * p<0.1*

Annex D: Estimation results on cooks' personal exposure

Table D.1 : Ventilation and personal exposure ($PM_{2.5}$): single ventilation indicators

PANEL A

	coeff (se) (1)	coeff (se) (2)	coeff (se) (3)	coeff (se) (4)	coeff (se) (5)	coeff (se) (6)	coeff (se) (7)	coeff (se) (8)	coeff (se) (9)	coeff (se) (10)
Walls: poor	-0.09	-0.12*	-0.12*	-0.14**	-0.11					
	(0.06)	(0.06)	(0.07)	(0.07)	(0.10)					
Walls: substantial	-0.10	-0.07	-0.10	-0.13	-0.10					
	(0.08)	(0.08)	(0.08)	(0.08)	(0.14)					
Walls: full	-0.15	-0.10	-0.06	-0.07	0.03					
	(0.10)	(0.09)	(0.09)	(0.10)	(0.19)					
Roof: poor						-0.07	-0.07	-0.06	-0.08	-0.17
						(0.11)	(0.10)	(0.10)	(0.10)	(0.16)
Roof: substantial						-0.03	-0.05	-0.05	-0.10	-0.12
						(0.09)	(0.09)	(0.09)	(0.10)	(0.15)
Roof: full						-0.08	-0.08	-0.05	-0.07	-0.07
						(0.10)	(0.09)	(0.09)	(0.09)	(0.18)
24-hours mean KC (log)					0.09**					0.08**
					(0.04)					(0.04)
Endline	-0.16**	-0.22***	-0.21***	-0.13*	-0.06	-0.16***	-0.22***	-0.21***	-0.12	-0.07
	(0.06)	(0.06)	(0.06)	(0.08)	(0.12)	(0.06)	(0.06)	(0.06)	(0.08)	(0.13)
Primary cook		0.48***	0.49***	0.52***	0.48***		0.48***	0.49***	0.52***	0.46***
		(0.07)	(0.07)	(0.07)	(0.10)		(0.07)	(0.08)	(0.08)	(0.10)
Secondary cook		0.08	0.07	0.10	0.07		0.09	0.08	0.10	0.08
		(0.08)	(0.09)	(0.09)	(0.15)		(0.09)	(0.09)	(0.09)	(0.15)
Main cooks (#)		-0.02	-0.03	-0.06	-0.00		-0.01	-0.03	-0.05	0.01
		(0.04)	(0.04)	(0.04)	(0.07)		(0.04)	(0.04)	(0.04)	(0.07)
PE daytime wearing compliance (#)		0.47***	0.51***	0.46***	0.58**		0.47***	0.50***	0.44***	0.57**
		(0.14)	(0.15)	(0.16)	(0.26)		(0.14)	(0.15)	(0.16)	(0.26)
Participant's age			-0.01**	-0.00*	-0.01			-0.00*	-0.00*	-0.01
			(0.00)	(0.00)	(0.00)			(0.00)	(0.00)	(0.00)
Participant is homemaker			-0.03	-0.05	-0.10			-0.03	-0.04	-0.07
			(0.06)	(0.06)	(0.10)			(0.06)	(0.06)	(0.10)
Participant is literate			0.06	0.05	-0.07			0.07	0.07	-0.05
			(0.08)	(0.08)	(0.11)			(0.08)	(0.08)	(0.11)
HH is primarily Wolof (d)			-0.09	-0.08	0.05			-0.08	-0.07	0.06
			(0.07)	(0.08)	(0.10)			(0.07)	(0.08)	(0.10)
HH size (#)			0.01*	0.00	0.01			0.01*	0.00	0.01
			(0.00)	(0.01)	(0.01)			(0.00)	(0.01)	(0.01)
HH has a private tap (d)			-0.07	-0.05	-0.19*			-0.06	-0.05	-0.19*
			(0.07)	(0.07)	(0.11)			(0.07)	(0.07)	(0.11)
HH has modern electricity (d)			0.14	0.11	0.14			0.14	0.10	0.13
			(0.10)	(0.10)	(0.18)			(0.10)	(0.10)	(0.17)
HH's normalized wealth index			-0.02	-0.01	-0.07			-0.01	-0.01	-0.08
			(0.04)	(0.05)	(0.06)			(0.05)	(0.05)	(0.06)
Basic metal stove				-0.09	0.07				-0.07	0.09
				(0.09)	(0.19)				(0.09)	(0.20)
Improved woodfuel stove				-0.10	-0.14				-0.09	-0.13
				(0.10)	(0.19)				(0.10)	(0.18)
LPG stove				-0.09	0.08				-0.08	0.06
				(0.11)	(0.19)				(0.11)	(0.20)
Share of cooking on OFS				0.10	0.13				0.10	0.13
				(0.08)	(0.13)				(0.08)	(0.13)
Total cooking duration				0.00	-0.00				0.00	-0.00
				(0.00)	(0.00)				(0.00)	(0.00)
Simple treatment stove				-0.04	-0.18				-0.06	-0.22
				(0.11)	(0.20)				(0.11)	(0.20)
Advanced treatment stove				0.03	-0.05				0.03	-0.04
				(0.09)	(0.17)				(0.09)	(0.17)
Person-caterings per day				0.00	0.00				0.00	0.00
				(0.00)	(0.00)				(0.00)	(0.00)
Burn agricultural waste at home (d)				0.03	0.15*				0.03	0.12
				(0.06)	(0.09)				(0.06)	(0.09)
Participant avoids kitchen smoke				0.01	-0.04				0.01	-0.02
				(0.07)	(0.10)				(0.07)	(0.10)
Smell neighbours' smoke weekly (d)				0.07	0.15				0.06	0.15
				(0.06)	(0.09)				(0.06)	(0.09)
Constant	4.89***	4.26***	4.24***	4.14***	3.69***	4.86***	4.24***	4.20***	4.11***	3.73***
	(0.17)	(0.18)	(0.23)	(0.27)	(0.42)	(0.18)	(0.19)	(0.23)	(0.26)	(0.41)
Community	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes

