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Women exposure to household air pollution after an improved cookstove program in rural San Luis Potosi, Mexico

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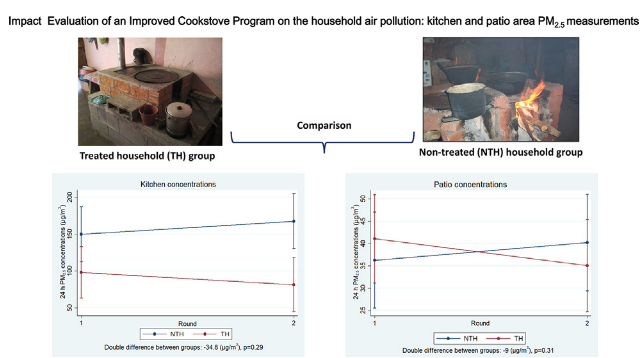
HIGHLIGHTS

- Kitchen and patio $PM_{2.5}$ levels using solid fuels in a Mexican rural context.
- The impact evaluation lost validity because of non-comparable groups.
- "Real scenario" analysis: an alternative evaluation of factors related to air pollution exposure.
- Wealthier households are more likely to present patterns of fuel-devices stacking.
- Improved cookstoves in good conditions or LPG can reduce daily $PM_{2.5}$ exposure up to 10 μg/m^3.

GRAPHICAL ABSTRACT



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ABSTRACT

The state government of San Luis Potosí (SLP), Mexico implemented an improved cookstove (ICS) program in rural areas. As part of the comprehensive program evaluation, we compared fine particulate material ($PM_{2.5}$) concentrations in kitchens and patios in treated (TH), and non-treated households (NTH), and analyzed pollutant levels according to patterns of fuels and devices use reported by the women.

A panel study was conducted in 728 households (357 TH and 371 NTH) in three regions of SLP including two sampling rounds in 2015–16. Data on exposure determinants, ICS conditions and cooking practices

Abbreviations: HAP, Household air pollution; SLP, San Luis Potosí; ICS, Improved cookstove; $PM_{2.5}$, Fine particulate matter; TH, Treated households; NTH, Non-treated households; OF, Open fire; LPG, Liquefied petroleum gas; CO, Carbon monoxide; DALY, Disability-adjusted life years; SEDESORE, Secretariat for Social and Regional Development; LOQ, Limit of quantification; SES, Socioeconomic status; IQR, Interquartile range; IOR, Indoor/outdoor ratio; FKR, Female/kitchen ratio; ICSp, Improved cook-stove in poor conditions; ICSg, Improved cook-stove in good conditions; LPG, liquefied petroleum gas stove. OF+ICSp/ICSp, Open fire plus Improved cookstove in poor condition or only improved cookstove in poor condition; OF+ICSp+LPG/OF+LPG, Open fire plus improve cookstove in poor condition plus LPG stove or Open fire plus LPG; OF+LPG, Open fire plus LPG stove; ICSg/ICSg+LPG, Improved cookstove in good condition or Improved cookstove in good condition plus LPG stove.

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were collected. Daily $PM_{2.5}$ in kitchen and patio was measured in a subsample. The average treatment effect was estimated using the double difference method. We constructed a mixed linear model to estimate $PM_{2.5}$ levels for the entire study sample and obtained personal exposure according to time-activity logs.

NTH had lower socioeconomic status compared to TH. The average daily $PM_{2.5}$ concentrations in NTH compared to TH were 155.2 and 92.6 μg/m^3 for kitchen and 35.4 and 39.8 μg/m^3 for patio, respectively. $PM_{2.5}$ levels showed significant regional differences but no significant treatment effect. In many cases, the ICS was added to previous open fire and LPG use (stacking). The household size, kitchen ventilation, relative humidity, temperature and the ratio of indoor/outdoor $PM_{2.5}$ concentration were significant predictors of kitchen $PM_{2.5}$ levels. The daily $PM_{2.5}$ personal exposure was significantly reduced using ICS in good conditions or LPG (57 μg/m^3) compared to the traditional open fire (86 μg/m^3).

This study strengthens the evidence on the potential daily $PM_{2.5}$ exposure reduction for women using an ICS in good conditions or LPG, displacing the polluting open fire. Comprehensive strategies tailored to the sociocultural context of the communities are needed to implement clean energy programs that achieve adoption and sustained use of ICS or LPG.

1. Introduction

Incomplete combustion of solid fuels (mostly biomass in Mexico) for cooking performed in inefficient open fires release a large and complex pollutant mixture of gases and particles, which have adverse effects on health (Lippmann et al., 2013; Naeher et al., 2007; Smith et al., 2014). These fuels are the primary source of household air pollution (HAP) in low and middle-income countries resulting in approximately 4 million premature deaths annually and 110 million of disability-adjusted life years (DALYs) (Bruce et al., 2015; Lim et al., 2012; Smith et al., 2014).

Improved cookstoves (ICS) is one of the strategies implemented to reduce emissions and exposure to household air pollutants. However, its implementation has not consistently shown enough decrease in concentrations of pollutants to achieve health benefits (Bruce et al., 2015; Pilishvili et al., 2016; Pope et al., 2017; Quansah et al., 2017). Assessments of HAP levels are scarce worldwide. Only a few studies have been published in Mexico (Armendariz-Arnez et al., 2008; Zuk et al., 2007). The available information on HAP levels shows high variability and is influenced by several factors, such as stove design, combined use of fuels-and stoves, cooking practices and other contextual factors related to the adoption and sustained use of the ICS across different regions (Baumgartner et al., 2011; Clark et al., 2013; Rehfuess et al., 2014; Shupler et al., 2018). A special focus should be placed on measuring the exposure to HAP in rural and indigenous communities worldwide to guide protection from its harmful effects (Balakrishnan et al., 2013; Landrigan et al., 2018; Shupler et al., 2018).

By the year 2010, 22.5 million solid-fuel users (mainly fuelwood) were estimated in Mexico, 16.4 million were exclusive users, and the rest mixed its use with liquified petroleum gas (LPG). Fuelwood users are mainly located in rural and peri-urban areas (Serrano-Medrano et al., 2014).

In 2010, 22.6% of households used solid fuel in San Luis Potosí (SLP) in North-Central Mexico (population 2,585,518). Most of these households were located in rural and indigenous communities. The state is divided into four geographical regions. The Central and Altiplano regions are located on a plateau and have a dry, steppe climate with scarce rainfall. The Media and Huasteca regions are hilly, with hot, humid jungle climate and concentrates the indigenous population and the solid fuel user (INEGI, 2017).

The Government of SLP through the Secretariat for Social and Regional Development (SEDESORE) implemented the Housing Improvement Program in the period 2010 to 2015, subsidizing over 60 thousand ICS with the goal of addressing the poverty in rural poor communities where they cook with fuelwood in open fires. The state government chose to install *in situ* construction and prefabricated plancha-type ICS with an improved combustion chamber, big flat pan or *comal*, two secondary pots and a metal chimney, in poor rural areas from the four regions (Sedesore, 2013).

In response to a state request, after operating the program for four years, we performed a comprehensive summative evaluation which was conducted in 2015–2016. Both the process and the impacts of the ICS program were assessed. One of the outcome variables in the *ex post* impact evaluation was HAP levels measured as $PM_{2.5}$ concentrations during two visits. Herein we report and compare the kitchen and patio $PM_{2.5}$ concentrations measured in treated and non-treated households. We also analyzed the HAP levels according to patterns of fuel and devices use reported by the households and we estimated the daily personal exposure as well for the rest of the study sample in SLP, Mexico.

