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Real-time indoor measurement of health and climate-relevant air pollution concentrations during a carbon-finance-approved cookstove intervention in rural India

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ABSTRACT

Biomass combustion in residential cookstoves is a major source of air pollution and a large contributor to the global burden of disease. Carbon financing offers a potential funding source for health-relevant energy technologies in low-income countries. We conducted a randomized intervention study to evaluate air pollution impacts of a carbon-finance-approved cookstove in rural South India. Prior research on this topic often has used time-integrated measures of indoor air quality. Here, we employed real-time monitors (~24 h measurement at ~ minute temporal resolution), thereby allowing investigation of minutely and hourly temporal patterns. We measured indoor concentrations of fine particulate matter ($PM_{2.5}$), black carbon (BC) and carbon monoxide (CO) in intervention households (used newer, rocket-type stoves) and control households ("nonintervention"; continued using traditional open fire stoves). Some intervention households elected not to use only the new, intervention stoves (i.e., elected not to follow the study-design protocol); we therefore conducted analysis for "per protocol" versus "intent to treat." We compared 24 h averages of air pollutants versus cooking hours only averages. Implementation of the per protocol intervention cookstove decreased median concentrations of CO (by 1.5 ppm (2.8 − 1.3; control − per protocol), $p = 0.28$) and $PM_{2.5}$ (by 148 μg/m^3 (365 − 217), $p = 0.46$) but increased BC concentration (by 39 μg/m^3 (26 − −12), $p < 0.05$) and the ratio of BC/$PM_{2.5}$ (by 0.25 (−0.28 − −0.03), $p < 0.05$) during cooking-relevant hours-of-day relative to controls. Calculated median effective air exchange rates based on decay in CO concentrations were stable between seasons (season 1: 2.5 h^{-1}, season 2: 2.8 h^{-1}). Finally, we discuss an analytical framework for evaluating real-time indoor datasets with limited sample sizes. For the present study, use of real-time (versus time-averaged) equipment substantially reduced the number of households we were able to monitor.

1. Introduction

Combustion of solid fuel (e.g., wood, animal manure, crop residue, or coal) in open fires and in traditional stoves affects human health and the environment (Venkataraman et al., 2005). The resulting household air pollution (HAP) includes CO, $PM_{2.5}$, and BC, and is associated with adverse health impacts in adults and children (Dherani et al., 2008; Smith et al., 2004) and affects regional and global climate (Bond et al., 2013; Janssen et al., 2012; Solomon et al., 2013). HAP from biomass and coal stoves was responsible for ~2.9 million premature deaths worldwide in 2015 (Forouzanfar et al., 2016), with low-income and industrializing countries most impacted.

Recently, there have been national and international efforts aimed to scale up stove and fuel interventions in India (Ministry of Petroleum and Natural Gas, 2016; Singh et al., 2017; Venkataraman et al., 2010). These efforts include cookstoves approved by the Clean Development Mechanism (CDM), established under the UN Framework Convention on Climate Change. Laboratory tests showed that, for example, "Chulika"

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rocket stoves had ~3-fold greater thermal efficiency than traditional open fire stoves (31% vs. 10%) and a two-fold wood savings; those stoves were subsequently approved for carbon financing (Central Power Research Institute, 2010; CDM Executive Board, 2006; Gold Standard Local Stakeholder Consultation Report, 2009).

Given the large impacts on health and the environment from solid-fuel combustion, a natural assumption would be that introducing a less polluting stove into a household would provide a net benefit for both. However, empirical evidence from intervention and observational studies has yielded mixed results (Chen et al., 2016; Khandelwal et al., 2017; Leavey et al., 2015; Pope et al., 2017; Wangchuk et al., 2017). For example, a meta-analysis of stove interventions in low- and middle-income countries conducted by Pope et al. (2017) reported improvements in HAP concentrations for intervention stoves over traditional stoves, though the 'improved' cookstoves often failed to achieve $PM_{2.5}$ concentrations close to the 24-h air quality guideline limit values. In addition, Khandelwal et al. (2017) highlight that adoption of intervention cookstoves over traditional stoves is limited despite promotion for decades; they highlight that stoves satisfy cultural and household needs beyond just cooking. Consequently, there is a need for better implementation and exposure assessment of intervention cookstoves. With few exceptions (Hankey et al., 2015; Carter et al., 2016; Chen et al., 2016), previous evaluations of cookstoves in rural areas have typically measured daily-average concentrations and have not analyzed data from real-time instrumentation, thereby preventing investigation of temporal patterns that may otherwise elucidate the effectiveness of the intervention stoves in reducing cooking pollution.

The present work is part of a larger energy intervention evaluation study of carbon-finance-approved cookstoves in the Koppal District of Karnataka State, India. Here, we discuss indoor concentrations of CO, $PM_{2.5}$, and BC concentrations during baseline and follow-up measurements (after the intervention) in houses using either traditional open fire stoves or carbon-finance-approved cookstoves. Seasonal and diurnal trends in the levels of indoor pollutants were analyzed using varying definitions of cooking time, to evaluate the effectiveness of the intervention stoves in reducing air pollution concentrations. Additionally, indoor air-exchange rates (AERs) were calculated based on CO decay patterns.

