Adoption of a semi-gasifier cookstove intervention and its impact on air pollution and cardiovascular health in southwestern China

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Abstract

Background: Almost half of the world's households and 46% of Chinese homes burn solid fuel (i.e., wood, coal) as their primary energy source for cooking, heating, and other household needs. Inefficient burning of solid fuel in traditional stoves emits high concentrations of health- and climate-harming pollutants into homes and communities. Exposure to household air pollution (HAP) is a leading contributor to the global burden of disease, with approximately half of all HAP-related deaths attributable to cardiovascular diseases. Since the 1970s, millions of improved (i.e., more efficient) biomass cookstoves have been distributed to households affected by HAP; however, the population levels of adoption has been low and evidence of health benefits is limited. Advanced combustion gasifier stoves and processed forms of biomass fuels are currently viewed as the next generation of household energy interventions in many low- and middle-income settings, though little is known about their potential scalability and ability to deliver health benefits under conditions of actual use.

Research Objectives: I conducted the first field-based evaluation of the adoption of an advanced semi-gasifier cookstove and pelletized biomass fuel intervention and its impacts on air pollution exposures and sub-clinical markers of cardiovascular health, which includes blood pressure, central hemodynamics, and arterial stiffness, in a rural China.

Methods: In summer 2014, we enrolled 205 women who regularly cooked with traditional wood-burning chimney stoves into a three-year intervention study in rural Sichuan Province, China (eastern Tibetan Plateau). The intervention was a high-performing semi-gasifier cooking and water heating stove and supply of processed biomass pellets to fuel the stove. We conducted two pre-intervention and three post-intervention household visits that represented both the heating and non-heating seasons. At each visit, we measured women's 48-h air pollution exposure ($PM_{2.5}$ mass and black carbon) and a comprehensive suite of cardiovascular markers, including brachial systolic (bSBP) and diastolic (bDBP) blood pressure, central systolic (cSBP) and diastolic (cDBP) blood pressure, central pulse pressure (cPP), and carotid-femoral pulse wave velocity (cfPWV). We also collected information on other fixed and time-varying cardiovascular risk factors, including features of diet (e.g., sodium intake), physical activity, body-mass index (BMI), exposure to second hand smoke, household socio-economic status, education, ethnicity, ambient and indoor temperature. We also assessed household stove use by placing objective temperature sensors (stove use monitors, “SUM”) on stoves for short- (48-h, n=140 homes) and long-term (5 or 13 months, n=38 homes) periods and administered a survey at 5-8 months after intervention in 113 homes.

Analysis: To evaluate the impact of the intervention on blood pressure, central hemodynamics, and arterial stiffness, I followed the Bayesian paradigm and built separate multivariable mixed-effects models, controlling for temporal correlation structures and known confounders, to estimate the within- and between-group effects of the intervention on bSBP, cSBP, bDBP, cDBP, cPP, and log-transformed cfPWV. I also did a descriptive analysis of the pre-and post-intervention group arithmetic means for intervention and control women in their personal exposures to $PM_{2.5}$ and BC.

For each stove type monitored, the SUM’s data were summarized as the average proportion of days’ that the stove was used during each measurement month, the daily average number of meals cooked on the stove, and the average duration of minutes that the stove was used over 48-h periods. Multivariable probit and hurdle regression models were built to estimate the associations between intervention uptake (yes/no), 48-h stove use (yes/no), and duration of use (minutes), with independent variables determined *a priori* from the literature.