2. Materials and methods

2.1. Study design and population

We selected 13 municipalities where the program was implemented during different years. The municipalities represented three of the state's regions: Altiplano (1), Centro (3) and the Huasteca (9). Within the municipalities, 54 villages were chosen (Fig. 1). ICS had been installed between 2010 and 2013. In each village, the treated households (TH) were selected from the beneficiary list provided by the program through random sampling. For each treated household, one non-treated household (NTH) was selected in the same village by random sampling (comparison group) as described in Figure S1 (Supplementary file). The sample included 728 households, 357 treated and 371 non-treated. The panel study included two rounds of data collection between February 2015 and April 2016. The time between rounds was, on average, eight months.

In a subsample of households (100 TH and 112 NTH), particulate matter with aerodynamic diameter of<2.5 μm ($PM_{2.5}$) concentrations were measured over a 24-h period at each of the two rounds in the kitchen and patio areas. The woman in charge of cooking in each household answered the questionnaires and the time-activity logs record as described in the Supplementary Material (Fig. S1).

The study was approved by the Research Ethics Committee of the National Institute of Public Health. All study participants provided written consent.

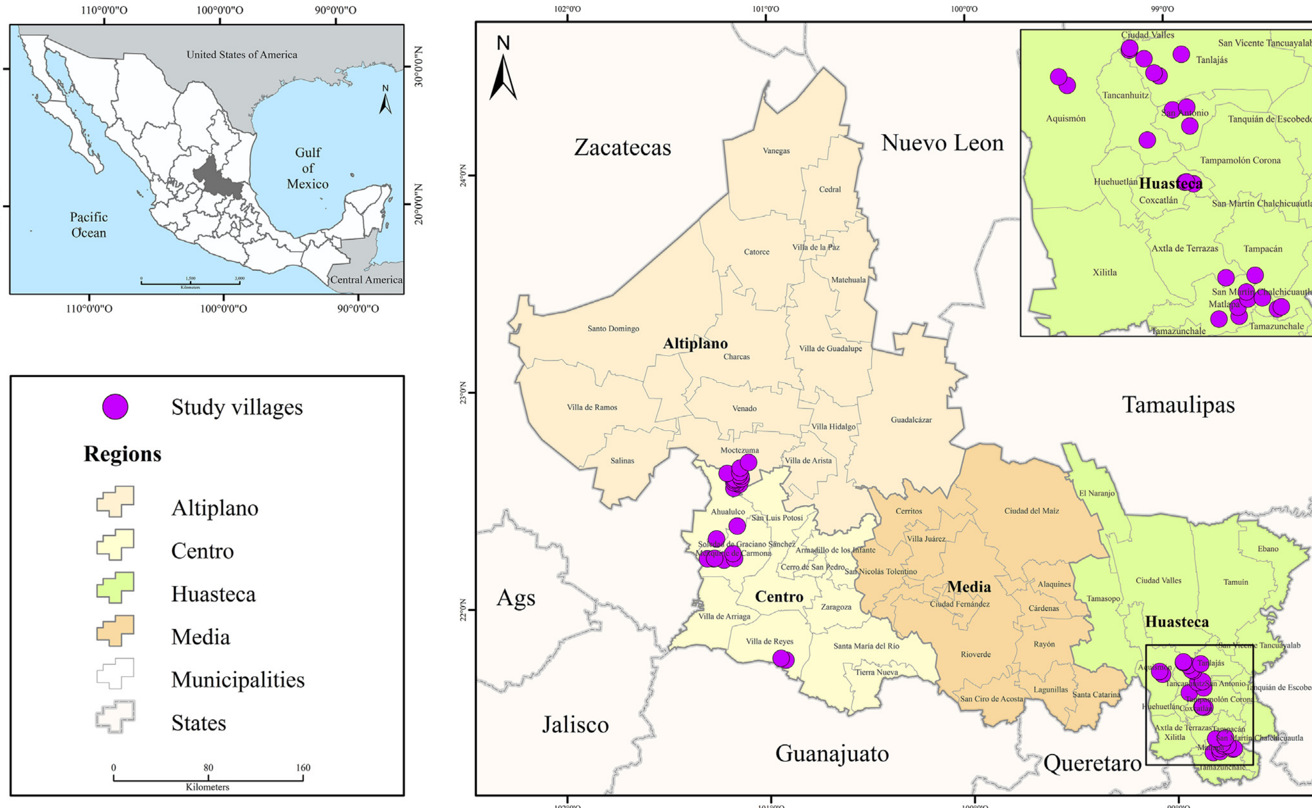

Figure 1. Map showing the state of San Luis Potosí in Mexico and the study villages located in Altiplano, Centro and Huasteca regions

2.2. Data collection

In the selected households, trained field staff administered detailed questionnaires to women in each of the rounds. The questionnaires have been used in previous studies at indigenous rural communities in Mexico (Romieu et al., 2009) and provide information about household and kitchen characteristics, such as construction materials, demographics, fuel use patterns, and cooking practices. Demographic data included number of inhabitants, income and possessions. Ventilation of the kitchen was classified as poor, regular and sufficient based on the number of open doors, windows and eave spaces. Women reported the presence and use of fuels and cooking devices and household fuel use categories were defined according to the patterns observed for this population. The condition of the ICS was classified as in good or in poor condition based on the state of the combustion chamber, metal chimney and comales. Information on other potential sources of air pollution such as backyard trash-burning, smoking and motor traffic was collected.

Daily data on temperature, relative humidity and rainfall were obtained from the National Meteorological Service of Mexico. Data for the study villages were assigned from the nearest meteorological station.

2.3. Air sampling methods

Kitchen and patio areas $PM_{2.5}$ air sampling was performed using MiniVol samplers (version 4.2; Airmetrics, Eugene, OR, USA) during 24-h periods in 47 mm Teflon filters (Pall Corporation, Ann Arbor, MI, USA) at a target flow of 5 l min^{-1}. Pre- and post-calibrations were made with a single flow tube rotameter for medium flow rate measurement (Aalborg Instruments & Controls Inc, NY, USA) in the field. The sampling procedures used are described in previous studies (Armendariz-Arnez et al., 2008; Zuk et al., 2007), briefly, the kitchen measurements were standardized at 1.25 m above ground, at a horizontal distance of 1 m from the primary cooking device and at least 1.5 m from windows and doors. The patio microenvironment was measured by placing monitors 1.5 m above ground and as close as possible to where the inhabitants reported spending the most time when outdoors. $PM_{2.5}$ concentrations were measured in a random subsample of 212 households (102 treated and 100 non-treated) at each of the two rounds. At the first round (February to September 2015) we collected samples in 109 households, the second (October 2015 to April 2016) included 103 households. A total of 75 households had samplings in both rounds.

Gravimetric analysis of the filters was conducted after and before sampling at controlled conditions (at 22 ± 3 °C with 40 ± 5% of relative humidity for 24-h); filters were weighted using an ultra-microbalance with 1 μg sensitivity (Cahn model C-35, Thermo Fisher, Germany), at the Laboratory from the Mexican National Institute of Ecology and Climate Change.

Approximately 5% (25 filters) of the total number of samples were used as field blanks. Field blank filters were handled identically to exposed filters, but no air passed through their surface. Approximately 3% (15 filters) of samples were duplicates placed in identical conditions, subject to the same field conditions and analyzed with the same protocol as the sample filters for quality control. The difference between the collocated samples was between 9 and 18%. Limit of detection (LOD) for $PM_{2.5}$ was estimated as three times the standard deviation (3δ) of the mass change in the field blanks divided by the 24-h nominal volume. The LOD for indoor and outdoor $PM_{2.5}$ measurements ranged from 1.80 to 4.61 μg/m^3, and from 1.65 to 4.24 μg/m^3, respectively. Laboratory limit of quantification (LOQ) was the lowest limit of the working range able to be weighted in the ultra-microbalance based on the laboratory blanks divided by the nominal volume of the corresponding exposure time (24-h). The average LOQ was found to be 0.1 μg/m^3.

