Nitrogen dioxide exposures from biomass cookstoves in the Peruvian Andes

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Abstract

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Background—Household air pollution from biomass cookstoves is a major contributor to global morbidity and mortality, yet little is known about exposures to nitrogen dioxide (NO_2).

Objective—To characterize NO_2 kitchen area concentrations and personal exposures among women with biomass cookstoves in the Peruvian Andes.

Methods—We measured kitchen area NO_2 concentrations at high-temporal resolution in 100 homes in the Peruvian Andes. We assessed personal exposure to NO_2 in a subsample of 22 women using passive samplers.

Results—Among 97 participants, the geometric mean (GM) highest hourly average NO_2 concentration was 723 ppb (geometric standard deviation (GSD) 2.6) and the GM 24-hour average concentration was 96 ppb (GSD 2.6), 4.4 and 2.9 times greater than WHO indoor hourly (163 ppb) and annual (33 ppb) guidelines, respectively. Compared to the direct-reading instruments, we found similar kitchen area concentrations with 48-hour passive sampler measurements (GM 108 ppb, GSD 3.8). Twenty-seven percent of women had 48-hour mean personal exposures above WHO annual guidelines (GM 18 ppb, GSD 2.3). In univariate analyses, we found that roof, wall, and floor type, as well as higher SES, was associated with lower 24-hour kitchen area NO_2 concentrations.

Practical Implications—Kitchen area concentrations and personal exposures to NO_2 from biomass cookstoves in the Peruvian Andes far exceed WHO guidelines. More research is warranted to understand the role of this understudied household air pollutant on morbidity and mortality and to inform cleaner-cooking interventions for public health.

Keywords

biomass cookstove; environmental justice; household air pollution; indoor air pollution; nitrogen dioxide; women's health

1 | INTRODUCTION

Nearly 40% of households worldwide use biomass fuels, such as charcoal, wood, and dung, as their primary source of cooking fuel.[1] These biomass cookstoves produce high levels of household air pollution (HAP) which can exceed WHO indoor guidelines[2] by orders of magnitude.[3] HAP from cookstoves is typically characterized by short-term, high-concentration spikes during cooking which gradually decay to background levels once cooking is complete. Women and children specifically face higher exposure to smoke from biomass cookstoves due to traditional labor roles and closer proximity to and involvement with cooking activities.[4,5] Emissions from biomass cookstoves are complex mixtures of a range of health-threatening pollutants,[6] yet the existing cookstove literature has focused on particulate matter and carbon monoxide (CO) as the components of HAP with the greatest impact on morbidity and mortality.[7] Exposure to HAP has been associated with acute lower respiratory infection in children,[8] COPD,[8–11] lung cancer,[12,13] and increased blood pressure[14,15] and was responsible for an estimated 1.6 million premature deaths worldwide in 2017.[16]

Little is known about nitrogen dioxide (NO_2) emissions and exposures from biomass cookstoves, in spite of NO_2 being a known by-product of biomass combustion[6,17–19] and a regulated hazard to human health.[18] According to the United States Environmental Protection Agency (US EPA), exposure to NO_2 is causally related to respiratory effects.[18] A growing body of literature suggests associations between NO_2 exposure and the development[20] and exacerbations[21–24] of pediatric asthma, COPD,[25,26] worse lung function in adults and children,[27–33] and all-cause mortality.[34,35] High-concentration spikes of NO_2 exposure are known to have different effects on health than chronic exposures,[18] and the WHO has developed separate annual and hourly guidelines for indoor NO_2 concentrations.[2] A few studies in Asia and Africa have measured 24- or 48-hour time-weighted average (TWA) concentrations of NO_2 in homes with biomass cookstoves. With one exception,[36] all studies reported mean kitchen area TWA concentrations between 1.5 and 6.5 times greater [37–43] than the WHO indoor annual guideline.[2] However, to our knowledge, no study has characterized NO_2 concentrations from biomass cookstoves at high-temporal resolution to quantify the potentially health-relevant concentration spikes from cooking or to assess whether kitchen concentrations exceed hourly guidelines. Additionally, we know of no assessments of personal exposure to NO_2 from cooking with biomass fuel. The dearth of knowledge on NO_2 exposures from biomass cookstoves leaves a critical gap in our understanding of the full impacts of biomass cookstoves on global morbidity and mortality and of the pollutant reductions needed to improve public health through cleaner-cooking interventions. To address this gap, this study aims to characterize daily and hourly kitchen area concentrations and personal exposures to NO_2 among women who use biomass cookstoves in rural Peru.