table continues next page

Observations	418	418	412	411	200	418	418	412	411	200
Mean(Y) reference cat.	146.2	146.2	147.1	147.1	153.7	129.6	129.6	130.6	130.6	139.6
R-squared	0.10	0.22	0.24	0.26	0.39	0.10	0.21	0.24	0.26	0.40

PANEL B

	coeff (se) (1)	coeff (se) (2)	coeff (se) (3)	coeff (se) (4)	coeff (se) (5)	coeff (se) (6)	coeff (se) (7)	coeff (se) (8)	coeff (se) (9)	coeff (se) (10)
Openings: poor	0.05	0.08	0.09	0.08	0.34**					
	(0.11)	(0.10)	(0.10)	(0.10)	(0.16)					
Openings: substantial	0.09	0.04	0.03	0.02	0.10					
	(0.09)	(0.09)	(0.09)	(0.10)	(0.15)					
Openings: full	-0.04	-0.03	-0.02	-0.04	0.01					
	(0.08)	(0.08)	(0.08)	(0.08)	(0.12)					
Volume: medium						0.04	0.06	0.04	0.04	0.16
						(0.08)	(0.07)	(0.07)	(0.07)	(0.11)
Volume: large						-0.01	0.02	-0.03	-0.04	0.06
						(0.08)	(0.07)	(0.07)	(0.07)	(0.12)
Volume: open						-0.18*	-0.14	-0.13	-0.13	-0.15
						(0.09)	(0.09)	(0.09)	(0.09)	(0.17)
24-hours mean KC (log)					0.08**					0.07*
					(0.04)					(0.04)
Endline	-0.16**	-0.22***	-0.21***	-0.13*	-0.09	-0.16**	-0.22***	-0.22***	-0.14*	-0.11
	(0.06)	(0.06)	(0.06)	(0.08)	(0.13)	(0.06)	(0.06)	(0.06)	(0.08)	(0.11)
Primary cook		0.47***	0.48***	0.51***	0.43***		0.48***	0.48***	0.52***	0.46***
		(0.07)	(0.08)	(0.08)	(0.11)		(0.06)	(0.07)	(0.07)	(0.10)
Secondary cook		0.07	0.06	0.08	-0.00		0.10	0.08	0.10	0.05
		(0.08)	(0.09)	(0.09)	(0.15)		(0.08)	(0.09)	(0.09)	(0.14)
Main cooks (#)		-0.01	-0.03	-0.05	0.03		-0.01	-0.03	-0.04	0.01
		(0.04)	(0.04)	(0.04)	(0.07)		(0.04)	(0.04)	(0.04)	(0.06)
PE daytime wearing compliance (#)		0.47***	0.50***	0.44***	0.52**		0.47***	0.51***	0.45***	0.61**
		(0.14)	(0.16)	(0.16)	(0.25)		(0.14)	(0.15)	(0.16)	(0.25)
Participant's age			-0.00*	-0.00	-0.01			-0.01**	-0.00*	-0.01
			(0.00)	(0.00)	(0.00)			(0.00)	(0.00)	(0.00)
Participant is homemaker			-0.03	-0.05	-0.08			-0.03	-0.05	-0.11
			(0.06)	(0.06)	(0.10)			(0.06)	(0.06)	(0.10)
Participant is literate			0.07	0.07	-0.06			0.07	0.07	-0.06