Of the 212 samples collected, 11 kitchen and 8 patio samples were excluded from the analysis because the sampling period was<18-h (Non-valid time).

2.4. Time-activity logs and women personal exposure estimation

Time-activity logs were applied to capture information about the place and time of all participanťs activities during the air sampling period. The daily estimated personal exposure to $PM_{2.5}$ was calculated as the time-weighted average area concentration, applying equation (1) (Clark et al., 2013; WHO, 2008)

$$Daily\,personal\,exposure = \sum_{i=1}^{n} (f_{\text{kitchen}} * PM_{2.5\,\text{kitchen}}) + (f_{otherindoorenvironment} * PM_{2.5\,patio}) + (f_{patio} * PM_{2.5\,patio}) \quad (1)$$

where f_i is the fraction of time spent in the microenvironment i (kitchen, other indoor microenvironment, and patio), $PM_{2.5\ i}$ is the 24-h $PM_{2.5}$ concentration in the microenvironment i (kitchen and patio) and n is the number of women with complete and valid data for air monitoring and time-activity logs (Armendariz-Arnez et al., 2008; Zuk et al., 2007). We assumed that the concentration of other indoor environments was the same as the patio concentration.

2.5. Statistical analysis

A descriptive analysis of the sociodemographic variables, characteristics of the house and kitchen, fuel and energy-use patterns, cooking practices, $PM_{2.5}$ measurements for each area and fractions in each microenvironment was carried out. A single socioeconomic status (SES) index was constructed using principal components analysis. The following ten socio-economic variables had been chosen *a priori*: (i) number of people per room; (ii) presence of specific housing characteristics; (iii) flooring material; (iv) drinking-water source; (v) toilet facility; (vi) land tenure; (vii) educational level; (viii) access to health services; (ix) household assets; (x) household income. The resulting SES score was categorized in five levels using quintiles.

With the information for the first round, the comparability of the study groups was verified, using *t*-test, Kruskal Wallis test, or chi-square test, as required.

The average treatment effect (ATE) of the program on $PM_{2.5}$ area concentrations and the daily personal exposure was calculated by the double difference (DD) estimation technique within mixed effects regression models. DD compares the changes in outcome over time (1st. difference) between the treatment and comparison groups (2nd difference) (Gertler et al., 2016). This allows correcting for any differences between the treatment and comparison groups that are constant over time. The estimating equation would be specified as follows:

$$Y_{it} = \alpha + \beta T_i + \gamma P_i + \delta T_i * P_i + \eta C_i + \varepsilon_{it} \quad (2)$$

In the equation (2), the coefficient δ on the interaction between the program treatment variable (T_i) and period of time (P = 1…2) gives the average DD effect of the program adjusted by covariates (C_i). A level of significance of p = 0.05 was specified. The analyses were performed using Stata version 14.2 (StataCorp, College Station, TX, USA).

2.6. $PM_{2.5}$ exposure model

The potential predictive variables of kitchen $PM_{2.5}$ concentrations according to previous studies were obtained from the household questionnaires and the time-activity logs: Region of residence (dichotomized as Altiplano-Centro and the Huasteca because of geographical and climatic differences), number of people who eat and live in the house, number of rooms in the house, type of building materials for roofs, walls and floors of household and kitchen, type and location of the kitchen, number of windows, doors and open eave spaces in the kitchen categorized as poor, regular and sufficient ventilation, daily use of the cooking devices: open fire (OF), improved cookstove (ICS), LPG stove (LPG) and their combinations; improved cookstove condition (good vs poor condition), number of hours cooking "tortillas" (traditional corn accompaniment for daily meals) and other foods, other uses of the cooking devices (lighting and heating), type and number of fuels used (LPG, fuelwood, crop residues, paper, plastic), backyard trash burning and presence and frequency of vehicle traffic. Improved cookstove in good condition and LPG stove were classified as efficient cooking devices. Any cooking device combined with open fire was classified as inefficient. Meteorological variables (temperature, pressure, altitude above sea level, relative humidity and climatic season) were also obtained and considered as predictive variables.

To explore outdoor contribution to indoor air pollution (Barraza et al., 2014), we calculated the indoor-to-outdoor (I/O) ratio of particle concentration, which was log-transformed because of skewed distribution and considered as a predictive variable. The Female/Kitchen (F/K) ratio for $PM_{2.5}$ concentrations was generated as the quotient between personal and kitchen $PM_{2.5}$ concentrations to compare our results with the average exposure ratios estimated by regions in the Global Burden of Disease Study (Shupler et al., 2018).

Mixed linear regression models were constructed using the log-transformed kitchen $PM_{2.5}$ concentration as the outcome variable to evaluate the association of potentially predictive variables described above. The variability due to unexplained "between-ho usehold" differences was modeled as a random effect, allowing for "within household" comparisons between follow-up periods in treated and non-treated groups. The analysis was adjusted for time-dependent variables, such as number people who eat and live in the house, daily hours cooking tortillas, weather variables and indoor/outdoor $PM_{2.5}$ ratio. The selection of the best model -- which is shown in equation (3) -- consisted of a leaps and bounds algorithm using adjusted R^2 and Mallow's Cp as information criteria (Lindsey and Sheather, 2010). The validation of the model was performed graphically and calculating Pearsońs correlation coefficient between the measured and estimated values.

$$\begin{aligned} E\{log(PM_{2.5})\} = {} & \beta_0 + \beta_R(Number\ of\ rooms\ in\ household) \\ & + \beta_P(Number\ of\ persons\ cooked\ for\ and\ living\ in\ the\ household) \\ & + \beta_{v1} I(Ventilation = regular) + \beta_{v2} I(Ventilation = sufficient) \\ & + \beta_{CD1} I(Cooking\ device = OF + ICS\ in\ poor\ condition \\ & /or\ only\ ICS\ in\ poor\ condition) + \beta_{CD2} I(Cooking\ device \\ & = OF + ICS\ in\ good\ condition + LPG/or\ OF + LPG) \\ & + \beta_{CD3} I(Cooking\ device = OF + LPG) \\ & + \beta_{CD4} I(Cooking\ device = ICS\ in\ good\ condition \\ & /or\ ICS\ in\ good\ condition + LPG) + \beta_{CD5} I(Cooking\ device = LPG) \\ & + \beta_{T1}(daily\ hours\ cooking\ tortillas) \\ & + \beta_{TE1}(daily\ mean\ ambient\ air\ temperature\ ^\circ C) \\ & + \beta_{H1}(daily\ mean\ ambient\ air\ humidity) \\ & + \beta_{RIE1}(log\ ratio\ indoor/outdoor\ PM_{2.5}) \end{aligned} \quad (3)$$

where $I(X = L) = 1$, if the categorical variable X assumes the level "L", otherwise is 0. Reference categories are "poor ventilation" for kitchen ventilation index and "Open fire (OF)" for daily use of cooking devices, respectively.

Estimated regression coefficients (and 95% confidence intervals) obtained from the model were exponentiated for interpretation (exp^{β}), and the percent change in kitchen $PM_{2.5}$ concentration expressed in percentage was calculated as: ($[exp^{\beta} - 1] \times 100$).

2.7. $PM_{2.5}$ exposure estimation

Using the model in equation (3), $PM_{2.5}$ concentrations in the kitchen were estimated for the whole sample of households in the study. The predictor variables were obtained in each round from the household questionnaire applied in the entire study sample. Mean daily temperature and humidity were obtained for the date of visit in each round.

Patio concentration for the study population without air sampling was assigned from the nearest household measured in the same village or the nearest village with measurement for each round, assuming neighborhood air pollution (Salje et al., 2014). Hence, the entire study sample had a patio and kitchen $PM_{2.5}$ concentration for one or both visits; this allowed us to estimate both the indoor-to-outdoor (I/O) ratio and the level of personal exposure.