2 | METHODS

2.1 | Study setting and design

This study was nested within a randomized controlled, field trial of a liquefied-petroleum gas (LPG) cleaner-cooking intervention in the Puno province of Peru. Puno is a rural, agricultural region in the southern Peruvian Andes at 3,825 meters above sea level. Openfire biomass-burning stoves are prevalent, and cow dung is the most common cooking fuel.[44] We enrolled study participants from predominantly Indigenous Aymara communities where daily life generally revolves around subsistence farming and small-scale quinoa and potato production. In these low-density communities, homes are located a median distance of 101 meters from the closest neighboring home[45] and local sources of ambient air pollution are minimal. Most households have separate kitchen and sleeping structures, which together surround a central courtyard.

In the Cardiopulmonary Outcomes and Household Air Pollution Trial (CHAP),[45] 180 women aged 25–64 years who used biomass fuel daily were enrolled and randomized 1:1 into an LPG intervention group or a control group. Participants in the intervention group received an LPG stove and free fuel delivered to their homes and installed by trained research staff for one year. Participants in the control group continued to use biomass and will receive an LPG stove and fuel after the first year of the study. The current study is based on results from the CHAP trial's baseline assessments of women who used

biomass cookstoves daily. Participants' demographic data were collected via questionnaire and kitchen characteristics were directly observed by trained field research staff. Wealth status was calculated using the Demographic and Health Survey (DHS) wealth quintiles, which were previously determined based on a nationally representative survey conducted in Peru.[46] We assigned each participant in our study a score based on their ownership of assets considered by the DHS (computer, bookshelf, windows with curtains, sofa, toilet connected to the sewer, reinforced concrete roof, and brick or cement walls).[47] We then classified participants into one of the five wealth quintiles based on their total score. Additional information about enrollment and assessments in the CHAP trial has been previously published.[45]

We randomly selected a subsample of 100 participants from the overall trial (n = 180) for NO_2 kitchen area assessment and inclusion in this study. Of those 100 participants, 22 participants were randomly selected to also receive personal exposure assessment. All participants provided informed consent verbally, and the trial received approval from the Johns Hopkins School of Public Health Institutional Review Board, AB PRISMA Ethical Institutional Committee, and the Universidad Peruana Cayetano Heredia Institutional Review Board.

2.2 | Exposure assessment of nitrogen dioxide

2.2.1 | Kitchen area assessment—We monitored kitchen area NO_2 concentrations for 48 hours in each household. We used direct-reading monitors to sample at high-temporal resolution in 100 households and collected additional, time-integrated measurements via passive samplers in a subsample of 20 households. All kitchen area samplers were placed in a wire birdcage suspended from the ceiling, located at 1.0 meter horizontal distance from the edge of the stove combustion zone and 1.5 meters above the floor. This standard location was chosen to approximate the breathing zone of a woman cooking at the stove. Field staff used a measuring tape to ensure consistent placement of the samplers in relation to the cookstove.

We sampled kitchen area NO_2 concentrations at high-temporal resolution using Aeroqual Series 500 portable direct-reading monitors with NO_2 sensor heads (Aeroqual Limited, Auckland, New Zealand). Measurements were recorded at one-minute temporal resolution throughout the 48-hour sample, with support from two auxiliary batteries to extend the sampling duration due to the lack of electricity in many households. To mitigate imprecision between sensors, we co-located Aeroqual monitors in the field office every four months and subjected all monitors to NO_2 concentrations ranging from ambient concentration to approximately 1000 ppb, using an LPG stove as the emissions source. We calculated intercept and slope adjustments for each sensor with robust linear regression using Siegel repeated medians (*mblm* R package v0.12.1; Komsta, 2019), comparing individual sensor readings with the median measurement from all collocated sensors. We found no evidence of a linear pattern in the drift of individual sensors across multiple collocations over time, and all collocations were pooled to create a single slope and intercept adjustment for each device. To determine the limit of detection (LOD), two devices were brought to the Johns Hopkins University for comparison with a gold standard reference instrument

(model 42c, Thermo Environmental Instruments Inc, Franklin). The LOD was calculated as three times the standard deviation (SD) of the difference between these two devices and reference instrument-confirmed zero-air from a dynamic gas calibrator (model 146i, Thermo Environmental Instruments Inc, Franklin). We estimated an LOD of 20 ppb, and 36% of all collected 1-minute measurements fell beneath the LOD. All concentrations <20 ppb were replaced with LOD/sqrt(2) ≈ 14.1 ppb, which is similar to a recent modeled estimate[48] of ambient NO_2 conditions in the Puno region (12 ppb). After twelve months of use, sensor heads were decommissioned and replaced with new, factory-calibrated sensors, as recommended by the manufacturer for high-concentration settings.

