Environment International 117 (2018) 116–124

Contents lists available at ScienceDirect

Environment International

journal homepage: www.elsevier.com/locate/envint

Impacts of stove use patterns and outdoor air quality on household air pollution and cardiovascular mortality in southwestern China[☆]

Graydon Snider[a,b], Ellison Carter[c], Sierra Clark[a,b], Joy (Tzu Wei) Tseng[a], Xudong Yang[d], Majid Ezzati[e], James J. Schauer[f,g], Christine Wiedinmyer[h], Jill Baumgartner[a,b,i,*]

[a] Institute for Health and Social Policy, McGill University, Montréal, QC, Canada
[b] Department of Epidemiology, Biostatistics & Occupational Health, McGill University, Montréal, QC, Canada
[c] Civil and Environmental Engineering, Colorado State University, Fort Collins, CO, USA
[d] Department of Building Science, Tsinghua University, Beijing, China
[e] MRC-PHE Centre for Environment and Health, School of Public Health, Imperial College London, London, UK
[f] Environmental Chemistry and Technology Program, University of Wisconsin, Madison, WI, USA
[g] Wisconsin State Laboratory of Hygiene, University of Wisconsin, Madison, WI, USA
[h] National Center for Atmospheric Research, Boulder, CO, USA
[i] Institute on the Environment, University of Minnesota, St. Paul, MN, USA

ARTICLE INFO

Keywords:
Biomass
Cardiovascular mortality
Cookstoves
Liquefied petroleum gas
$PM_{2.5}$
Semi-gasifier

ABSTRACT

Background: Decades of intervention programs that replaced traditional biomass stoves with cleaner-burning technologies have failed to meet the World Health Organization (WHO) interim indoor air quality target of 35-μg m^{-3} for $PM_{2.5}$. Many attribute these results to continued use of biomass stoves and poor outdoor air quality, though the relative impacts of these factors have not been empirically quantified.
Methods: We measured 496 days of real-time stove use concurrently with outdoor and indoor air pollution ($PM_{2.5}$) in 150 rural households in Sichuan, China. The impacts of stove use patterns and outdoor air quality on indoor $PM_{2.5}$ were quantified. We also estimated the potential avoided cardiovascular mortality in southwestern China associated with transition from traditional to clean fuel stoves using established exposure-response relationships.
Results: Mean daily indoor $PM_{2.5}$ was highest in homes using both wood and clean fuel stoves (122 μg m^{-3}), followed by exclusive use of wood stoves (106 μg m^{-3}) and clean fuel stoves (semi-gasifiers: 65 μg m^{-3}; gas or electric: 55 μg m^{-3}). Wood stoves emitted proportionally higher indoor $PM_{2.5}$ during ignition, and longer stove use was not associated with higher indoor $PM_{2.5}$. Only 24% of days with exclusive use of clean fuel stoves met the WHO indoor air quality target, though this fraction rose to 73% after subtracting the outdoor $PM_{2.5}$ contribution. Reduced $PM_{2.5}$ exposure through exclusive use of gas or electric stoves was estimated to prevent 48,000 yearly premature deaths in southwestern China, with greater reductions if local outdoor $PM_{2.5}$ is also reduced.
Conclusions: Clean stove and fuel interventions are not likely to reduce indoor $PM_{2.5}$ to the WHO target unless their use is exclusive and outdoor air pollution is sufficiently low, but may still offer some cardiovascular benefits.

1. Introduction

Over 600 million Chinese and 2.8 billion people globally use solid fuel (i.e., biomass and coal) stoves for cooking, space heating, and other energy needs (Bonjour et al., 2013). Traditional solid fuel stoves emit high concentrations of health damaging pollutants, including particulate matter < 2.5 μm in diameter ($PM_{2.5}$), that contribute to both household and outdoor air pollution (Chafe et al., 2014). Household air pollution is responsible for an estimated 2.6 million yearly premature deaths, including 1.2 million deaths from ischemic heart disease and stroke, two leading causes of death in China and globally (Gakidou et al., 2017).

Replacing traditional biomass stoves with cleaner-burning technologies has the potential to reduce air pollution and its health impacts.

[☆] The authors declare they have no actual or potential competing financial interests regarding this publication.
* Corresponding author at: Department of Epidemiology, Biostatistics & Occupational Health and Institute for Health and Social Policy, McGill University, Montréal, QC, Canada.
E-mail address: jill.baumgartner@mcgill.ca (J. Baumgartner).

https://doi.org/10.1016/j.envint.2018.04.048
Received 15 December 2017; Received in revised form 28 March 2018; Accepted 27 April 2018
0160-4120/

Yet decades of efforts to implement cleaner-burning stoves (Manibog, 1984; Kshirsagar & Kalamkar, 2014) have largely failed to measurably reduce air pollution or meet air quality guidelines (Pope et al., 2017; Quansah et al., 2017). Many studies attribute these disappointing results to poor stove maintenance, low uptake of the new stove, and continued use of traditional stoves, i.e., mixed use or "stove stacking" (Ruiz-Mercado & Masera, 2015; Rehfuess et al., 2014). Air pollution from local sources including industry, traffic, and neighbours' solid fuel burning may also influence $PM_{2.5}$ exposures, and subsequently mask or negate the benefits of clean stove interventions (Alexander et al., 2018; Mortimer et al., 2017; Smith et al., 2011; Secrest et al., 2017; Piedrahita et al., 2016).