			(0.08)	(0.08)	(0.10)			(0.08)	(0.08)	(0.11)
HH is primarily Wolof (d)			-0.08	-0.06	0.08			-0.08	-0.06	0.08
			(0.07)	(0.08)	(0.09)			(0.07)	(0.08)	(0.10)
HH size (#)			0.01	0.00	-0.00			0.01	0.00	0.00
			(0.00)	(0.01)	(0.01)			(0.00)	(0.01)	(0.01)
HH has a private tap (d)			-0.06	-0.04	-0.18			-0.05	-0.03	-0.15
			(0.07)	(0.07)	(0.11)			(0.07)	(0.07)	(0.10)
HH has modern electricity (d)			0.14	0.11	0.14			0.13	0.10	0.11
			(0.10)	(0.10)	(0.17)			(0.10)	(0.10)	(0.17)
HH's normalized wealth index			-0.01	-0.01	-0.08			-0.00	0.00	-0.06
			(0.04)	(0.05)	(0.06)			(0.04)	(0.05)	(0.05)
Basic metal stove				-0.07	0.15				-0.07	0.07
				(0.10)	(0.19)				(0.09)	(0.20)
Improved woodfuel stove				-0.10	-0.12				-0.09	-0.15
				(0.10)	(0.18)				(0.10)	(0.20)
LPG stove				-0.07	0.13				-0.06	-0.00
				(0.11)	(0.22)				(0.11)	(0.19)
Share of cooking on OFS				0.09	0.13				0.09	0.13
				(0.08)	(0.12)				(0.08)	(0.13)
Total cooking duration				0.00	-0.00*				0.00	-0.00
				(0.00)	(0.00)				(0.00)	(0.00)
Simple treatment stove				-0.05	-0.19				-0.04	-0.15
				(0.11)	(0.20)				(0.11)	(0.19)
Advanced treatment stove				0.03	-0.06				0.04	-0.00
				(0.09)	(0.17)				(0.10)	(0.16)
Person-caterings per day				0.00	0.00				0.00	0.00*
				(0.00)	(0.00)				(0.00)	(0.00)
Burn agricultural waste at home (d)				0.04	0.13				0.04	0.10
				(0.06)	(0.08)				(0.06)	(0.09)
Participant avoids kitchen smoke				0.01	-0.01				-0.00	-0.02
				(0.07)	(0.10)				(0.07)	(0.10)
Smell neighbours' smoke weekly (d)				0.05	0.10				0.06	0.16*
				(0.06)	(0.09)				(0.05)	(0.09)
Constant	4.82***	4.19***	4.18***	4.08***	3.81***	4.85***	4.18***	4.19***	4.09***	3.73***
	(0.18)	(0.19)	(0.23)	(0.27)	(0.39)	(0.16)	(0.18)	(0.23)	(0.27)	(0.39)
Community	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Observations	418	418	412	411	200	418	418	412	411	200
Mean(Y) reference cat.	140.3	140.3	140.8	140.8	136.5	135.9	135.9	138.0	138.0	130.2
R-squared	0.10	0.22	0.24	0.26	0.41	0.11	0.22	0.24	0.26	0.40