In a subset of 20 households, we sampled time-integrated kitchen area NO_2 concentrations with Ogawa Passive Samplers (Ogawa USA, Pompano Beach). Samples were analyzed at the Universidad Peruana Cayetano Heredia in Lima, Peru, using standard colorimetric methods.[49] Temperature and relative humidity were measured during each sample by a collocated Enhanced Children's Monitor (RTI Inc, Research Triangle Park) for calculation of the final TWA NO_2 concentration. Temperature data for one sample were missing due to instrument failure and were imputed using the median temperature from all kitchen samples. Field blanks were taken every 10th sample, and we calculated the LOD as the mean plus SD*3 concentration among blanks. We estimated the LOD to be 2.6 ppb, similar to the manufacturer recommended lower range of accuracy (2 ppb), and none of the passive sampler kitchen area concentrations fell beneath the LOD.

2.2.2 | Personal exposure assessment—We assessed personal exposure for 48 hours using Ogawa Passive Samplers as described above. These passive badge samplers are small and lightweight and, unlike the heavier Aeroqual direct-reading monitors, can be easily worn by participants. The passive samplers were attached to aprons which had been altered to hold personal exposure monitors for $PM_{2.5}$ and CO and were provided to the participants.[45] Participants were asked to wear the apron at all times during waking hours and to place the apron nearby when sleeping or bathing. The NO_2 sampler and temperature and relative humidity loggers were placed over each participant's central chest region, to approximate conditions in each woman's breathing zone. One personal sample had missing temperature data, which was replaced with the median temperature among all personal samples. We used the same LOD of 2.6 ppb for personal exposure samples, and one personal exposure sample (4%) which was below the LOD was replaced with LOD/sqrt(2) ≈ 1.8 ppb.

2.3 | Statistical methods

All samples from the direct-reading kitchen monitors that did not meet a minimum duration of 20 hours were excluded from the analysis. We hypothesized that mean kitchen area concentrations would largely be driven by a small number of biomass cooking events throughout the day and that samples that lasted less than the targeted 48 hours would be biased by which cooking events were or were not captured in the final sampling day. As 15% of sample durations were >24 hours but   44 hours, we used only data from sampling hours 0–24 to calculate a 24-hour mean, for consistency. Because of the high-altitude setting, we assumed conditions of 10°C and an altitude of 3825 MASL to estimate an atmospheric pressure of 625 hPa and convert mass concentration guidelines

to setting-specific ppb (annual, 40 μg/m^3 = 33 ppb; hourly 200 μg/m^3 = 163 ppb).[2] We calculated the highest hourly average concentration as the highest 60-minute centered rolling mean throughout the entire duration of each kitchen area sample. To understand the duration of high exposures, we estimated the number of hours per day where kitchen area concentration exceeded 163 ppb, the WHO indoor NO$_2$ hourly guideline.[2] We calculated summary statistics for the direct-reading measurements and the time-integrated passive samplers. We performed a Shapiro-Wilk test of the log-transformed 24-hour mean kitchen area concentrations, which failed to reject the null of a lognormal distribution (*P*-value = .052). Therefore, we calculated and reported geometric mean (GM) and geometric standard deviation (GSD) for descriptive results of NO$_2$ concentrations, as a compliment to the arithmetic mean and standard deviation. We also estimated the Spearman's correlation coefficient of 48-hour passive samples comparing concurrent measurements of kitchen area concentration and personal exposure.

We used linear regression to examine associations between 24-hour mean kitchen area NO$_2$ concentrations and characteristics of participants and their kitchens. We log-transformed NO$_2$ concentrations to meet model assumptions of homoscedasticity. All regression estimates were transformed to represent the percent difference in NO$_2$ concentration (the dependent variable) associated with a unit increase in the independent variables. We used simple linear regression to analyze the single variable associations between 24-hour mean NO$_2$ and age (in one-year increments), education (primary school or less vs. secondary school), SES quintiles (1st [lowest] vs. 2nd or 3rd), chimney (none vs. roof opening vs. chimney), roof type (thatch/natural fiber/other vs. corrugated metal), wall type (adobe without plaster vs. adobe with plaster/other), floor type (earth vs. cement), and number of windows (0, 1, 2+). We did not include kitchen area entrances in this analysis as all observed kitchens had exactly one entrance.

We also examined the correlation between co-located direct-reading monitors and passive samplers in kitchens, however a substantial number of co-located direct-reading monitors did not achieve the entire 48-hour duration of the passive samplers due to insufficient battery power. All analyses were performed using R (www.r-project.org).

3 | RESULTS

3.1 | Participant characteristics

We successfully completed assessments for 97 participants (Table 1), as three kitchen area assessments did not meet a minimum duration of 20 hours due to battery failure. The average age among participants was 48 years, and 95% of participants were in the two lowest national wealth quintiles. Within participant homes, kitchens generally had either a non-specific opening in the roof or no ventilating structures, with walls made of adobe and earthen floors. We observed a range of 0–6 windows in the kitchens with a median of one window.