3. Results

3.1. Household characteristics and energy use

A total of 357 treated (TH) and 371 non-treated households (NTH) were selected proportionally to the regional prevalence of solid fuel use in the Altiplano-Centro and Huasteca regions (Table 1 and Fig. 1). As shown in the study population flow diagram (Supplementary file, Fig. S1), a 13% (99) was lost to follow up for the second round, mainly because of refusal to participate. The losses to follow up were more likely from the non-treated group (18% vs. 9%, p = 0,001) but had no other significant differences with the participants in both rounds.

As shown in Table 1, the Huasteca region is poorer compared to Altiplano-Centro region, as can be observed by a lower SES (29 vs.1%, p < 0.001), and households are more likely to have soft roofing materials and dirt floors. The NTH were poorer (25 vs. 17%, p = 0.005), had slightly fewer rooms, and were more likely to have a dirt floor and no electricity compared to the treated group. In more than half of the households the kitchen was a separate building. Huasteca's kitchens were more likely to have dirt floors but also had better ventilation, as compared with the Altiplano-Centro region. These differences were also significant between study groups.

The traditional open fire was observed in almost all non-treated households, and a significant reduction (27%, 95% CI: 33,21%) was achieved with the ICS program in the treated group. Other fuels, such as plastic, paper, and crop residues, were also burned in a

Table 1
Household and kitchen characteristics, energy use and cooking practices by study group and region, SLP Mexico.

Characteristics	Altiplano-Centro (n = 230)		Huasteca (n = 498)		Total (N = 728)	
	NTH (n = 110)	TH (n = 120)	NTH (n = 261)	TH (n = 237)	NTH (n = 371)	TH (n = 357)
Household characteristics	n (%)	n (%)	n (%)	n (%)	n (%)	n (%)
Persons living and eating in the household, mean (SD)	5.7 (2.5)	5.8 (2.7)	5.5 (2.1)	5.6 (2)	5.5 (2.2)	5.6 (2.3)
Rooms in household, mean (SD)	2.6 (1.2)	2.8 (0.9)	3.2 (1.3)	3.2 (1.5)	2.6 (1.2)*	2.9 (1.4)*
Firm vs soft roofing material[2]	66 (60)	78 (65)	58 (22)	50 (21)	124 (33)	128 (36)
Dirt vs firm floor	1 (1)	3 (3)	52 (20)	22 (9)	53 (14)†	25 (7)†
Electricity	108 (98)	119 (99)	211 (81)	206 (87)	319 (86)*	325 (91)*
Piped water supply	29 (27)	27 (23)	51 (20)	60 (25)	80 (22)	87 (24)
Trash-burning	90 (82)	102 (88)	173 (66)*	177 (75)*	263 (71)*	279 (79)*
Motor traffic near the household	20 (18)	27 (23)	91 (35)	78 (33)	111 (30)	105 (30)
Socioeconomic status index						
First Quintile (lowest)	2 (1.8)	1 (1)	90 (34.6)‡	56 (23.7) ‡	92 (24.9) ‡	57 (16.5) ‡
2nd Quintile	4 (3.6)	6 (5.5)	72 (27.7)	60 (25.4)	76 (20.5)	66 (19.1)
3rd Quintile	15 (13.6)	15 (13.6)	57 (21.9)	59 (25)	72 (19.5)	74 (21.4)
4th Quintile	36 (32.7)	32 (29.1)	26‡ (10)	44‡ (18.6)	62 (16.8)	76 (21.9)
5th Quintile (highest)	53 (48.3)	56 (50.8)	15 (5.8)	17 (7.2)	68 (18.3)	73 (21.1)
Kitchen characteristics						
Kitchen as a separate building	54 (55)	74 (64)	179 (69)	162 (69)	233 (65)	236 (67)
Firm vs soft roofing material[2]	54 (49)	61 (51)	13 (5)	3 (1)	67 (18)	64 (18)
Dirt vs firm floor	9 (8)	7 (6)	124 (48)*	86 (36)*	133 (36)‡	93 (26)‡
Ventilation[3]						
Poor	35 (32)	42 (35)	63 (24)	46 (19)	98 (26)	88 (25)
Regular	75 (68)	75 (63)	139 (53)	152 (64)	214 (58)	227 (64)
Sufficient	0 (0)	3 (2)	59 (23)	39 (17)	59(16)	42 (12)
Household energy use and cooking practices						
Fuels used						
Wood	108 (98)	116 (98)	258 (99)	236 (99)	366 (99)	352 (99)
LPG	94 (85)	98 (82)	31 (12)	43 (18)	125 (34)	141 (40)
Plastic	34 (31)	32 (27)	111 (43)	104 (44)	145 (39)	136 (38)
Others (Paper, crop residues, cardboard)	24 (22)	20 (17)	76 (29)*	89 (38)*	100 (27)	109 (31)
Presence of cooking device						
Open fire	90†	65†	90†	62†	90†	63†
ICS	15†	90†	31†	85†	27†	87†
LPG stove	83	79	18	22	37	41
Others (electric, grill, oven, bath open fire)	10	8	7	7	7	8
ICS in good condition	68	73	72	71	71	72
Daily tortilla cooking time, hours, mean (SD)	1.7 (1.3)	1.7 (1.2)	1.1 (0.9)	1.1 (0.8)	1.3 (1.1)	1.3 (0.9)
Daily food cooking time, hours, mean (SD)	3.7 (1.9)	3.6 (1.7)	2.6 (1.4)	2.7 (1.5)	2.9 (1.7)	3 (1.6)
Weather conditions for air sampling						
Average daily temperature (°C), mean (SD)	16 (4)	16 (4)	25 (4)	24 (4)	21 (6)	21 (5)
Relative humidity (%), mean (SD)	61.5 (14.2)	63.7 (14.9)	81.6 (12.9)	83.8 (9.2)	72.1 (16.8)	75.9 (15.4)

Values shown are percentages of group totals unless otherwise specified.
SD: Standard deviation, LPG: Liquefied petroleum gas, ICS: improved cookstove, °C: degrees Celsius, NTH: Non-treated household, TH: Treated household. Significant difference between groups. P-value*< 0.05, ‡p < 0.01, †p < 0.001.
1. National Council for the Evaluation of Social Development Policy. 2. Firm roof: concrete slab, partition, brick and roof beams. 3. Kitchen ventilation index: presence of open windows when cooking + presence of open doors when cooking + number of eave spaces.

higher percentage in the Huasteca region. LPG stove presence was higher in the Altiplano-Centro compared to the Huasteca region (81% vs.20%, $p < 0.001$), but no significant difference was observed between treatment groups (37% vs. 41%, p = 0.22). The women spent on average 4 to 5-h cooking every day. The households subsample where air was monitored was similar to the total sample, except that the former was more likely to have electricity (96% vs. 87%, p = 0.005).

The Supplementary Material Fig. S2 summarizes the multiple fuel-devices use patterns for the cooking practices reported in the study groups by region. The prevalence of daily use of the traditional open fire (OF) was much higher in the Huasteca region compared to the Altiplano-Centro region (53% vs. 9%, p = 0.001). The ICS program replaced the daily use of open fire in greater proportion in the TH group compared to the NTH (39% vs. 10%, p = 0.001). However, no differences were found in the OF replacement between regions (25% vs. 24%, p = 0.92). The daily use of LPG stoves was significantly higher in the Altiplano-Centro region than in the Huasteca (15% vs. 2%, p = 0.001). The prevalence of multiple device use (stacking) was higher in the Altiplano-Centro region (77% vs. 46%, p = 0.001).