PANEL C

	coeff (se) (1)	coeff (se) (2)	coeff (se) (3)	coeff (se) (4)	coeff (se) (5)	coeff (se) (6)	coeff (se) (7)	coeff (se) (8)	coeff (se) (9)	coeff (se) (10)
Separation: attached	0.30**	0.38***	0.37***	0.35***	0.37*					
	(0.15)	(0.13)	(0.13)	(0.13)	(0.22)					
Separation: detached	0.06	0.13	0.14	0.12	0.09					
	(0.09)	(0.10)	(0.09)	(0.09)	(0.16)					
Separation: open air	-0.02	0.09	0.12	0.10	0.11					
	(0.12)	(0.13)	(0.12)	(0.12)	(0.21)					
Open air						-0.13	-0.09	-0.06	-0.04	0.04
						(0.09)	(0.09)	(0.09)	(0.09)	(0.17)
24-hours mean KC (log)					0.08**					0.08**
					(0.04)					(0.04)
Endline	-0.16**	-0.22***	-0.21***	-0.13*	-0.07	-0.16**	-0.22***	-0.21***	-0.13*	-0.08
	(0.06)	(0.06)	(0.06)	(0.08)	(0.12)	(0.06)	(0.06)	(0.06)	(0.08)	(0.12)
Primary cook		0.48***	0.49***	0.53***	0.49***		0.48***	0.49***	0.52***	0.48***
		(0.07)	(0.07)	(0.08)	(0.10)		(0.06)	(0.07)	(0.08)	(0.10)
Secondary cook		0.08	0.07	0.10	0.08		0.10	0.08	0.11	0.07
		(0.09)	(0.09)	(0.09)	(0.15)		(0.08)	(0.09)	(0.09)	(0.15)
Main cooks (#)		-0.01	-0.03	-0.05	0.01		-0.01	-0.03	-0.05	0.01
		(0.04)	(0.04)	(0.04)	(0.07)		(0.04)	(0.04)	(0.04)	(0.07)
PE daytime wearing compliance (#)		0.49***	0.53***	0.48***	0.57**		0.46***	0.50***	0.44***	0.57**
		(0.14)	(0.16)	(0.17)	(0.26)		(0.14)	(0.15)	(0.16)	(0.26)
Participant's age			-0.01**	-0.00*	-0.01			-0.00**	-0.00*	-0.01
			(0.00)	(0.00)	(0.00)			(0.00)	(0.00)	(0.00)
Participant is homemaker			-0.02	-0.04	-0.07			-0.03	-0.05	-0.09
			(0.06)	(0.06)	(0.10)			(0.06)	(0.06)	(0.10)
Participant is literate			0.06	0.06	-0.07			0.07	0.07	-0.07
			(0.08)	(0.08)	(0.11)			(0.08)	(0.08)	(0.11)
HH is primarily Wolof (d)			-0.08	-0.07	0.08			-0.07	-0.06	0.09
			(0.07)	(0.08)	(0.10)			(0.07)	(0.08)	(0.10)
HH size (#)			0.01*	0.00	0.01			0.01	0.00	0.00
			(0.00)	(0.01)	(0.01)			(0.00)	(0.01)	(0.01)
HH has a private tap (d)			-0.05	-0.03	-0.17			-0.06	-0.04	-0.18
			(0.07)	(0.07)	(0.11)			(0.07)	(0.07)	(0.11)
HH has modern electricity (d)			0.14	0.11	0.11			0.14	0.11	0.13
			(0.10)	(0.10)	(0.17)			(0.10)	(0.10)	(0.17)
HH's normalized wealth index			-0.01	-0.01	-0.06			-0.00	-0.00	-0.06
			(0.04)	(0.04)	(0.06)			(0.04)	(0.05)	(0.06)
Basic metal stove				-0.10	0.07				-0.07	0.09
				(0.10)	(0.19)				(0.09)	(0.19)
Improved woodfuel stove				-0.10	-0.14				-0.09	-0.14
				(0.10)	(0.19)				(0.10)	(0.19)
LPG stove				-0.06	0.12				-0.06	0.09
				(0.11)	(0.20)				(0.11)	(0.19)
Share of cooking on OFS				0.07	0.13				0.09	0.11
				(0.08)	(0.13)				(0.08)	(0.13)
Total cooking duration				0.00	-0.00				0.00	-0.00
				(0.00)	(0.00)				(0.00)	(0.00)
Simple treatment stove				-0.06	-0.21				-0.06	-0.20
				(0.11)	(0.20)				(0.11)	(0.19)
Advanced treatment stove				0.02	-0.04				0.02	-0.04
				(0.09)	(0.16)				(0.09)	(0.16)
Person-caterings per day				0.00	0.00				0.00	0.00
				(0.00)	(0.00)				(0.00)	(0.00)
Burn agricultural waste at home (d)				0.04	0.13				0.03	0.14
				(0.06)	(0.09)				(0.06)	(0.09)
Participant avoids kitchen smoke				0.02	-0.02				0.01	-0.03
				(0.07)	(0.10)				(0.07)	(0.10)
Smell neighbours' smoke weekly (d)				0.05	0.13				0.06	0.14
				(0.06)	(0.09)				(0.05)	(0.09)
Constant	4.75***	4.01***	3.97***	3.89***	3.56***	4.84***	4.20***	4.17***	4.05***	3.64***
	(0.19)	(0.20)	(0.25)	(0.28)	(0.41)	(0.16)	(0.18)	(0.22)	(0.26)	(0.40)
Community	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Observations	417	417	411	410	200	418	418	412	411	200
Mean(Y) reference cat.	101.6	101.6	101.6	101.6	93.7	137.7	137.7	138.7	138.9	138.6
R-squared	0.11	0.23	0.25	0.27	0.39	0.10	0.21	0.24	0.26	0.39
delta									1.7	