3.2 | Kitchen area concentrations of nitrogen dioxide

Results from the direct-reading instruments at one-minute temporal resolution indicate short-term concentration spikes in kitchen areas orders of magnitude above the WHO indoor annual and hourly guidelines. These data are presented as a bar plot of study-wide concentrations throughout each minute of the day (Figure 1). Dark blue indicates the proportion of households with kitchen NO_2 concentrations <33 ppb at a given time of day, with other colors representing increasingly higher concentration bins as indicated in the legend. A substantial proportion of kitchens experience high concentrations during common cooking times (5:00–9:00 and 18:00–20:00 hours). For example, at approximately 8:00 hours, NO_2 concentrations were 1000 ppb in 20% of households (red color), 500 ppb in 40% of households (red and orange colors), and the WHO indoor hourly guideline of 163 ppb in 60% of households (red, orange, yellow, and light blue colors).

The GM highest hourly average NO_2 concentration was 723 ppb (GSD 2.6) (Table 2), over four times greater than the hourly guideline of 163 ppb. The distribution of highest hourly averages per sample is presented as a modified empirical cumulative distribution function plot (Figure 2). The x-axis represents NO_2 concentration and the y-axis represents the percent of observations with hourly average concentrations less than the corresponding concentration. Ninety-one percent of kitchens had highest hourly average concentrations above the WHO indoor hourly guideline (163 ppb), and 40% of households had hourly averages which exceeded 1000 ppb. Kitchen concentrations exceeded the hourly guideline for a mean duration of 3.0 hours or 12.5% of daily time (Table 2). The GM 24-hour TWA NO_2 concentration from the direct-reading instruments was 96 ppb (GSD 2.2) (Table 2), 2.9 times greater than the WHO annual guideline of 33 ppb. In a modified empirical cumulative distribution plot of 24-hour TWA kitchen concentrations, only 12% of kitchens had 24-hour TWA NO_2 concentrations below the annual guideline and 51% of households had 24-hour TWA concentrations more than three times (99 ppb) greater than the WHO annual guideline (Figure 3). In the subsample of 20 kitchens where NO_2 was measured using passive samplers, one sample was lost during processing. In the successful 19 kitchen area passive samples, the GM 48-hour TWA NO_2 concentration was 108 ppb (Table 2).

3.3 | Associations between participant and kitchen characteristics and nitrogen dioxide concentrations

In the single variable regression analysis, higher SES, corrugated metal roofs (vs. thatch/natural/other), walls of adobe with plaster/other (vs. adobe without plaster), and cement floors (vs. earth) were associated with lower 24-hour mean kitchen area NO_2 concentrations (Table 3). Notably, neither chimney type nor number of kitchen windows were associated with kitchen area NO_2 concentration.

3.4 | Personal exposure to nitrogen dioxide

Personal exposure to NO_2 was sampled in 22 women using passive samplers attached to aprons worn by participants. The GM time-integrated personal exposure to NO_2 during a 48-hour sample was 18 ppb (GSD 2.3) (Table 2). Twenty-seven percent of women experienced mean personal exposures in excess of the WHO annual guideline (33 ppb) (Figure 4).

Among 19 concurrent passive samples of NO_2 kitchen area concentration and personal exposure, we observed a Pearson correlation coefficient of 0.43.

4 | DISCUSSION

To our knowledge, this is the first study to measure kitchen area NO_2 concentrations at high-temporal resolution and personal exposure to NO_2 from biomass cookstoves. Using direct-reading instruments allows for the characterization of concentration spikes from cooking events, which are known to have different health impacts than chronic NO_2 exposures and are poorly quantified by integrated sampling methods. Among women with biomass cookstoves in Peru, 91% of households sampled had highest hourly NO_2 concentrations above the WHO indoor hourly guideline, with a GM 4.4 times above the same guideline. Chronic exposures were also excessive, and two different sampling methods recorded GM daily kitchen area NO_2 concentrations approximately three times greater than the WHO indoor annual guideline. We observed that 27% of women in this study experienced 48-hour TWA personal exposures to NO_2 that exceeded annual guidelines.