3.2. Household and personal air pollution exposure levels

Overall, the $PM_{2.5}$ concentrations in the kitchen area -- where the emission source is located -- were higher compared to those found in the patio. The mean (and standard deviation) and median (and interquartile range IQR) of the total 24-h measurements in the kitchen were 122.8 ± 146.9 μg/m^3 and 71.3 μg/m^3 (IQR: 42, 120.9). The mean 24-h kitchen concentrations considering all samples in the treated households was 40% lower compared to the NTH group (92.6 ± 110 μg/m^3 vs. 155.2 ± 172.9 μg/m^3; p = 0.002). Similarly, the median kitchen concentrations in the TH was 18% lower compared to the NTH group [77.4 (IQR: 43.7,188.9) vs. 65.9 μg/m^3 (IQR: 36.6,99.3); p = 0.01]. By regions, Altiplano-Centro reported higher mean kitchen $PM_{2.5}$ concentration compared to the Huasteca region (168.3 ± 201.6 vs. 87.4 ± 63.6 μg/m^3; p = 0.0001). (Fig. 2A). However, the average effect of the program (estimated as the double difference) of the ICS program was a non-significant difference of 34.8 μg/m^3 (95% CI: −99.9,30.2; p = 0.294) in the kitchen area from the TH.

The global mean and median of 24-h $PM_{2.5}$ patio concentrations were 35.6 ± 21.7 and 32.4 μg/m^3 (IQR: 19.1–47.3). The Altiplano-Centro region showed a lower concentration of the pollutant in the patio compared to the Huasteca (23.9 ± 15.1 μg/m^3 vs. 48.1 ± 45.2 μg/m^3, respectively; p = 0.001). No significant average effect of the program was found for $PM_{2.5}$ patio concentrations (p = 0.9) (Fig. 2B).

The global I/O ratio (IOR) was 4.8 ± 7.7 (CI 95%: 3.7, 5.9) showing a significant difference between study groups (NTH 6.5 ± 9.4 vs. TH 3.3 ± 5.2; p = 0.003), and by regions where the Altiplano-Centro region had a higher I/O ratio compared with the Huasteca (8.1 ± 10.5 vs. 2.2 ± 1.9); p = 0.001). No difference was found between rounds (4.1 ± 5.6 vs.5.5 ± 9.3; p = 0.20).

The fraction of time spent in each microenvironment contributed differently to participants' daily average $PM_{2.5}$ exposure. The time spent in the kitchen area represented the largest fraction (0.44) from the participantś total indoor activities (0.78). No differences were found for the fraction of time spent in the microenvironments between study groups or regions, so these values were used for the personal exposure estimation for the whole sample.

$PM_{2.5}$ daily average estimation of personal exposure in the participants from the air sampling subsample was 36% lower in the TH group. The largest crude reduction in estimated exposure between study groups was observed during the second round: 62 μg/m^3, 95% CI: 19, 107; p = 0.005. Personal exposure in the Altiplano-Centro region decreased 48% (65 μg/m^3, 95% CI: 8, 120; p = 0.03) while in the Huasteca personal exposure decreased only 19% (15 μg/m^3, 95% CI:-6, 36 μg/m^3; p = 0.16) (Fig. 2C). Otherwise, the ICS program average effect in daily personal exposure for the women of the subsample showed a non-significant difference of 30.9 μg/m^3 (95% CI: −78.2, 15.4; p = 0.2).

As described in Table S1 of the Supplementary Material, women using ICS in good condition or LPG stove or both as the primary cooking device had the lowest daily personal exposure compared to the use of traditional open fire. This use represents a reduction in the exposure between 13 and 26%. Within the regions, this gradient was greater for the Altiplano-Centro (37 to 52%) while exposure in the Huasteca diminished by 14 to 31% (Table S1).

The female/kitchen ratio (FKR) for the subsample was 0.8 ± 0.9 (CI 95%: 0.75, 0.99) without differences between study groups (p = 0.37). By regions, it was greater in the Huasteca compared to Altiplano-Centro region (0.9 ± 1.1 vs. 0.7 ± 0.3, p = 0.02) (Table 2).

Table 2 shows the descriptive and multivariate log-linear regression analysis for kitchen $PM_{2.5}$ concentrations. The variables selected in the model were the kitchen characteristics related to ventilation, cooking practices and environmental conditions (temperature and humidity). Other household structural characteristics were not significantly associated with pollution and therefore not included in the final model. Kitchen $PM_{2.5}$ concentrations decreased significantly in the households with more rooms, and especially with sufficiently ventilated kitchens (37%, 95% CI: 49%, 21%; p = 0.001).

Several behavioral factors of cooking practices were significant predictors of $PM_{2.5}$ concentrations in the kitchen area. A large number of people living and eating in the household increased $PM_{2.5}$ levels by 3% (95% CI: 0%, 6%; p = 0.09), and so did a larger number of daily hours cooking tortillas (4%, 95% CI: −2%, 11%; p = 0.171). In contrast, in the household where a daily mixed use of cooking devices was reported, the combination of improved cookstove in good condition with LPG stove (-8%, 95% CI: –23%, 11%, p = 0.38) and open fire with LPG stove (-13%, 95% CI: −28%, 5%; p = 0.15) had the greatest reductions in $PM_{2.5}$ concentrations.

The increase in ambient temperature (4%, 95% CI: 3%, 5%; $p < 0.001$) and relative air humidity (1%, 95% CI: 0%, 1%, p = 0.007) were associated with small but significant higher $PM_{2.5}$ concentrations in the kitchen. We found no association of the pollutant with other climatic factors (atmospheric pressure, season, day of the week and month of the visit, altitude above sea level or type cooking fuel).

The log-linear regression for 24-h kitchen $PM_{2.5}$ concentration had an adjusted R^2 of 0.78 (Table 2) with a fair degree of correlation (r = 0.86) between estimated and measured values (Figure S3 in Supplementary file).

3.3. Women exposure estimation

After estimating the kitchen and patio concentration for the whole sample considering both rounds, the average daily personal exposure was 71.8 μg/m^3 (95% CI: 69.9, 73.5), with no significant difference between treatment groups (NTH 72.6 ± 33 vs. TH 70.8 ± 33.7 μg/m^3; p = 0.32). Levels of exposure of women of the Huasteca region were, on average, 15% lower than in women of the Altiplano-Centro [68.01 μg/m^3 (CI 95%: 66.7, 69.3) vs. 79.8 μg/m^3 (95% CI: 75,84.6); p = 0.001]. In the second round, womeńs personal exposure was lower than the first [68.7 μg/m^3 (CI 95%: 66.1, 71.3) vs. 74.3 μg/m^3 (95% CI: 71.9, 76.8); p = 0.002].

By household energy categories, users of an ICS in poor condition had the highest mean daily personal exposure, increased by 24% (18.2 μg/m^3) compared with the open fire users [94.1 μg/m^3 (95% CI: 82, 106) vs. 75.9 μg/m^3 (95% CI: 73.3, 78.3); p = 0.002]. This increase in the personal exposure was 25% in the Altiplano-

