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Seasonal variation in outdoor, indoor, and personal air pollution exposures of women using wood stoves in the Tibetan Plateau: Baseline assessment for an energy intervention study☆

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ABSTRACT

Cooking and heating with coal and biomass is the main source of household air pollution in China and a leading contributor to disease burden. As part of a baseline assessment for a household energy intervention program, we enrolled 205 adult women cooking with biomass fuels in Sichuan, China and measured their 48-h personal exposure to fine particulate matter ($PM_{2.5}$) and carbon monoxide (CO) in winter and summer. We also measured the indoor 48-h $PM_{2.5}$ concentrations in their homes and conducted outdoor $PM_{2.5}$ measurements during 101 (74) days in summer (winter). Indoor concentrations of CO and nitrogen oxides (NO, NO_2) were measured over 48-h in a subset of ~80 homes. Women's geometric mean 48-h exposure to $PM_{2.5}$ was 80 μg/m^3 (95% CI: 74, 87) in summer and twice as high in winter (169 μg/m^3 (95% CI: 150, 190), with similar seasonal trends for indoor $PM_{2.5}$ concentrations (winter: 252 μg/m^3; 95% CI: 215, 295; summer: 101 μg/m^3; 95% CI: 91, 112). We found a moderately strong relationship between indoor $PM_{2.5}$ and CO (r = 0.60, 95% CI: 0.46, 0.72), and a weak correlation between personal $PM_{2.5}$ and CO (r = 0.41, 95% CI: −0.02, 0.71). NO_2/NO ratios were higher in summer (range: 0.01 to 0.68) than in winter (range: 0 to 0.11), suggesting outdoor formation of NO_2 via reaction of NO with ozone is a more important source of NO_2 than biomass combustion indoors. The predictors of women's personal exposure to $PM_{2.5}$ differed by season. In winter, our results show that primary heating with a low-polluting fuel (i.e., electric stove or wood-charcoal) and more frequent kitchen ventilation could reduce personal $PM_{2.5}$ exposures. In summer, primary use of a gaseous fuel or electricity for cooking and reducing exposure to outdoor $PM_{2.5}$ would likely have the greatest impacts on personal $PM_{2.5}$ exposure.

1. Introduction

Household cooking and heating with biomass and coal (i.e., solid fuel) is a widespread source of air pollution exposure that affects almost half the world's population (Bonjour et al., 2013). Incomplete combustion of solid fuel emits high concentrations of hazardous air pollutants, including fine particulate matter, carbon monoxide, nitrogen oxides, polyaromatic hydrocarbons (PAHs), and volatile and semi-volatile organic compounds (Naeher et al., 2007). In China, despite widespread access to electricity and low-polluting gaseous fuels like liquefied petroleum gas (LPG), over 40% of homes cook with traditional solid fuel stoves (Bonjour et al., 2013; Duan et al., 2014) and 30% use solid fuel heating stoves (Duan et al., 2014).

Exposure to household air pollution from biomass and coal has been associated with a range of health outcomes including low birth weight and stillbirth (Pope et al., 2010), respiratory illness and diseases in children and adults including acute lower respiratory infections, chronic obstructive pulmonary disease, and lung cancer (Dherani et al., 2008; International Agency for Research on Cancer, 2006; Kurmi et al.,

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2010), and subclinical cardiovascular outcomes including higher blood pressure (Baumgartner et al., 2014a; Norris et al., 2016; McCracken et al., 2007; McCracken et al., 2011; Clark et al., 2013a). Cooking with solid fuel is responsible for an estimated 3.5 million annual premature deaths globally (Lim et al., 2013) and approximately 800,000 annual premature deaths in China (Forouzanfar et al., 2015). It is also an important contributor to ambient air pollution (Chafe et al., 2014) and to global and regional climate change due to emissions of short-lived climate pollutants like black carbon (Bond et al., 2013; Ramanathan & Carmichael, 2008) and greenhouse gases including carbon dioxide, nitrogen dioxide, and methane (Ramanathan & Feng, 2009).

Evaluating the realized or potential climate and health benefits of cleaner-burning stoves and fuels relies on detailed information of air pollution exposures under baseline scenarios. Only a small number of studies have assessed personal exposures to fine particulate matter ($PM_{2.5}$) and carbon monoxide (CO) (Clark et al., 2013b). The lack of comprehensive information on personal exposures to household air pollution impedes quantification of health impacts of interventions and disease burden estimates. Further, the relationships between pollutants from indoor and outdoor sources and their relative contribution to personal exposures in rural settings is poorly understood. Very few field studies have measured indoor nitrogen oxides (NO_x) in settings with residential biomass burning (St. Helen et al., 2015a; Kumie et al., 2009; Liu et al., 2007), and these only measured NO_2. Field measurements of nitrogen dioxide (NO_2) and nitrogen oxide (NO) together are valuable for health and climate modeling and can facilitate investigation of the impacts of outdoor air pollution and chemistry on indoor air quality.