The mean NO_2 kitchen area concentrations we observed in this study (129 ppb arithmetic mean, direct-reading), where dung is the predominant biomass fuel, are similar to those observed by Colbeck et al in biomass-burning kitchens in rural Pakistan (136 ppb).[39] An assessment of NO_2 in 36 homes in rural Kenya who used a mix of crop residues and wood as fuel observed 24-hour mean concentrations of 90 ppb.[43] Padhi et al reported mean kitchen NO_2 concentrations of 72 ppb among 378 households in rural India who used a mix of wood, cow dung, agricultural residue, and dried leaves.[41] The largest assessment to date, by Kumie et al, recorded a mean of 52 ppb NO_2 among 17,215 samples of kitchen areas in Ethiopia where burning of dung is common.[37] Cookstove emissions of NO_2 are partially a function of biomass fuel type and physical combustion processes.[50] However, the relative importance of differences in cooking behaviors associated with different fuel types (eg cooking duration, number of cooking events, household sociodemographic differences, or confounding by regional social and cultural traditions) and kitchen characteristics (eg household ventilation) is poorly understood. In studies which specifically report wood as the primary biomass fuel,[36,38,40,42] mean NO_2 concentrations are lower ($\approx$30 ppb) than observed in this and other studies in which dung, agricultural residue, or a mix of biomass fuels were used. Lower NO_2 emissions from wood compared to dung fuel were also observed in brief assessments of kitchen area NO_2 concentrations while cooking in rural India.[51] It is worth noting that in spite of possibly lower concentrations in wood-burning kitchens, all but one study[36] of wood-fueled cookstoves report mean concentrations that exceed WHO annual guidelines.

While 27% of participants had 48-hour personal exposures above the WHO annual guideline, GM personal exposures were 5 and 6 times lower than direct-reading and passive sampler kitchen area concentrations, respectively. Though we are aware of no prior HAP studies which compare kitchen area concentrations and personal exposures to NO_2, a systematic review by the WHO of biomass-related $PM_{2.5}$ estimated $PM_{2.5}$ personal exposures 3.6 times lower than $PM_{2.5}$ kitchen area concentrations.[52] In our rural setting, sources of ambient air pollution are minimal and personal exposures are likely dominated

by cooking-related exposures while inside the kitchen area. Qualitative research in our study has shown that women frequently do not stay inside the kitchen throughout the entire cooking event. Compared to populations in settings with higher ambient air pollution, participants in our study likely have lower personal exposure to NO_2 and other air pollutants when outside the kitchen area, and a larger difference between kitchen area concentrations and personal exposures is plausible.

In our single variable analysis of participant and kitchen characteristics and 24-hour kitchen area NO_2 concentration, higher SES as well as type of roof (metal), wall (plastered adobe), and floor (cement) were associated with lower kitchen area NO_2. A 2014 study by Pollard et al examining kitchen characteristics and $PM_{2.5}$ concentrations in rural Puno[53] did not find an association between kitchen area $PM_{2.5}$ and SES, though they did observe a lack of association between kitchen area $PM_{2.5}$ and windows similar to our study. The apparent lack of importance of number of kitchen windows may be related to the cold climate in Puno, as windows are often kept closed for comfort and may have a relatively minor impact on ventilation. Pollard also reported an association between metal roofs and lower kitchen area $PM_{2.5}$, which we found for lower kitchen area NO_2. It is plausible that these associations are related to ceiling ventilation. In Puno, corrugated metal roofing sheets are commonly attached to the rafters in a manner which creates a gap between the roof and the kitchen wall, potentially facilitating ventilation. In contrast, thatch roofs a few decimeters thick often sit directly on top of the kitchen wall, providing limited airflow. If roof material or design is related to kitchen area NO_2 concentration, it provides a potential point of intervention to reduce NO_2 exposures from biomass cookstoves.

We observed similar GM kitchen area daily concentrations using the passive samplers and the direct-reading monitors. While the number of passive samples was relatively small, these passive samplers are considered a gold standard method, and the similar magnitude of daily concentrations observed corroborates the high daily concentrations reported by the direct-reading monitors. We intended to compare measurements from collocated direct-reading monitors and passive samplers, yet many of the direct-reading samples did not achieve the full 48 hours of duration of the passive samplers, due to battery failure. To determine if the first and second days of direct-reading sampling were interchangeable, we compared mean concentrations between hours 0–24 and hour 24 through the end of each direct-reading sample. We estimated an adjusted R^2 of 0.33 using the mean concentration during the first day of sampling to predict mean concentrations during the second day. Because of the substantial within-household variability between the first and second sampling days with the direct-reading monitors, we concluded that the measurements of physically collocated direct-reading monitors (ranging from 20 to 48 hours duration) and passive sampler (≈48 hours duration) measurements were not directly comparable given the differences in sampling duration.