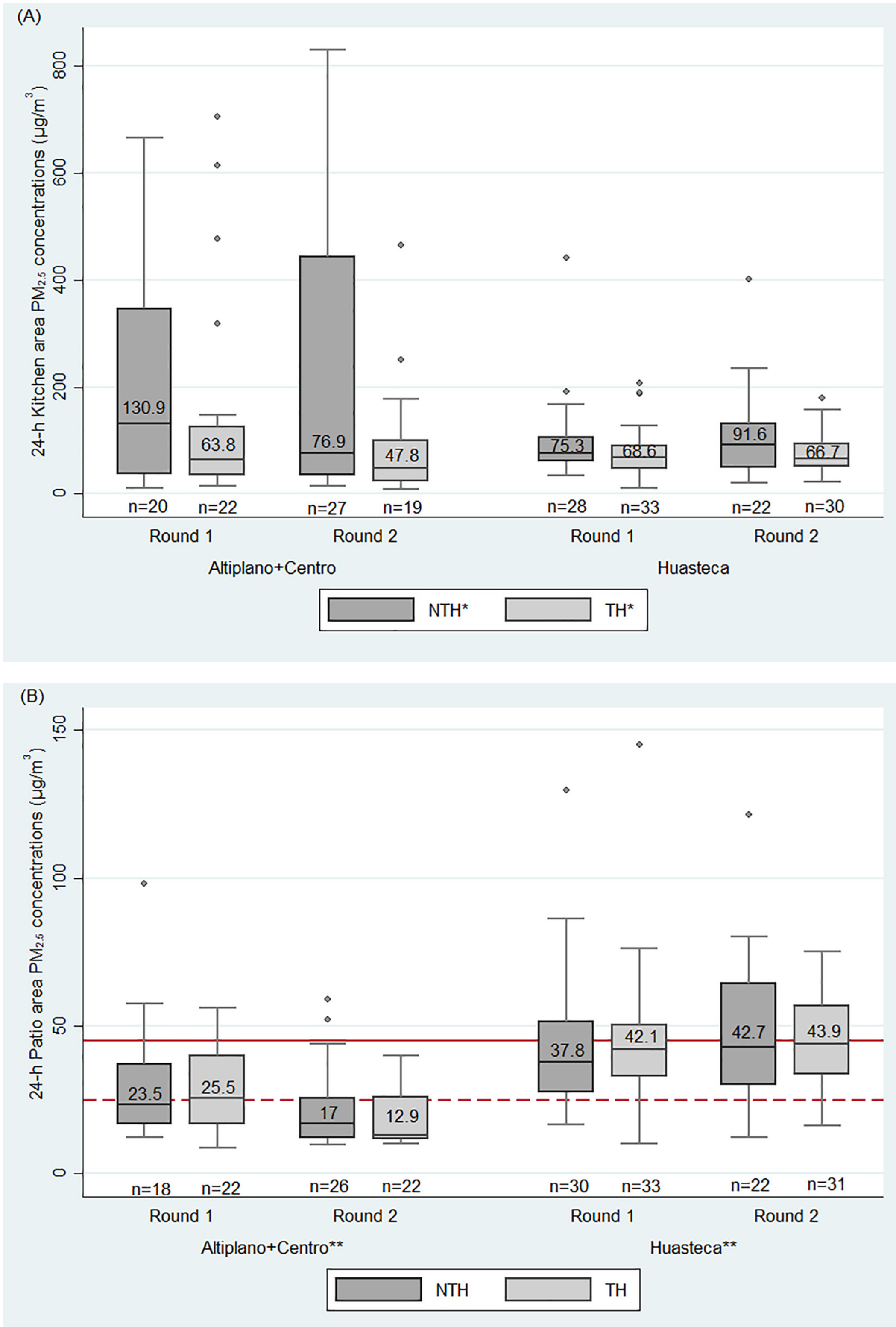

Figure 2. 24-hour PM2.5 (µg/m³) concentrations in kitchen, patio area and estimated personal exposure by treated group and region. A. Kitchen area, B. Patio area, C. Personal exposure estimation

Centro region [159.4 µg/m³ (95% CI: 120.7, 197.9) vs. 119.4 µg/m³ (95% CI: 95.6, 143.2); p = 0.257] and 6% in the Huasteca [78.5 µg/m³ (95% CI: 72.2, 84.8) vs. 72.5 µg/m³ (95% CI: 70.8, 74.2); p = 0.77] (Fig. 3). On the whole sample, efficient cooking devices users had on average 13% less exposure than the women who used inefficient technologies. This lower exposure was greater in Altiplano-Centro region [22%, 71.4 µg/m³ (CI 95%: 62.3,80.4) vs. 91.3 µg/m³ (95% CI: 82.9,99.7); p = 0.001].

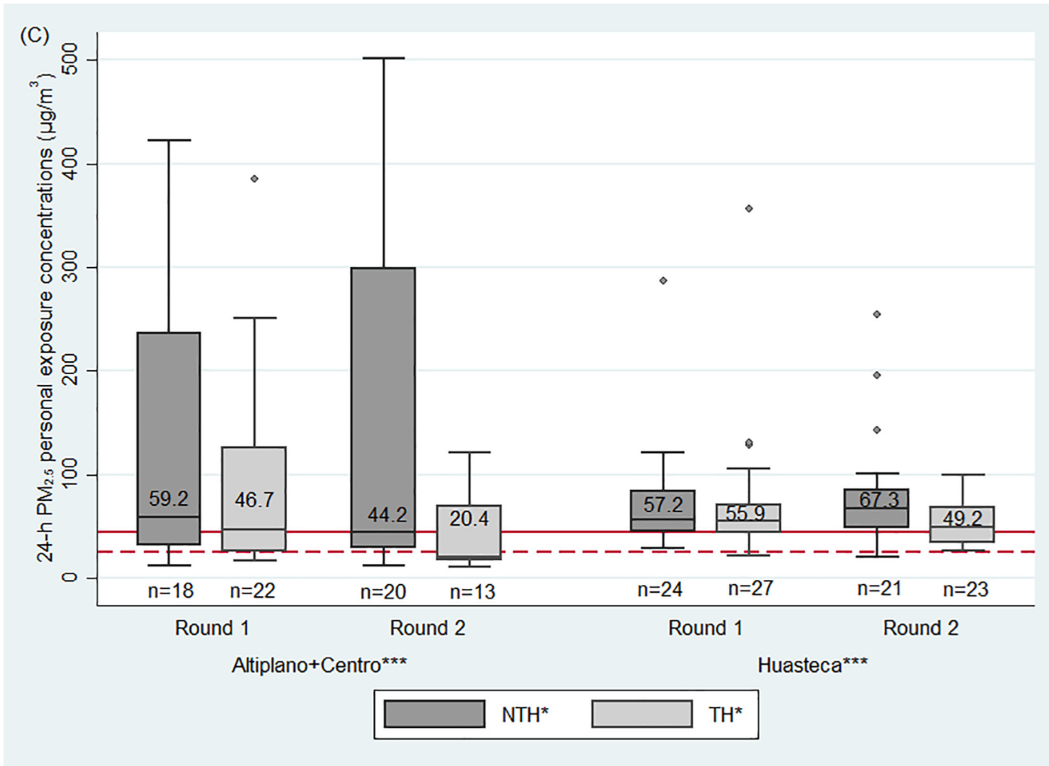

Fig. 2 (*continued*)

Table 2
The association between transformed log $PM_{2.5}$ (μg/m^3) concentrations in the kitchen area and household, environmental and cooking factors.