*Notes: The dependent variable is log of 24-hour average personal exposure to $PM_{2.5}$. Standard errors are clustered at the household level and displayed in parentheses. The reference category of all variables of interest is their lowest category, i.e. most closed/smallest kitchen. *** p<0.01, ** p<0.05, * p<0.1*

Table D.2 : Ventilation and personal exposure ($PM_{2.5}$) : composite ventilation indicators

PANEL A

	coeff (se) (1)	coeff (se) (2)	coeff (se) (3)	coeff (se) (4)	coeff (se) (5)	coeff (se) (6)	coeff (se) (7)	coeff (se) (8)	coeff (se) (9)	coeff (se) (10)
Aggregated ventilation	-0.15	-0.12	-0.10	-0.13	-0.04					
	(0.11)	(0.11)	(0.11)	(0.11)	(0.20)					
Aggregated ventilation: poor						0.04	0.06	0.05	0.02	-0.08
						(0.09)	(0.09)	(0.08)	(0.09)	(0.13)
Aggregated ventilation: substantial						-0.12	-0.12*	-0.13*	-0.15**	-0.09
						(0.08)	(0.07)	(0.07)	(0.08)	(0.11)
Aggregated ventilation: full						-0.05	-0.03	-0.02	-0.05	-0.06
						(0.09)	(0.08)	(0.09)	(0.09)	(0.15)
24-hours mean KC (log)					0.08**					0.08**
					(0.04)					(0.04)
Endline	-0.16**	-0.22***	-0.21***	-0.12	-0.08	-0.16**	-0.22***	-0.22***	-0.13*	-0.07
	(0.06)	(0.06)	(0.06)	(0.08)	(0.12)	(0.06)	(0.06)	(0.06)	(0.08)	(0.12)
Primary cook		0.47***	0.49***	0.52***	0.48***		0.48***	0.50***	0.53***	0.48***
		(0.07)	(0.07)	(0.08)	(0.10)		(0.07)	(0.07)	(0.08)	(0.10)
Secondary cook		0.10	0.08	0.11	0.08		0.11	0.10	0.12	0.08
		(0.08)	(0.09)	(0.09)	(0.15)		(0.08)	(0.09)	(0.09)	(0.15)
Main cooks (#)		-0.01	-0.03	-0.05	0.01		-0.01	-0.03	-0.05	0.00
		(0.04)	(0.04)	(0.04)	(0.07)		(0.03)	(0.04)	(0.04)	(0.07)
PE daytime wearing compliance (#)		0.48***	0.51***	0.44***	0.57**		0.50***	0.53***	0.47***	0.58**
		(0.14)	(0.15)	(0.16)	(0.26)		(0.14)	(0.15)	(0.16)	(0.25)
Participant's age			-0.01**	-0.00*	-0.01			-0.00*	-0.00*	-0.01
			(0.00)	(0.00)	(0.00)			(0.00)	(0.00)	(0.00)
Participant is homemaker			-0.03	-0.05	-0.08			-0.04	-0.06	-0.09
			(0.06)	(0.06)	(0.10)			(0.06)	(0.06)	(0.10)
Participant is literate			0.07	0.07	-0.07			0.07	0.07	-0.07
			(0.08)	(0.08)	(0.11)			(0.08)	(0.08)	(0.11)
HH is primarily Wolof (d)			-0.07	-0.05	0.09			-0.08	-0.07	0.08
			(0.07)	(0.08)	(0.10)			(0.07)	(0.08)	(0.10)
HH size (#)			0.01*	0.00	0.00			0.01*	0.00	0.01
			(0.00)	(0.01)	(0.01)			(0.00)	(0.01)	(0.01)
HH has a private tap (d)			-0.06	-0.04	-0.18			-0.08	-0.06	-0.18*
			(0.07)	(0.07)	(0.11)			(0.07)	(0.07)	(0.11)
HH has modern electricity (d)			0.14	0.11	0.13			0.15	0.11	0.12
			(0.10)	(0.10)	(0.17)			(0.10)	(0.10)	(0.16)
HH's normalized wealth index			-0.01	-0.01	-0.07			-0.01	-0.01	-0.07
			(0.04)	(0.04)	(0.06)			(0.04)	(0.04)	(0.06)
Basic metal stove				-0.07	0.10				-0.07	0.10
				(0.09)	(0.19)				(0.09)	(0.19)
Improved woodfuel stove				-0.10	-0.14				-0.09	-0.13
				(0.10)	(0.19)				(0.10)	(0.19)
LPG stove				-0.07	0.08				-0.09	0.05
				(0.11)	(0.19)				(0.11)	(0.20)
Share of cooking on OFS				0.09	0.12				0.10	0.13
				(0.08)	(0.13)				(0.08)	(0.13)
Total cooking duration				0.00	-0.00				0.00	-0.00
				(0.00)	(0.00)				(0.00)	(0.00)
Simple treatment stove				-0.06	-0.20				-0.04	-0.20
				(0.11)	(0.20)				(0.11)	(0.20)
Advanced treatment stove				0.02	-0.04				0.03	-0.04
				(0.09)	(0.16)				(0.09)	(0.16)
Person-caterings per day				0.00	0.00				0.00	0.00
				(0.00)	(0.00)				(0.00)	(0.00)
Burn agricultural waste at home (d)				0.04	0.14				0.03	0.14*
				(0.06)	(0.08)				(0.06)	(0.08)
Participant avoids kitchen smoke				0.01	-0.03				0.01	-0.05
				(0.07)	(0.10)				(0.07)	(0.10)
Smell neighbours' smoke weekly (d)				0.06	0.14				0.07	0.15*
				(0.06)	(0.09)				(0.06)	(0.09)
Constant	4.89***	4.24***	4.21***	4.12***	3.70***	4.86***	4.18***	4.15***	4.06***	3.74***
	(0.18)	(0.19)	(0.23)	(0.27)	(0.43)	(0.18)	(0.18)	(0.24)	(0.27)	(0.44)
Community	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Observations	418	418	412	411	200	418	418	412	411	200
Mean(Y) reference cat.	.	.	.	.	.	144.9	144.9	145.4	145.4	149.9
R-squared	0.10	0.22	0.24	0.26	0.39	0.11	0.22	0.25	0.27	0.39
delta					291.0					