The three contributions of this study are: (1) evaluation of the effectiveness of a carbon-financed-approved cookstove intervention in the field, via a randomized control trial, (2) use of real-time rather than time-integrated measures of air pollution, thereby shedding light on impacts during times of cooking, and (3) calculation of air-exchange rates for a context where few AER measurements exist. This work can be referenced to, for example, create more detailed and sensitive emissions inventories, energy-use patterns, and health analyses in regions impacted by air pollution.

2. Material and methods

2.1. Study setting and research design

In this intervention study, households were randomly assigned to receive ("intervention") or not receive ("controls") the CDM-approved intervention. "Intervention" consisted of replacing the traditional open fire stoves with a new hearth and two chulika stoves. The chulika stoves are single-pot "rocket stoves", a type of natural-draft biomass stove. The study was conducted in two seasons: a pre-intervention baseline (September 2, 2011–December 10, 2011; "Season 1"/"S1") and a post-intervention follow-up (March 11, 2012–August 1, 2012; "Season 2"/ "S2").

Our study was conducted in a rural village in the Koppal district of northern Karnataka, a state with a population of ~1.2 million people that covers 7190 square kilometers. Approximately 35% of Koppal residents are day-wage laborers earning less than one dollar per day and an estimated 99% of households use traditional stoves (indoor, open fires) to cook food and heat bath water (Fair Climate Network, 2012).

We partnered with a local nongovernmental organization that was the first in India to obtain CDM approval for a cookstove intervention program. The overall goal of the larger study was to evaluate climate and health impacts of a CDM-approved intervention. Additional details on the study design, the setting, and the CDM intervention are provided in Aung et al. (2016) and Grieshop et al. (2017).

Fig. 1 displays the study design of the field campaign, which used a parallel assignment structure. Of the 300 eligible households in the study village, 187 households met the inclusion criteria and were eligible to enroll into the study. Households were excluded if the family did not primarily burn biomass for cooking, if more than seven people lived in the household, or if the family planned to seasonally migrate during the next year. Of enrolled households, 96 households were randomly selected to receive the intervention CDM-approved cookstoves following baseline assessment, while the remaining 91 households served as controls and received the stoves following the completion of the study. We randomly selected 32 households (16 interventions, 16 controls) for 24 h, real-time monitoring of CO, $PM_{2.5}$, and BC in both seasons. Adherence to protocol was determined through a questionnaire that asked occupants about stove use practices at each visit and through visible inspection of the kitchen.

2.2. Indoor air pollution monitoring

Three instruments, sampling from a common inlet installed approximately 1 m from combustion zone and 0.6 m above the floor were used for continuous monitoring of household air pollution concentrations: a DustTrak Aerosol Monitor (Model #8520, TSI, Inc., Shoreview, MN) measured $PM_{2.5}$, an IAQ-Calc (Model #7545, TSI, Inc., Shoreview, MN) measured CO, and a MicroAethelometer (Model #AE51; wavelength: 880 nm, AethLabs, San Francisco, CA) measured BC. We selected the location of measurement to be consistent among households and to approximate the breathing location of people in this community when

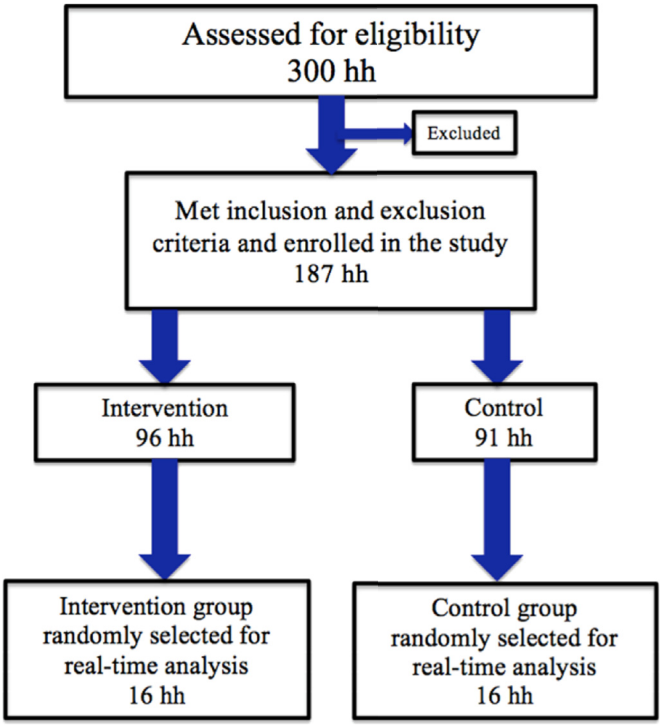

Fig. 1. Baseline enrollment and follow-up after a CDM-approved cookstove intervention in Koppal, India. Household (hh) eligibility assessment and inclusion and exclusion criterion were applied to establish randomized control and intervention treatment groups.

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