Factor	Dependent variable: ln ($PM_{2.5}$)		
	Descriptive analysis	Multivariate analysis	
	Mean (SD) $PM_{2.5}$ concentration (μg/m^3)	Percent (%) change in PM based on log regression[a], **95% CI**	*P-value*
Number of household rooms		−7 (-13, −1)	**0.021**
Persons living and eating in the household		3 (0,6)	**0.093**
Kitchen ventilation			
Poor (n = 43)	189.2 (209.5)	Reference	
Regular (n = 112)	118.8 (136.4)	−31 (-42,-17)	**0.001**
Sufficient (n = 43)	70.3 (43.9)	−37 (-49,-21)	**0.001**
Household daily energy use			
OF (n = 73)	146.3 (145.2)	Reference	
OF + ICSp / ICSp (n = 9)	310 (2 5 8)	14 (-17,58)	0.419
OF + ICSp/ OF + ICSp + LPG (n = 21)	80 (34.1)	−6 (-25,19)	0.621
OF + LPG (n = 35)	140.2 (153.7)	−13 (-28,5)	0.155
ICSg/ ICSg + LPG (n = 48)	85.5 (132.9)	−8 (−23,11)	0.388
LPG (n = 15)	33.9 (20.8)	−31 (-48,-7)	**0.016**
Daily mean ambient air temperature °C		4 (3,5)	**0.001**
Daily mean relative ambient air humidity %		1 (0,1)	**0.007**
Ratio Indoor/Outdoor $PM_{2.5}$ concentration		106 (92,122)	**0.001**
Daily hours cooking tortillas		4 (-2,11)	0.171

PM, particulate matter; CI, Confidence interval; OF, open fire; ICS, Improved cook-stoves; ICSp, improved cook-stove in poor conditions; ICSg, improved cook-stove in good condition; LPG, liquefied petroleum gas stove. OF + ICSp/ICSp: Open fire plus improved cookstove in poor condition or only improved cookstove in poor condition. OF + ICSp + LPG/OF + LPG: Open fire plus improve cookstove in poor condition plus LPG stove or Open fire plus LPG, OF + LPG: Open fire plus LPG stove, ICSg/ICSg + LPG: Improved cookstove in good condition or Improved cookstove in good condition plus LPG stove.
Interpretation note: For one room increment in the household the $PM_{2.5}$ concentration was reduced 7%. For each one percent increment in the ratio Indoor/Outdoor, the concentration of $PM_{2.5}$ increases 10,6%.
[a] Regression of log PM exposure can be converted to the percent (%) change in PM exposure using the equation ([$\exp^{\beta} - 1$] X 100), where b is the change in log PM exposure associated with a one-unit change in the independent variable. Adjusted determination coefficient model by 132 households and 201 observations was 78%. Bold types denote statistical significance (P < 0.05).

Women using biomass (wood, crop residues, paper) as their primary cooking fuel had a 33% higher exposure than women cooking with LPG [69.4 μg/m^3 (95% CI: 67.1, 71.7) vs. 51.9 μg/m^3 (95% CI: 41.6, 61.3); p = 0.39].

4. Discussion

In this study, more than 700 households participated in a comprehensive impact evaluation of a government ICS program imple-

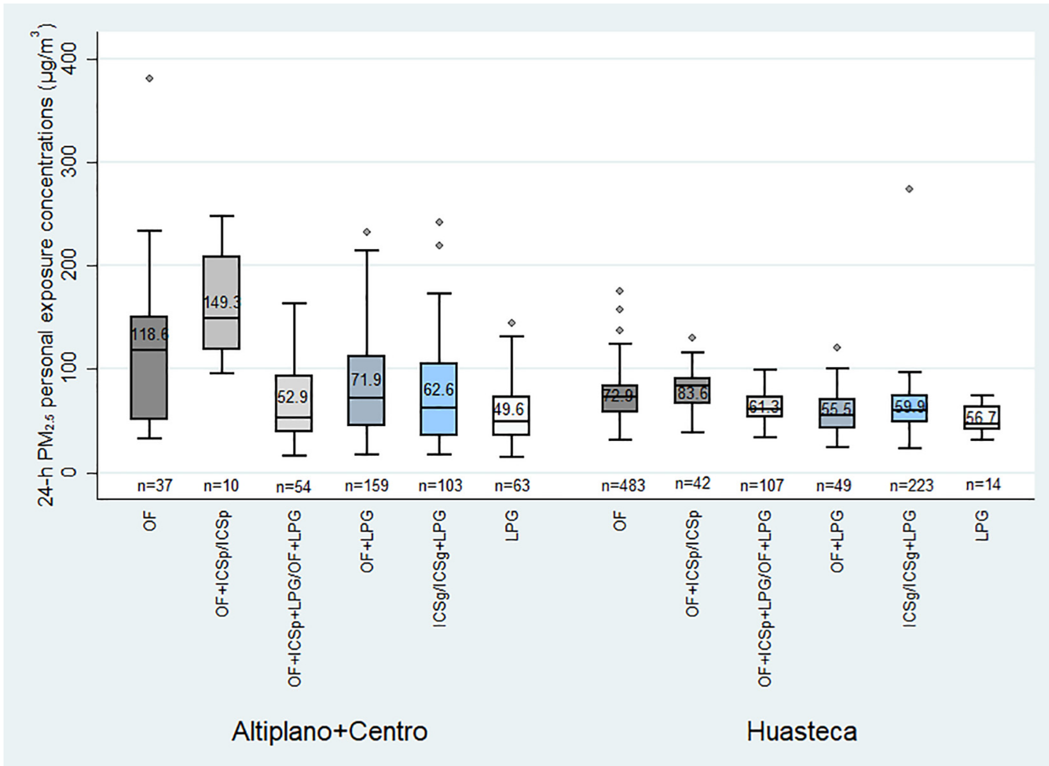

Figure 3. Estimated daily personal exposure to $PM_{2.5}$ ($\mu g/m^3$) by cooking device use and region for the complete study population.

mented in the geoclimatic and sociocultural diverse state of San Luis Potosí in Mexico. A panel type design was chosen to assess the households energy use outcomes comparing treated and non-treated groups. The non-treated households were poorer, and their overall 24-hour kitchen and personal $PM_{2.5}$ exposures were almost twice as high as the treated ones. The ICS program average effect estimated by double difference was not significant despite a higher percentage of households that displaced the open fire during follow-up. We also detected fuel and device stacking, so we conducted an additional analysis according to the reported household energy use.

The stacking phenomenon has been described in previous evaluations carried out in Mexico and other countries, stressing the importance of an holistic approach to programs addressing household energy issues to ensure the sustained use of the ICS in the long-term to improve health outcomes (Berrueta et al., 2017; Ruiz-Mercado and Masera, 2015). In this study, the stacking phenomenon was observed mainly in the treated households, where the ICS was added to the devices already used. This information should be considered in the design and implementation phases of future interventions (Pilishvili et al., 2016; Ruiz-Mercado and Masera, 2015).

The "real scenario" analysis according to the reported patterns of fuel and devices use shows the importance of displacing open fires to decrease $PM_{2.5}$ concentrations, particularly in regions where there is limited access to cleaner fuels such as LPG (Masera et al., 2005; Rosenthal et al., 2017; Ruiz-García et al., 2018; Smith, 2017). In rural, hilly and poor regions such as the Huasteca, with high prevalence of the open fire use, switching fuel at a large-scale will not occur unless its economy becomes substantially more developed (Zhang et al., 2007). In these communities with low purchasing power, the improved cookstove is a feasible approach (EkouevI and Tuntivate, 2012). LPG users were concentrated in the Altiplano-Centro, the region with the higher socioeconomic level, a higher prevalence of stacking. These results corroborate that households in developing countries are following more complex energy transition trajectories than those described by the energy ladder model, presenting a multidimensional challenge (EkouevI and Tuntivate, 2012; Muller and Yan, 2018) which must be addressed by community-based methods to meet the needs and preferences of users and reduce the HAP levels (Bielecki and Wingenbach, 2014; Rosenthal et al., 2017).

The 24-hour mean concentrations of kitchen $PM_{2.5}$ observed in this study were lower than those reported by other studies performed in Mexico (Armendariz-Arnez et al., 2008; Masera et al., 2007; Zuk et al., 2007), but similar to the levels found in India (Balakrishnan et al., 2013). This finding can be explained by the fact that in more than half of the evaluated households, the kitchen was an independent structure, often built in the patio. The great variation of $PM_{2.5}$ levels in kitchen areas between regions may be associated with the absence of eave spaces and open windows while cooking, as well as a less number of rooms in the Altiplano-Centro region households. The association between these conditions and higher levels of indoor pollutants has been described in previous studies demonstrating the consistency of our results (Balakrishnan et al., 2013; Baumgartner et al., 2011).