PANEL B

	coeff (se) (1)	coeff (se) (2)	coeff (se) (3)	coeff (se) (4)	coeff (se) (5)	coeff (se) (6)	coeff (se) (7)	coeff (se) (8)	coeff (se) (9)	coeff (se) (10)
PCA ventilation	-0.22*	-0.16	-0.15	-0.17	-0.03					
	(0.12)	(0.11)	(0.11)	(0.11)	(0.21)					
Quartile PCA ventilation: poor						0.03	0.02	-0.01	-0.02	0.04
						(0.08)	(0.08)	(0.07)	(0.08)	(0.14)
Quartile PCA ventilation: substantial						-0.02	-0.01	-0.07	-0.08	0.05
						(0.08)	(0.08)	(0.08)	(0.08)	(0.13)
Quartile PCA ventilation: full						-0.06	-0.03	-0.03	-0.05	0.09
						(0.08)	(0.07)	(0.07)	(0.08)	(0.12)
24-hours mean KC (log)					0.08**					0.09**
					(0.04)					(0.03)
Endline	-0.16**	-0.22***	-0.21***	-0.13*	-0.08	-0.16**	-0.22***	-0.21***	-0.13*	-0.09
	(0.06)	(0.06)	(0.06)	(0.08)	(0.12)	(0.06)	(0.06)	(0.06)	(0.08)	(0.12)
Primary cook		0.47***	0.49***	0.52***	0.48***		0.47***	0.49***	0.52***	0.49***
		(0.07)	(0.07)	(0.08)	(0.10)		(0.07)	(0.07)	(0.08)	(0.10)
Secondary cook		0.10	0.08	0.11	0.08		0.09	0.07	0.10	0.07
		(0.08)	(0.09)	(0.09)	(0.15)		(0.09)	(0.09)	(0.09)	(0.15)
Main cooks (#)		-0.01	-0.03	-0.05	0.01		-0.01	-0.03	-0.05	0.01
		(0.04)	(0.04)	(0.04)	(0.07)		(0.04)	(0.04)	(0.04)	(0.07)
PE daytime wearing compliance (#)		0.48***	0.51***	0.44***	0.57**		0.48***	0.51***	0.45***	0.56**
		(0.14)	(0.15)	(0.16)	(0.26)		(0.14)	(0.15)	(0.16)	(0.26)
Participant's age			-0.00*	-0.00*	-0.01			-0.01**	-0.00*	-0.01
			(0.00)	(0.00)	(0.00)			(0.00)	(0.00)	(0.00)
Participant is homemaker			-0.03	-0.05	-0.09			-0.03	-0.04	-0.09
			(0.06)	(0.06)	(0.10)			(0.06)	(0.06)	(0.10)
Participant is literate			0.07	0.07	-0.06			0.08	0.08	-0.06
			(0.08)	(0.08)	(0.11)			(0.08)	(0.08)	(0.11)
HH is primarily Wolof (d)			-0.07	-0.06	0.09			-0.08	-0.07	0.09
			(0.07)	(0.08)	(0.10)			(0.07)	(0.08)	(0.10)
HH size (#)			0.01*	0.00	0.00			0.01*	0.00	0.00
			(0.00)	(0.01)	(0.01)			(0.00)	(0.01)	(0.01)
HH has a private tap (d)			-0.06	-0.04	-0.18			-0.06	-0.04	-0.18
			(0.07)	(0.07)	(0.11)			(0.07)	(0.07)	(0.11)
HH has modern electricity (d)			0.14	0.10	0.13			0.14	0.11	0.12
			(0.10)	(0.10)	(0.17)			(0.10)	(0.10)	(0.19)
HH's normalized wealth index			-0.01	-0.00	-0.06			-0.00	-0.00	-0.06
			(0.04)	(0.05)	(0.06)			(0.04)	(0.05)	(0.06)
Basic metal stove				-0.06	0.10				-0.06	0.10
				(0.09)	(0.19)				(0.09)	(0.19)
Improved woodfuel stove				-0.09	-0.14				-0.09	-0.13
				(0.10)	(0.19)				(0.10)	(0.20)
LPG stove				-0.06	0.08				-0.06	0.11
				(0.11)	(0.19)				(0.11)	(0.19)
Share of cooking on OFS				0.10	0.12				0.10	0.11
				(0.08)	(0.13)				(0.08)	(0.13)
Total cooking duration				0.00	-0.00				0.00	-0.00
				(0.00)	(0.00)				(0.00)	(0.00)
Simple treatment stove				-0.05	-0.20				-0.05	-0.20
				(0.11)	(0.20)				(0.11)	(0.20)
Advanced treatment stove				0.03	-0.04				0.03	-0.04
				(0.10)	(0.16)				(0.09)	(0.16)
Person-caterings per day				0.00	0.00				0.00	0.00
				(0.00)	(0.00)				(0.00)	(0.00)
Burn agricultural waste at home (d)				0.04	0.14				0.04	0.14
				(0.06)	(0.08)				(0.06)	(0.09)
Participant avoids kitchen smoke				0.01	-0.03				0.01	-0.03
				(0.07)	(0.10)				(0.07)	(0.10)
Smell neighbours' smoke weekly (d)				0.06	0.14				0.06	0.13
				(0.05)	(0.09)				(0.05)	(0.09)
Constant	4.93***	4.26***	4.24***	4.14***	3.68***	4.83***	4.19***	4.17***	4.05***	3.58***
	(0.18)	(0.19)	(0.23)	(0.27)	(0.42)	(0.18)	(0.18)	(0.23)	(0.26)	(0.41)
Community	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Observations	418	418	412	411	200	418	418	412	411	200
Mean(Y) reference cat.	.	.	.	.	.	138.1	138.1	139.4	139.4	130.7
R-squared	0.10	0.22	0.24	0.26	0.39	0.10	0.21	0.24	0.26	0.39
delta					25.1					