The extent to which stove-use patterns, i.e., frequency and duration of stove use, and outdoor air quality impact the success of stove interventions in reducing indoor $PM_{2.5}$ is not well quantified (Khandelwal et al., 2017). Field studies in China, India, Ghana, and Mexico measured the post-stove intervention changes in stove use, but not the impacts on air pollution (Piedrahita et al., 2016; Clark et al., 2017; Mukhopadhyay et al., 2012; Ruiz-Mercado et al., 2012; Pillarisetti et al., 2014). A study in Kenya evaluated the indoor $PM_{2.5}$ in homes using different stoves, but did not assess duration of stove use (Lozier et al., 2016). Johnson and Chiang (Johnson & Chiang, 2015) modeled the indoor $PM_{2.5}$ impacts of different stove-use duration scenarios, but built their models from laboratory stove tests, which are known to differ considerably from field studies (Roden et al., 2009). Further, none of these studies accounted for the contribution of outdoor air pollution, which is regarded as a barrier to clean indoor air in cities, but its contribution in rural areas is poorly understood (Bruce et al., 2015). Field studies that combine quantitative measures of indoor and outdoor air pollution and household stove-use patterns can provide more realistic insights into which stove intervention programs can meet air quality targets and achieve their intended health benefits.

We investigated the associations between stove-use patterns and indoor $PM_{2.5}$ in rural Chinese homes, also accounting for outdoor $PM_{2.5}$ that was measured concurrently. Drawing from our empirical results on indoor $PM_{2.5}$ for different fuel-stove combinations, we also estimated the potential avoided cardiovascular mortality associated with partial and complete transition to clean fuel stoves in southwestern China. To our knowledge, this is the first empirical study to quantitatively assess the independent and combined impacts of stove-use patterns and same-day outdoor air quality on indoor $PM_{2.5}$ concentrations.

2. Methods

2.1. Study location

We conducted the study in 12 villages along the eastern edge of the Tibetan Plateau in Beichuan County, Sichuan Province, China (+31.814°, +104.457°) (Fig. S1). We selected this location because of a government-supported rural energy intervention program that provided homes with low-polluting semi-gasifier cookstoves and a supply of pelletized biomass fuel. The region's temperate climate is characterized by mean temperatures of 20–30 °C in June–August and 4–14 °C in November–January. The nearest metropolitan area is Mianyang City, about 50 km southeast, which has a population of 5.5 million. Detailed information about the study site is published elsewhere (Ni et al., 2016; Shan et al., 2014).

2.2. Study design

In this study we used the post-intervention rounds of data collected in summer (June–August 2016) and winter (November 2016–January 2017) in 150 homes that were enrolled in a stove intervention study. Seasonal measurements were used to capture the increased frequency and duration of stove combustion events in winter, likely due to space heating (Carter et al., 2016). In both seasons, field staff traveled to participants' homes to measure 48-h stove use and kitchen air pollution concentrations, and to administer questionnaires. Ethical review boards at McGill University, the University of Minnesota, Tsinghua University, and the University of Wisconsin-Madison approved this study.

2.3. Housing characteristics and energy-use practices

Housing characteristics and energy use practices in our study homes are described elsewhere (Clark et al., 2017; Ni et al., 2016). Briefly, houses were one or two stories and constructed of either wooden frames with partial earth exteriors or of brick and cement, and were clustered relatively close together (average distance to nearest neighbour = 34 m). Natural ventilation practices (e.g. opening of doors and windows to the outside) were common, resulting in high air exchange rates in kitchens (mean = 17 h^{-1}) (Carter et al., 2016). All kitchens had wood-burning chimney stoves that vented outdoors. Most homes (79%) had received a semi-gasifier stove and supply of pelletized biomass fuel approximately 4–7 months before this study's measurements began. Many (42%) had a liquefied petroleum gas (LPG) and/or electric stove (Fig. S2). The wood-chimney stoves rank as Tier 1 (lowest performing group) for air pollution emissions according to the International Organization for Standardization International Workshop Agreement (IWA, 2012), whereas the LPG and electric stoves are classified as low-polluting Tier 4 stoves (highest performing group). The semi-gasifier stove can also perform at the Tier 4 level (Carter et al., 2014; Shan et al., 2017).

2.4. Household questionnaires

Primary cooks completed questionnaires on household energy use and ventilation, and the presence of other air pollution sources (e.g., tobacco smokers) at each visit. Questions were adapted from previous energy surveys conducted in China (Baumgartner et al., 2011) and retested prior to implementation.

2.5. Measurement of household stove-use frequency and duration

Stove use was objectively measured for 48-h periods in each season using real-time temperature sensors with a resolution of 1 °C (Thermochron iButtons, Models DS1922L/DS1921G, Berkeley Air, USA). Sensors were placed on all stoves used at least once per month and programmed to record temperature every 10-min, a frequency shown to detect all stove-use events (Clark et al., 2017). A control sensor was wall-mounted in kitchens, away from heating sources, to distinguish indoor temperature fluctuations from stove use. A previous study showed that 48-h measurement was representative of "usual" stove-use behaviour in that season, and that the presence of air monitoring equipment did not alter stove-use patterns (Clark et al., 2017).

The number and duration of stove-use events were identified from temperature data using an algorithm adapted from Ruiz-Mercado et al. (2013). Briefly, a stove-use event was defined as a time period during which the stove surface temperature exceeded the wall control temperature by at least 5 °C and met other conditions of peak shape that distinguished it from room temperature change. To identify events, we generated time-resolved graphs of 48-h stove and wall control temperatures using an online software package (Plotly 2015) and MATLAB (2012). Each 48-h session was divided into two 24-h periods (SI section S.1). Temperature data were magnified so that the start and end time of each event could be visually identified within a ± 5-min window of uncertainty. Duration of the stove-use event (minutes) was calculated as the time between the start of a temperature increase to the temperature maxima, given field observations that a sustained decrease in stove temperature indicated the end of active use. Multiple events within an hour were considered a single event, where duration was calculated as the time between the start of a temperature increase to the temperature maxima of the final peak (Fig. S3).