In the analysis based on reported patterns of fuel and devices use, we observed lower personal $PM_{2.5}$ exposure among women primarily cooking with ICS in good condition or LPG stove or both, compared to users of the traditional open fire. These reductions support the benefit of the use of ICS in good condition, resulting in a pattern similar to the exposure evaluation in a group of adult women who use solid fuels in rural communities of China (Baumgartner et al., 2011). Nonetheless, the $PM_{2.5}$ concentrations for the kitchen area according to our stacking analysis, still lies above the interim target-1 (IT-1) of World Health Organization (WHO) air quality guidelines, established to avoid significant mortality and morbidity caused by PM air pollution based on scientific evidence (Bruce et al., 2015).

Almost one-third of the daily mean concentrations of patio $PM_{2.5}$ were above the 24-h guideline value of WHO (World Health Organization, 2006) and the Mexican outdoor air standards (Secretaria de Salud de México, 2014). These air pollution levels can be explained by other environmental sources of $PM_{2.5}$ such as backyard trash-burning, as well as by the impact of chimney emissions in the neighborhood (Ruiz-García et al., 2018). In addition, the weather conditions can disseminate, dilute or accumulate atmospheric pollutants and affect the mass concentration of $PM_{2.5}$ (Wang and Ogawa, 2015). In this study, temperature and humidity had a positive association with indoor particles concentration (Lv et al., 2017), indicating the contribution of geographical and meteorological conditions of each region on the pollutant concentration.

The indoor/outdoor ratio of $PM_{2.5}$ resulted to be a significant predictor of pollutant concentration in the kitchen, because it is associated with the variability in the size-dependent indoor particle sources emission rates, air exchange rates of closed or open windows, characteristics of the household (geometry of cracks in building envelopes) and the habits of the participants (Chen and Zhao, 2011). Although air exchange rates were not measured in this study, the information related to kitchen and household ventilation and other $PM_{2.5}$ indoor and outdoor sources (opening or closing windows, number of eave spaces and type of materials of walls, roof, and floor) were recorded. These factors influence personal exposure because women spent a larger fraction of the day in the indoor microenvironment (Bruce et al., 2015; Smith and Pillarisetti, 2017).

Several studies in Guatemala and Mexico have reported reductions in $PM_{2.5}$ levels in the household after ICS intervention programs (Albalak et al., 2001; Armendariz-Arnez et al., 2008; Masera et al., 2007). However, reductions may be affected by physical conditions of the house, household income, type of kitchen, design, and location of the ICS, and preferential use of different fuel/stove for cooking certain foods, among other factors. Among the strengths of our study is the longitudinal design allowing repeated measurement of the pollutant by areas in treated and not treated households, the patterns of use of fuels-devices to cook, as well as the comparison of the time-activity patterns reported by the participants between rounds. This is very important data to advance our understanding of how communities respond to programs in a changing condition (Quinn et al., 2018). The identification of key factors influencing indoor and outdoor air quality are an input for the redesign of stove intervention and switching to cleaner fuels programs that promote sustainable use to improve household environment in the rural areas (Puzzolo et al., 2016; Quansah et al., 2017; Smith et al., 2014).

Another strength of this study was the representativeness of $PM_{2.5}$ measurements by areas and the characterization of household air pollution in different rural context at the state level. Our results contribute to increase the evidence to estimate the exposure of vulnerable socioeconomic groups such as indigenous population in Mexico and other Latin American countries (Clark et al., 2013; Matz et al., 2015). In addition, the use of standardized environmental measurement protocols with information from the state weather network increases the level of quality control and homogeneity in data collection. Finally, the estimation of the levels of household pollutants associated to the different patterns of fuel-devices use in cooking practices provides exposure data to estimate the burden of disease caused by this environmental factor (Burnett et al., 2014; Pope et al., 2017). Our $PM_{2.5}$ personal exposure estimates agree with the global estimation of exposure to household air pollution from different countries of the world, including Latin America region (Shupler et al., 2018).

The methods for the exposure assessment, characterization of $PM_{2.5}$ concentrations in indoor and outdoor areas for 24-h in sub-sampled populations plus semiquantitative measurements of the time-activity patterns of women in different study groups, provide a reasonable and cost-effective proxy to estimate personal exposure, contributing to the knowledge of the variation observed in the behavior of the individuals and communities (Clark et al., 2013; Quinn et al., 2018). However, the lack of continuous measurements of pollutant emissions in each of the areas did not allow the evaluation of daily temporal and spatial variability in the microenvironments from rural households, which is a limitation of this study (Armendariz-Arnez et al., 2008). To reduce this uncertainty, it would be necessary to perform personal measurements in real time for several days (Clark et al., 2013), as has been reported in other studies using portable ultrasonic $PM_{2.5}$ measuring devices (Volckens et al., 2017). The use of simple filter reading protocols improve the characterization of the time-activity patterns in the different areas, reducing possible measurement errors (Arku et al., 2018; Zuk et al., 2007). The effects of ICSs on the reduction of the daily mean personal $PM_{2.5}$ exposure estimated by this study was lower compared to other studies conducted in Mexico and India (Armendariz-Arnez et al., 2008; Balakrishnan et al., 2002; Zuk et al., 2007) and the cause remains to be determined. However the potential subjectivity in the self-report of the time-activity patterns in each microenvironment by the participants could contribute and underestimate the level of exposure (Zuk et al., 2007).

We had losses in the follow-up visit, but considering the number of valid measurements obtained from the concentrations of $PM_{2.5}$ in the kitchen and the type of study design used, a post hoc statistical power higher than 90% was estimated (to identify that our methods could have detected the associated effect size, if that effect was present). Other limitations included assessing $PM_{2.5}$ concentrations and levels of exposure only after the implementation of the stove program (*ex post* evaluation), lack of baseline data, non-random treatment assignment by program administrators (selection bias) and spillover effect (adoption of ICS by several non-treated households). To evaluate the impact of the intervention, an alternative analysis was carried out to determine the association between the different patterns or types of primary use of fuels and devices (Pillarisetti et al., 2014).

5. Conclusions

The impact evaluation showed that the expected benefits of the program on air pollution levels have not been achieved. Under a "real-life" scenario, we found a reduction in mean daily personal $PM_{2.5}$ exposure in women using ICS in good condition or LPG compared to the use of the traditional open fire, which can contribute to a cleaner and healthier environment. However, pollutant concentrations per area, as well as personal exposure remain above air quality standards and pose a health risk to the rural population. It is necessary to formulate comprehensive strategies to ensure the implementation, cultural adoption and sustained use of the ICS, displacing the polluting open fire, involving the users in the different phases of the program. Access to cleaner fuels and housing improvements in rural communities of low- and middle-income countries, require novel public policies to break the poverty trap and achieve the Sustainable Development Goals.

6. Capsule

An improved cookstove in good condition is a feasible approach to reduce indoor air pollution in the poor rural context. Systematic community feedback should be considered to redesign comprehensive social policies.

CRediT authorship contribution statement

Jesús Alejandro Estévez-García: Methodology, Investigation, Data curation, Formal analysis, Writing - original draft. **Astrid Schilmann:** Conceptualization, Methodology, Supervision, Project administration, Funding acquisition, Data curation, Formal analysis, Writing - original draft. **Horacio Riojas-Rodríguez:** Conceptualization, Methodology, Validation, Formal analysis, Writing - original draft. **Víctor Berrueta:** Conceptualization, Methodology, Investigation, Validation. **Salvador Blanco:** Conceptualization, Methodology, Investigation, Resources, Validation. **César Gerardo Villaseñor-Lozano:** Data curation, Formal analysis. **Rogelio Flores-Ramírez:** Methodology, Validation, Formal analysis. **Marlene Cortez-Lugo:** Formal analysis. **Rogelio Pérez-Padilla:** Methodology, Validation, Writing - original draft.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.scitotenv.2019.134456.

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