This study has many strengths, including the use of monitors with high-temporal resolution to detect time-weighted average concentrations and acute concentration spikes, the use of both passive and direct-reading samplers to take field measurements, and the collection of personal exposure samples. This study is limited by the relatively small number of personal samples, though this is the first assessment of personal exposure to NO_2 from

biomass cookstoves to the authors' knowledge. While direct-reading instruments allowed us to observe NO_2 concentrations at high-temporal resolution among a much larger sample of kitchen areas, we do not know how these concentrations relate to true personal exposures as individual behavior such as timing and duration of time spent in the kitchen or proximity to other sources of NO_2 is unknown. Furthermore, while Aeroqual NO_2 monitors were calibrated in high-altitude Puno, the estimation of the LOD was performed at approximately sea level in Baltimore, USA. A recent study of Aeroqual O_3 monitors, with similar electrochemical sensors to the NO_2 monitors in this study, found comparable correlations with reference-instruments in both high-altitude (approximately 1650 MASL) Denver, USA, and low-altitude (approximately 300 MASL) Atlanta, USA.[54] While the effect of atmospheric pressure on electrochemical sensors is expected to be minimal by design, we cannot rule out the possibility of bias in our LOD estimates from varying altitude.

5 | CONCLUSIONS

Current efforts to reduce morbidity and mortality from emissions from biomass cookstoves have focused on $PM_{2.5}$ and CO as the primary risks to health. However, this study provides evidence of acute and long-term NO_2 area concentrations and personal exposures at levels known to harm health, using two different sampling methods. We also found evidence that NO_2 concentrations are associated with kitchen roof, wall, and floor materials, which may be actionable points of intervention to reduce NO_2 exposure among biomass fuel users. While this study is based in the Peruvian Andes, studies in Pakistan, Kenya, India, and Ethiopia have also indicated high mean concentrations of NO_2 with a similar magnitude in homes with biomass cookstoves. If NO_2 exposures from biomass cookstoves are present in other settings globally, the public health community may be underestimating true morbidity and mortality from biomass cookstove emissions by focusing only on the risks from $PM_{2.5}$ and CO. Children in particular are known to be vulnerable to NO_2 exposure, which can lead to the development and exacerbation of pediatric asthma and limit lung development with permanent effect. Further attention is warranted to characterize the global presence of acute and chronic NO_2 exposures from biomass cookstoves, understand how this is impacting the health of women, children, and others who cook with biomass fuel, and ensure that cleaner-cooking public health interventions are effective at reducing not only $PM_{2.5}$ and CO, but also NO_2.

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APPENDIX

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Practical Implications

- Epidemiologic studies and public health interventions of household air pollution (HAP) have focused on particulate matter and carbon monoxide as the byproducts of biomass combustion of greatest concern to public health. Little is known about HAP-related exposures to nitrogen dioxide (NO_2), a known byproduct of biomass combustion and a threat to respiratory health.

- We measured NO_2 kitchen area concentrations at high-temporal resolution and personal exposure among women with biomass cookstoves in Peru. We found NO_2 kitchen area concentrations and personal exposures which far exceed WHO annual and hourly guidelines.

- Further attention is warranted to understand the impact of HAP-associated chronic and acute exposures to NO_2 on morbidity and mortality, and to inform cleaner-cooking interventions that aim to reduce exposures to all health-threatening household air pollutants.
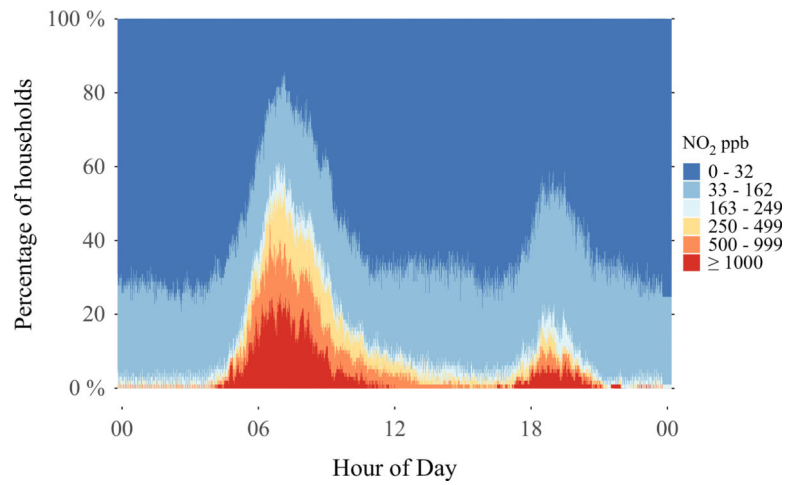
FIGURE 1.