PANEL C

	coeff (se) (1)	coeff (se) (2)	coeff (se) (3)	coeff (se) (4)	coeff (se) (5)
CHAID ventilation: poor	0.02	0.08	0.03	-0.00	-0.01
	(0.16)	(0.15)	(0.16)	(0.17)	(0.17)
CHAID ventilation: substantial	-0.02	0.08	0.01	-0.06	-0.04
	(0.13)	(0.12)	(0.14)	(0.14)	(0.15)
CHAID ventilation: full	-0.16	-0.04	-0.08	-0.14	-0.07
	(0.15)	(0.15)	(0.15)	(0.16)	(0.17)
24-hours mean KC (log)					0.08**
					(0.04)
Endline	-0.23**	-0.32***	-0.32***	-0.05	-0.07
	(0.09)	(0.09)	(0.10)	(0.12)	(0.12)
Primary cook		0.47***	0.48***	0.50***	0.47***
		(0.09)	(0.09)	(0.10)	(0.10)
Secondary cook		-0.05	-0.02	0.07	0.07
		(0.13)	(0.14)	(0.15)	(0.15)
Main cooks (#)		0.04	0.03	-0.01	0.01
		(0.06)	(0.06)	(0.07)	(0.07)
PE daytime wearing compliance (#)		0.53**	0.61**	0.62**	0.57**
		(0.26)	(0.26)	(0.24)	(0.25)
Participant's age			-0.00	-0.01	-0.01
			(0.00)	(0.00)	(0.00)
Participant is homemaker			-0.03	-0.06	-0.09
			(0.10)	(0.10)	(0.10)
Participant is literate			-0.01	-0.03	-0.07
			(0.11)	(0.11)	(0.11)
HH is primarily Wolof (d)			0.08	0.09	0.09
			(0.09)	(0.11)	(0.10)
HH size (#)			0.01	0.01	0.01
			(0.01)	(0.01)	(0.01)
HH has a private tap (d)			-0.21*	-0.18	-0.18*
			(0.11)	(0.11)	(0.11)
HH has modern electricity (d)			0.19	0.14	0.13
			(0.17)	(0.19)	(0.18)
HH's normalized wealth index			-0.04	-0.06	-0.07
			(0.06)	(0.06)	(0.06)
Basic metal stove				0.14	0.09
				(0.19)	(0.19)
Improved woodfuel stove				-0.13	-0.14
				(0.20)	(0.19)
LPG stove				-0.00	0.07
				(0.22)	(0.20)
Share of cooking on OFS				0.18	0.12
				(0.13)	(0.13)
Total cooking duration				-0.00	-0.00
				(0.00)	(0.00)
Simple treatment stove				-0.17	-0.20
				(0.21)	(0.20)
Advanced treatment stove				-0.05	-0.05
				(0.16)	(0.16)
Person-caterings per day				0.00*	0.00
				(0.00)	(0.00)
Burn agricultural waste at home (d)				0.14	0.14
				(0.09)	(0.08)
Participant avoids kitchen smoke				-0.02	-0.03
				(0.10)	(0.10)
Smell neighbours' smoke weekly (d)				0.17*	0.14
				(0.09)	(0.09)
Constant	5.03***	4.16***	4.16***	4.01***	3.74***
	(0.24)	(0.33)	(0.38)	(0.42)	(0.42)
Community	Yes	Yes	Yes	Yes	Yes
Observations	200	200	200	200	200
Mean(Y) reference cat.	146.0	146.0	146.0	146.0	146.0
R-squared	0.16	0.28	0.31	0.38	0.39

*Notes: The dependent variable is log of 24-hour average personal exposure to $PM_{2.5}$. Standard errors are clustered at the household level and displayed in parentheses. The reference category of all variables of interest is their lowest category, i.e. most closed/smallest kitchen. *** p<0.01, ** p<0.05, * p<0.1*

Table D.3: Correlates of behavioural smoke avoidance

PANEL A

	avoids smoke									
	coeff *(se)* (1)	*coeff* *(se)* (2)	*coeff* *(se)* (3)	*coeff* *(se)* (4)	*coeff* *(se)* (5)	*coeff* *(se)* (6)	*coeff* *(se)* (7)	*coeff* *(se)* (8)	*coeff* *(se)* (9)	*coeff* *(se)* (10)
Walls: poor	-0.41									
	(0.33)									
Walls: substantial	-0.02									
	(0.43)									
Walls: full	-0.37									
	(0.47)									
Roof: poor		-0.19								
		(0.42)								
Roof: substantial		-0.41								
		(0.41)								
Roof: full		-0.46								
		(0.41)								
Openings: poor			0.40							
			(0.48)							
Openings: substantial			-0.52							
			(0.43)							
Openings: full			-0.38							
			(0.37)							
Volume: medium				0.67*						
				(0.34)						
Volume: large				-0.53						
				(0.34)						
Volume: open				-0.41						
				(0.48)						
Open air					-0.35					
					(0.41)					
Aggregated ventilation						-0.85				
						(0.53)				
Aggregated ventilation: poor							-0.29			
							(0.42)			
Aggregated ventilation: substantial							-0.17			
							(0.39)			
Aggregated ventilation: full							-0.76*			
							(0.42)			
PCA ventilation								-0.94*		
								(0.55)		
Quartile PCA ventilation: poor									0.10	
									(0.35)	
Quartile PCA ventilation: substantial									-0.37	
									(0.36)	
Quartile PCA ventilation: full									-0.31	
									(0.36)	
CHAID ventilation: poor										0.15
										(0.96)
CHAID ventilation: substantial										-1.70**
										(0.73)
CHAID ventilation: full										-1.26*
										(0.77)
Constant	2.13*	2.25**	2.05*	2.18**	2.02*	2.41**	2.51**	2.42**	1.99*	1.97
	(1.18)	(1.14)	(1.12)	(1.11)	(1.13)	(1.13)	(1.17)	(1.13)	(1.11)	(2.35)
Community and year	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Cook and household	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Further cooking behaviour	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Observations	393	393	393	393	393	393	393	393	393	182
Pseudo R-squared	0.11	0.11	0.11	0.13	0.11	0.11	0.11	0.11	0.11	0.20