Results: I did not find an impact of the intervention on any of the six vascular markers. The estimated mean difference between intervention and control women in their estimated mean change in vascular markers over time was slightly positive for bSBP (mean posterior effect 1.44 mmHg [95% posterior credible interval (CI^e) -2.5, 5.2]), cSBP (0.55 mmHg [95% CI^e-3.0, 4.1]), bDBP (1.73 mmHg [95% CI^e -0.2, 3.5]), cDBP (1.19 mmHg [95% CI^e -0.8, 3.1]), cPP (0.23 mmHg [95% CI^e -1.8, 1.1]), and no difference for log-cfPWV (0.03 log-m/s [95% CI^e -0.03, 0.08]), though in all cases the 95% credible intervals crossed zero. Null or slightly positive intervention effects were the result of an overall decrease in average BP and cPP for the entire study population, with larger decreases observed within the control group. Similarly, average 48-h personal exposures to air pollution decreased for the entire study population over time ($PM_{2.5}$ mass: -28% intervention group, -19% control group; black carbon: -56% intervention group, -59% control group). However, post-intervention exposures for intervention women remained well above the World Health Organization (WHO) interim indoor $PM_{2.5}$ pollution exposures target of 35 ug/m^3 ($PM_{2.5}$: 91.6 ug/m^3 [95% CI 76.7, 106.3]; black carbon: 2.0 ug/m^3 [95% CI 1.7, 2.3]).

The lack of an observed intervention effect on cardiovascular health was likely due to the modest levels of intervention stove use. Of the intervention homes interviewed, only 79% tried cooking with the semi-gasifier stove at least once (self-reported uptake), and in the first 1-5 months following intervention, daily use of the semi-gasifier stove was modest (mean percentage of days in use per month: 40% [95% CI 34, 47]), and further declined after 13 months. Homes that received the first batch of stoves used it more frequently than homes that received it in the second batch, likely because of stove quality and user training. Household intervention use was positively associated with reported cooking needs, and negatively associated with age of the main cook, household socioeconomic status, and ownership of other non-biomass stoves. The majority of intervention homes continued to regularly use their traditional wood chimney stoves after intervention (77% of homes).

As China and other countries create policies and promote interventions to reduce the burden of CVD caused by environmental factors such as household air pollution, my thesis provides useful and timely information on the lack of an impact that a high-performing gasifier stove intervention had on reducing air pollution and improving vascular makers of CVD in a rural Chinese setting.

Résumé

Contexte: Quasiment la moitié des ménages et 46% de ceux-ci chinois consomment principalement du combustible solide (bois, charbon) pour la cuisine, le chauffage et d'autres besoins énergétiques. La combustion inefficace du combustible solide dans les poêles traditionnels émet des concentrations élevées de polluants nocifs pour la santé et le climat dans les maisons et les collectivités. L'exposition à la pollution de l'air domestique (HAP) est l'un des principaux contributeurs au fardeau mondial de la maladie, avec environ la moitié de tous les décès liés à la HAP attribuables aux maladies cardiovasculaires. Depuis les années 1970, des millions de fourneaux améliorés ont été distribués aux ménages et aux communautés touchés par la HAP, mais les niveaux d'adoption de ces technologies et de ces combustibles ont été faibles et les avantages pour la santé sont limités. Les foyers semi-gazéifiants à combustion avancée et les formes transformées de biocombustibles sont actuellement considérés comme la prochaine génération d'interventions énergétiques ménagères dans de nombreux pays à revenu faible ou intermédiaire, même si l'on sait peu de choses sur leur évolutivité potentielle et leur capacité à offrir des bienfaits pour la santé en utilisation réelle.

Objectifs de recherche: J'ai mené la première étude de terrain sur l'adoption d'une cuisinière semi-gazéifère avancée et d'un bouilleur d'eau et d'une biomasse granulée en milieu rural en Chine, ainsi que son impact sur la pollution atmosphérique et les indicateurs sub-cliniques de la santé cardiovasculaire, incluant la pression artérielle et la raideur artérielle.

Méthodes: Au cours de l'été 2014, nous avons recruté 205 femmes qui cuisinaient régulièrement avec des poêles à bois traditionnels dans le cadre d'une étude d'intervention de trois ans dans la province rurale du Sichuan, en Chine. L'intervention consistait en une cuisinière semi-gazéifère à haut rendement et un chauffe-eau, et une provision annuelle de granulés de biomasse transformés pour alimenter le poêle. Nous avons effectué deux visites pré-intervention et trois visites post-intervention représentatives des saisons de chauffage et de non-chauffage dans la région. À chaque visite, nous avons mesuré l'exposition des femmes à la pollution atmosphérique de 48 heures ($PM_{2,5}$ masse et carbone noir) et mesuré une série complète d'indicateurs sub-cliniques cardiovasculaires, incluant systolique brachiale (bSBP) et diastolique (bDBP) et systolique centrale (cSBP) et la pression artérielle diastolique (cDBP), la pression pulsée centrale (cPP) et la vitesse de l'onde de pouls carotido-fémorale (cfPWV). Nous avons également recueilli des informations sur d'autres facteurs de risque cardiovasculaires fixes et variables, notamment