Prevalence of indoor NO_2 concentrations by calendar minute in 97 kitchens with biomass cookstoves in rural Peru. For example, at approximately 8:00 h, NO_2 concentrations were 1000 ppb in 20% of households (red color), 500 ppb in 40% of households (red and orange colors), and the WHO indoor hourly guideline of 163 ppb in 60% of households (red, orange, yellow, and light blue colors)
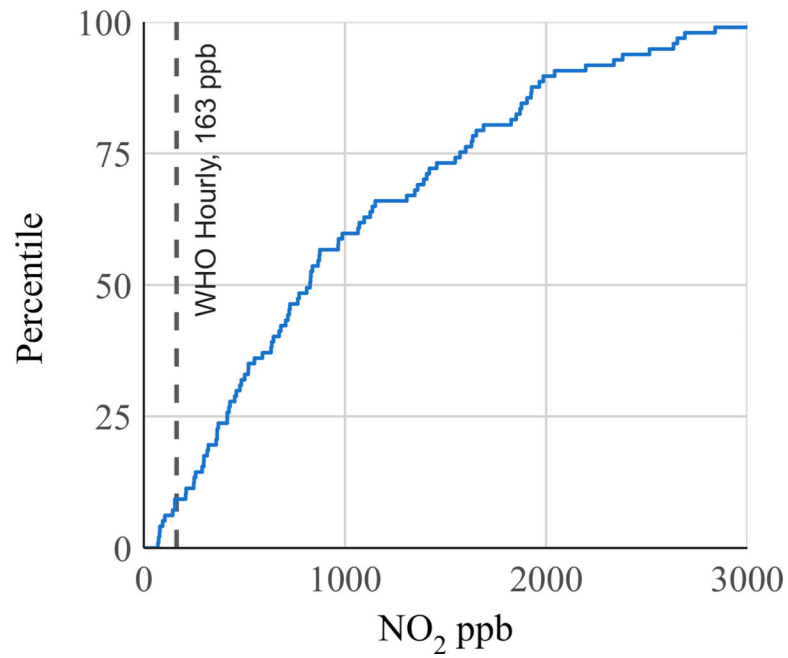
FIGURE 2.

Distribution of highest hourly mean NO_2 concentrations in 97 kitchens with biomass cookstoves in rural Peru, with WHO indoor NO_2 hourly guideline of 163 ppb. The *x*-axis represents NO_2 concentration and the *y*-axis represents the percent of observations with hourly average concentrations less than the corresponding concentration
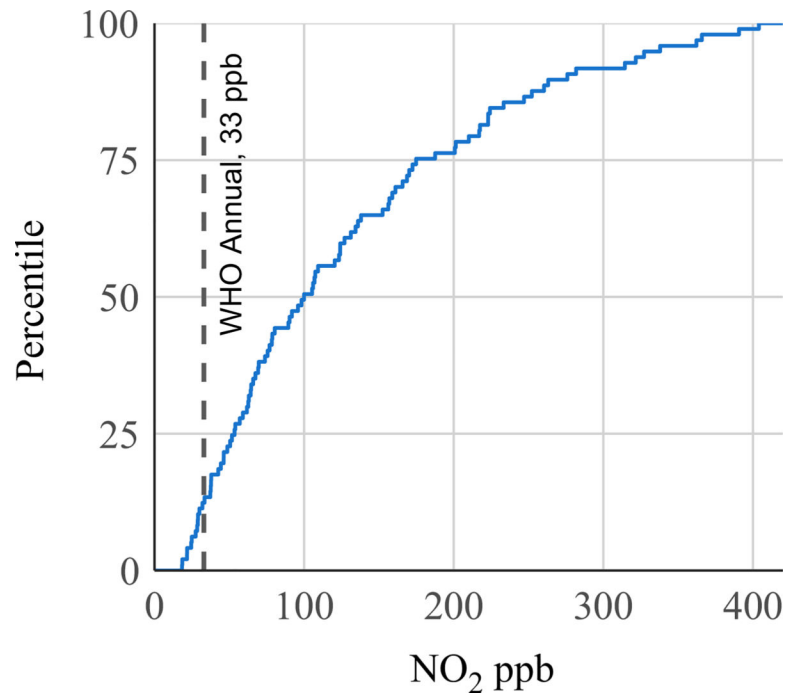
FIGURE 3.