We enrolled 205 women in the eastern Tibetan Plateau and measured their 48-h indoor concentrations and personal exposures to health- and climate-relevant air pollutants including $PM_{2.5}$, CO, nitrogen oxide (NO), and nitrogen dioxide (NO_2) in winter and summer. Daily outdoor $PM_{2.5}$ concentrations were also measured. Using these data, we assessed seasonal and day-to-day variability in outdoor, indoor, and personal air pollution exposures, evaluated the usefulness of surrogate measures of personal $PM_{2.5}$ exposure such as personal CO exposure and indoor $PM_{2.5}$, and estimated the influence of various environmental, household, and individual factors on women's personal exposure to $PM_{2.5}$. This comprehensive set of air pollution measurements and analyses forms the baseline assessment of an energy intervention study where homes will receive semi-gasifier cookstoves and a supply of processed biomass fuel during a government-supported clean energy program. The processed biomass fuel is produced at a factory near the study villages.

2. Methods

2.1. Study location

We conducted our study in four administrative villages on the eastern edge of the Tibetan Plateau in Beichuan Qiang Autonomous County, Sichuan Province, China (N 31°53′, E 104°26′). The climate is relatively mild with average temperatures of 23.4 °C in July and 4.6 °C in January. The altitude of study homes ranged from 1000–1450 m ASL (above sea level). We selected this location because of its vulnerability to the climate impacts of household biomass burning (Bond et al., 2013) and the planned clean energy program. Additional details about the study site are provided elsewhere (Ming et al., 2014).

2.2. Participant recruitment

We enrolled 205 women living in 204 homes. Our sample size was determined by power calculations for a separate health study. Women were eligible to participate if they regularly cooked with biomass fuel and currently lived in one of the four study villages. They were excluded from the study if they were previous or current smokers, pregnant at enrolment, or less than 25 years old since women in this age group were more likely to become pregnant during the study. Local field staff introduced the study and its measurements to eligible women and other household occupants. Women interested in participating were read the consent form and the field staff answered any questions posed. Women provided oral informed consent.

Our participation rate was 71%. Most of the 85 eligible women who declined to participate did so because they worked outside of the village such that wearing the air pollution monitors was logistically difficult or impossible. Measurements were conducted in summer (May 10–August 14, 2014) and winter (November 15, 2014–February 9, 2015) to capture seasonal variability in household energy use. We conducted measurements on every day of the week except for holidays or other special occasions when household energy use is not representative of usual activities. The study protocols were reviewed and approved by the University of Minnesota (#1304S31002), McGill University (#A01-E01-14A), and Tsinghua University.

2.3. Housing and energy use behaviors

The participants lived in single or two-story homes, most (90%) of which were built or renovated between 2009–2012 during a post-earthquake reconstruction effort. Older homes had wooden frames and partial earth exteriors whereas new homes were constructed of brick and cement. All homes cooked food and animal fodder using biomass in traditional chimney stoves. Most regularly used one or more clean burning stove-fuel combination such as biogas, LPG, electric water heaters, and induction stoves (Fig. 1). Space heating with biomass fuels was common in winter since centralized heating was unavailable, often done in combination with cooking or boiling water. Rooms were typically heated by burning wood or wood-charcoal in the chimney cookstoves or free-standing metal fire pans, though electric heaters are also used (Fig. 2). Further details on housing and ventilation are provided elsewhere (Ming et al., 2014; Carter et al., under review).

Wood logs and branches were used for cooking and heating in all homes and were the primary cooking fuel for 88% of homes (Table S1). Most homes also cooked with electricity, and over a third of homes combined wood and electricity with at least one gaseous fuel (Fig. 2a). Gaseous fuels were not used for space heating, but over half (52%) of the homes heated with electricity, wood, and wood-charcoal (Fig. 2b).

2.4. Personal exposure to $PM_{2.5}$ and carbon monoxide

We measured each participant's 48-h integrated gravimetric exposure to particulate matter <2.5 μm in aerodynamic diameter ($PM_{2.5}$) in winter and summer using Personal Exposure Monitors (PEMs) with a d_{50} of 2.5-μm at 1.8 lpm (±10%) and a greased impaction surface (Demokritou et al., 2001). The PEMs held 37 mm PTFE filters (VWR, USA, 2.0-μm pore size) and were connected to pumps (Apex Pro, Casella CEL, UK). Participants wore the monitors in waist packs (Fig. S1). They

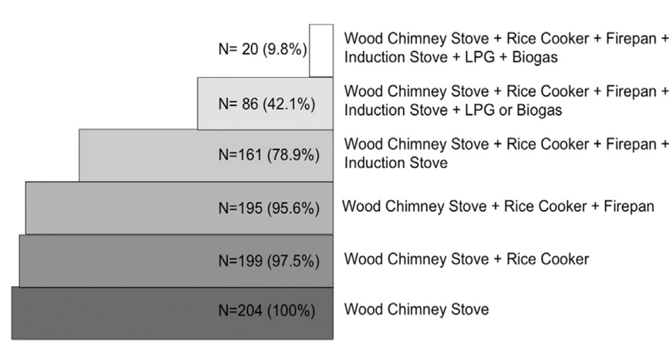

Fig. 1. Number (percentage) of study homes (N = 204) using different stove combinations in the eastern Tibetan Plateau.

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