l'alimentation (par ex., consommation de sodium et GSM/MSG), l'activité physique, l'indice de masse corporelle (IMC/BMI), l'exposition au tabagisme passif, le statut socio-économique, l'éducation, l'origine ethnique, et la température ambiante et intérieure. Nous avons également évalué l'adoption de l'intervention et les modes d'utilisation des poêles domestiques exclusifs et mixtes en appliquant des capteurs de température objectifs sur les poêles à court (48-h, n = 140 ménages) et à long terme (5 ou 13 mois, n = 38) périodes de surveillance de l'utilisation du poêle et nous avons administré une enquête 5 à 8 mois après l'intervention de 113 maisons.

Analyse: Pour évaluer l'impact de l'intervention sur les indicateurs sub-cliniques de la santé cardiovasculaire, j'ai construit des modèles multivariables et multi-niveaux, contrôlant les structures de corrélation temporelles et les facteurs de confusion connus, afin d'estimer les différences moyennes intra (avant et après intervention) et inter groupes (groupes d'intervention et de contrôle) de bSBP, cSBP, bDBP, cDBP, cfPWV transformé en log et cPP. J'ai suivi le paradigme bayésien et utilisé les approximations Monte Carlo à chaîne de Markov pour estimer les paramètres inconnus. J'ai également fait une analyse descriptive des moyens arithmétiques de groupe avant et après intervention pour l'intervention et le contrôle des femmes dans leurs expositions personnelles aux $PM_{2.5}$ et au carbone noir.

Pour évaluer l'adoption et l'utilisation de l'intervention, j'ai identifié le nombre et la durée des événements de combustion du poêle à partir des données SUMs en utilisant un algorithme que j'ai adapté de la littérature. Les données ont été résumées comme la proportion moyenne de jours d'utilisation des fourneaux chaque mois, le nombre quotidien moyen de repas cuisinés sur chaque poêle et la durée moyenne des fourneaux des minutes sur une période de 48 heures. Des modèles de probit et de régression de haies multivariés ont été construits pour estimer les associations entre l'absorption du poêle d'intervention (oui / non, réponse au questionnaire), l'utilisation du réchaud 48 heures (oui / non, SUM) et la durée d'utilisation (minutes, SUM). variables prédicteurs déterminées *a priori* de la littérature.

Résultats: Nous n'avons trouvé aucun effet statistiquement significatif de l'intervention sur l'un de nos six indicateurs cardiovasculaires. L'effet d'intervention sur bSBP (effet postérieur moyen 1,44 mmHg [intervalle crédible 95% -2,5, 5,2]), cSBP (0,55 mmHg [intervalle crédible 95% -3,0, 4,1]), bDBP (1,73 mmHg [-0,2, 3,5]), cDBP (1,2 mmHg [-0,8, 3,1]), cPP (0,23 mmHg [-1,8, 1,1]), et log cfPWV (0,03 log-m/s [-0,03, 0,08]), étaient proches de zéro et les 95% d'intervalles crédibles croissaient à zéro. La pression artérielle moyenne et la cPP ont diminué

pour l'ensemble de la population étudiée, bien que des diminutions moyennes plus importantes aient été observées dans le groupe témoin, tandis que le log cfPWV n'a pas changé au fil du temps chez les femmes témoins ou d'intervention. Les expositions personnelles moyennes non ajustées sur 48 heures (ug/m^3) aux PM$_{2,5}$ (groupe d'intervention de -28% et groupe témoin de -19%) et au carbone noir (groupe d'intervention de -56% et groupe témoin de -59%) ont été réduites pour la population d'étude entière au fil du temps (diminution en pourcentage: -%), bien que l'exposition après l'intervention chez les femmes (PM$_{2,5}$: 91.6 ug/m^3 [IC à 95% 76.7, 106.3]; BC: 2.0 ug/m^3 [IC à 95%; 1.7, 2.3]) est resté bien au-dessus de la cible provisoire de 35 ug/m^3 de l'Organisation mondiale de la santé (OMS/WHO) pour PM$_{2,5}$.