Distribution of 24-h mean NO$_2$ concentrations in 97 kitchens with biomass cookstoves in rural Peru, with WHO indoor NO$_2$ annual guideline of 33 ppb
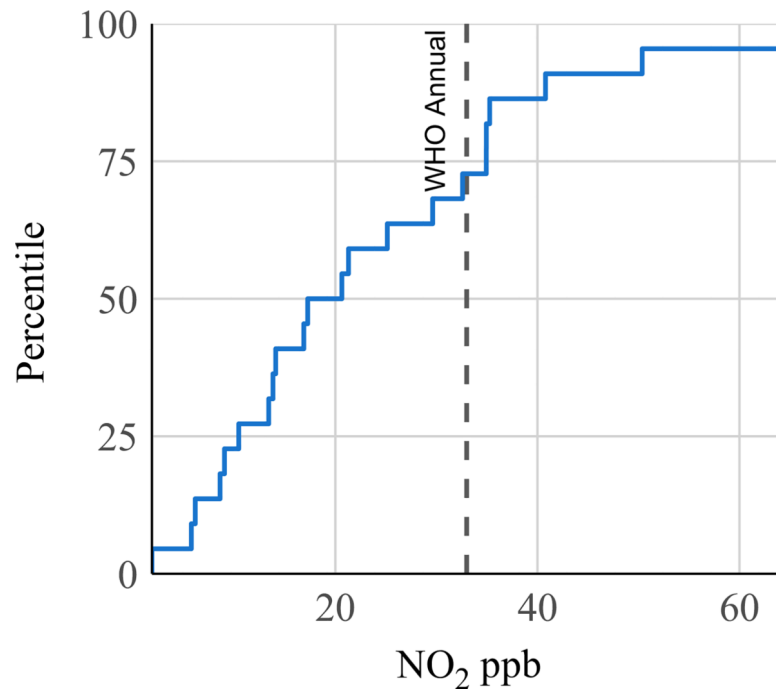
FIGURE 4.

Distribution of 48-h mean personal exposure to NO_2 among 22 women who use biomass cookstoves in rural Peru, with WHO indoor NO_2 annual guideline of 33 ppb

TABLE 1

Characteristics of study participants and their kitchens in Puno, Peru

	N (%) or Mean (SD)
Number of participants	97
Age in years	48 (10)
Education	
Primary or less	57 (59%)
Secondary	40 (41%)
National SES quintile	
1 (lowest)	55 (57%)
2	37 (38%)
3	5 (5%)
4	0 (0%)
5 (highest)	0 (0%)
Cookstove ventilation	
Chimney	9 (9%)
Roof opening	48 (49%)
No cookstove ventilation	40 (41%)
Roof type	
Corrugated metal	43 (44%)
Natural fiber (thatch)	53 (55%)
Other	1 (1%)
Wall type	
Adobe/mud with plaster	26 (27%)
Adobe/mud without plaster	65 (67%)
Other	6 (6%)
Floor type	
Dirt	89 (92%)
Cement	8 (8%)
Kitchen windows (#)	
0	38 (39%)
1	42 (43%)
2 +	17 (18%)
Kitchen doors/entryways (#)	
1	97 (100%)

Note: SD, standard deviation; SES, socio-economic status.

TABLE 2

Nitrogen dioxide kitchen concentrations and personal exposures among women with biomass cookstoves in Puno, Peru

	N	Mean	SD	GM	GSD	Min	25th %ile	Median	75th %ile	Max
Kitchen area: direct-reading										
Highest hourly means (ppb)	97	1027	781	723	2.6	70	415	826	1572	3901
24-h means (ppb)	97	129	97	96	2.2	18	54	100	175	404
Daily hours > 163 ppb	97	3.0	2.1	2.0	3.4	0.0	1.3	2.8	4.5	9.8
Kitchen area: passive badge										
48-h means (ppb)	19	199	192	108	3.8	7	67	117	387	593
Personal exposure: passive badge										
48-h means (ppb)	22	23	16	18	2.3	2	11	19	34	64

Note: GM, geometric mean; GSD, geometric standard deviation; ppb, parts per billion; SD, standard deviation.

TABLE 3

Associations of 24-h mean NO_2 concentrations in 97 kitchen areas of biomass cookstove users in Puno, Peru, presented as percent concentration difference associated with participant and kitchen characteristics

	Univariate
Age (one-year increase)	1.3 (−0.4, 3.0)
Education	
Primary or less	Ref
Secondary	−14.6 (−38.7, 18.9)
SES	
1st quintile (lowest)	Ref
2nd or 3rd quintile	−29.4 (−48.9, −2.5)[*]
Chimney	
None	Ref
Opening	3.8 (−26.3, 46.1)
Chimney	−37.0 (−65.1, 13.5)
Roof type	
Thatch/natural/other	Ref
Corrugated metal	−49.1 (−62.3, −31.3)[*]
Wall type	
Adobe w/o plaster	Ref
Adobe w plaster/Other	−31.9 (−51.5, −4.3)[*]
Floor type	
Earth	Ref
Cement	−48.2 (−71.0, −7.5)[*]
Windows	
0	Ref
1	−4.9 (−33.9, 36.7)
2 +	4.5 (−34.9, 67.8)

Note: SES, socio-economic status.

[*] *P*-value < 0.05.