PANEL B

	share of cooking time spent off the stove									
	coeff *(se)* (1)	*coeff* *(se)* (2)	*coeff* *(se)* (3)	*coeff* *(se)* (4)	*coeff* *(se)* (5)	*coeff* *(se)* (6)	*coeff* *(se)* (7)	*coeff* *(se)* (8)	*coeff* *(se)* (9)	*coeff* *(se)* (10)
Walls: poor	-0.04*									
	(0.03)									
Walls: substantial	-0.03									
	(0.03)									
Walls: full	-0.06*									
	(0.04)									
Roof: poor		-0.03								
		(0.03)								
Roof: substantial		-0.05								
		(0.04)								
Roof: full		-0.00								
		(0.04)								
Openings: poor			0.04							
			(0.04)							
Openings: substantial			-0.03							
			(0.03)							
Openings: full			-0.01							
			(0.03)							
Volume: medium				0.04						
				(0.03)						
Volume: large				0.06*						
				(0.03)						
Volume: open				-0.01						
				(0.04)						
Open air					-0.03					
					(0.03)					
Aggregated ventilation						-0.03				
						(0.04)				
Aggregated ventilation: poor							0.00			
							(0.03)			
Aggregated ventilation: substantial							-0.01			
							(0.03)			
Aggregated ventilation: full							-0.01			
							(0.03)			
PCA ventilation								-0.01		
								(0.05)		
Quartile PCA ventilation: poor									0.08**	
									(0.03)	
Quartile PCA ventilation: substantial									0.04	
									(0.03)	
Quartile PCA ventilation: full									0.02	
									(0.03)	
CHAID ventilation: poor										0.00
										(0.08)
CHAID ventilation: substantial										-0.11*
										(0.06)
CHAID ventilation: full										-0.05
										(0.07)
Constant	0.27***	0.25**	0.23**	0.22**	0.24**	0.25**	0.24**	0.23**	0.22**	0.32**
	(0.10)	(0.10)	(0.10)	(0.10)	(0.10)	(0.10)	(0.10)	(0.10)	(0.10)	(0.15)
Community and year	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Cook and household	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Further cooking behaviour	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Observations	412	412	412	412	412	412	412	412	412	203
R-squared	0.19	0.19	0.19	0.19	0.18	0.18	0.18	0.18	0.20	0.29

Table D.4: Ventilation and personal exposure ($PM_{2.5}$), with health covariates

	coeff *(se)* (1)	*coeff* *(se)* (2)	*coeff* *(se)* (3)	*coeff* *(se)* (4)	*coeff* *(se)* (5)	*coeff* *(se)* (6)	*coeff* *(se)* (7)	*coeff* *(se)* (8)	*coeff* *(se)* (9)
Walls: poor	-0.14**								
	(0.07)								
Walls: substantial	-0.13								
	(0.08)								
Walls: full	-0.06								
	(0.10)								
Roof: poor		-0.08							
		(0.10)							
Roof: substantial		-0.10							
		(0.10)							
Roof: full		-0.07							
		(0.09)							
Openings: poor			0.08						
			(0.10)						
Openings: substantial			0.02						
			(0.10)						
Openings: full			-0.04						
			(0.08)						
Volume: medium				0.04					
				(0.07)					
Volume: large				-0.04					
				(0.07)					
Volume: open				-0.13					
				(0.10)					
Separation: attached					0.35***				
					(0.13)				
Separation: separated					0.12				
					(0.09)				
Separation: open					0.10				
					(0.12)				
Open air						-0.04			
						(0.09)			
Aggregated ventilation: poor							0.02 (0.09)		
Aggregated ventilation: substantial							-0.15** (0.08)		
Aggregated ventilation: full							-0.05 (0.09)		
Quartile PCA ventilation: poor								-0.02 (0.08)	
Quartile PCA ventilation: substantial								-0.08 (0.08)	
Quartile PCA ventilation: full								-0.05 (0.08)	
CHAID ventilation: poor									0.01
									(0.17)
CHAID ventilation: substantial									-0.07 (0.14)
CHAID ventilation: full									-0.13
									(0.17)
Participant has normal blood pressure	0.04 (0.06)	0.02 (0.06)	0.03 (0.06)	0.02 (0.06)	0.02 (0.06)	0.02 (0.06)	0.03 (0.06)	0.02 (0.06)	0.10 (0.08)
Participant has red eyes at least sometimes	0.01 (0.08)	-0.01 (0.07)	-0.01 (0.07)	-0.01 (0.07)	-0.02 (0.07)	0.00 (0.07)	0.01 (0.07)	-0.00 (0.07)	0.04 (0.11)
Constant	4.12***	4.10***	4.07***	4.09***	3.88***	4.04***	4.05***	4.05***	3.99***
	(0.27)	(0.26)	(0.27)	(0.27)	(0.28)	(0.27)	(0.28)	(0.27)	(0.41)
Community and year	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Measurement	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Cook and household	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Cooking behaviour	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Observations	411	411	411	411	410	411	411	411	200
Mean(Y) reference cat.	147.1	130.6	140.8	138.0	101.6	138.9	145.4	139.4	146.0
R-squared	0.26	0.26	0.26	0.26	0.27	0.26	0.27	0.26	0.38

*Notes: The dependent variable is log of 24-hour average personal exposure to $PM_{2.5}$. Standard errors are clustered at the household level and displayed in parentheses. The reference category of all variables of interest is their lowest category, i.e. most closed/smallest kitchen. *** p<0.01, ** p<0.05, * p<0.1*