L'absence d'un effet d'intervention observé sur la santé cardiovasculaire était probablement attribuable aux niveaux modestes de prise, d'adoption et d'utilisation des interventions. Parmi les maisons d'intervention interrogées, 79% ont essayé le réchaud semi-gazéificateur au moins une fois (absorption autodéclarée) et la majorité des ménages accueillis ont continué à l'utiliser 5-10 mois après l'intervention (92%) (adoption auto-déclarée). Au cours des 1 à 5 mois suivant l'intervention, l'utilisation quotidienne du semi-gazéificateur était modeste (40,4% en moyenne [IC à 95%: 34,3, 46,6] jours d'utilisation par mois) et diminuait encore après 13 mois. Les ménages ayant reçu le premier lot de poêles l'utilisaient plus fréquemment que les ménages qui l'ont reçu dans le deuxième lot, probablement en raison de la qualité de la cuisinière et de la formation des utilisateurs. L'utilisation des interventions ménagères était positivement associée aux besoins de cuisson signalés et négativement associée à l'âge du cuisinier principal, au statut socioéconomique du ménage et à la possession d'autres poêles sans biomasse. La majorité des foyers d'intervention ont continué à utiliser régulièrement leurs poêles à bois traditionnels après l'intervention (77%).

Alors que la Chine et d'autres pays élaborent des politiques et promeuvent des interventions pour réduire la charge de MCV causée par des facteurs environnementaux tels que la pollution atmosphérique, ma thèse fournit des informations utiles et opportunes sur l'absence d'impact d'une intervention la pollution et l'amélioration des marqueurs cardiovasculaires dans un milieu rural chinois.

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It is with the upmost sincerity that I thank my primary supervisor, Dr. Jill Baumgartner, for her profound and endless support of my research activities throughout my Masters degree as well as my development as an environmental health scientist throughout the process. Dr. Baumgartner's commitment to fostering an atmosphere of intellectual curiosity, rigor while engaging in the scientific process, and exploring novel approaches to science communication, pushed my research in ways that I could not have imagined. Thank you, Dr. Baumgartner, for all of your immeasurable support of which I will always be grateful.

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Much thanks to Joy Tseng for accompanying me for one month in China for field-work, translating all of the stove use questionnaires from English to Mandarin-Chinese, and providing in-person and real-time English-Mandarin translations for me while in China. I probably would not have made it to the field site without Joy.

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I could not have written this thesis or communicated these results without saying how thankful I am to all of the women in Shiyi, Liangfengya, Yangliuping, and Jingjia villages who participated in this research.

Preface

Author contributions

I am the primary author of this thesis, which includes one peer-reviewed publication, and one other manuscript in preparation for peer-review. From McGill, I coordinated with the Chinese field staff on data collection in each of the post-intervention campaigns, and designed the study protocol for objective stove use monitoring. In China, I assembled a questionnaire on stove use and oversaw its administration at our field site. I also assisted with the collection of post-intervention air pollution and health measurements (May-August 2016). I then travelled to the University of Wisconsin-Madison (January-May 2017) to learn about gravimetric, optical, and chemical analyses of $PM_{2.5}$ samples and helped to organize and process the post-intervention $PM_{2.5}$ samples for gravimetric (mass) and optical analysis (black carbon). Finally, from McGill, I carried out the statistical analyses of the adoption of the intervention and its impact on air pollution and cardiovascular health, and wrote the results into my thesis and separate manuscripts. Finally, I researched and wrote the two literature reviews (Chapters 3 and 6) that proceed each manuscript.

Dr. Jill Baumgartner is an Assistant Professor in the Department of Epidemiology, Biostatistics and Occupational Health and the Institute for Health and Social Policy at McGill University. Dr. Baumgartner is the Principal Investigator of the EPA-funded cookstove intervention study that my thesis is nested within; she designed the study and its protocols, facilitated and made international collaborations to support the work, and she provided counsel and support on all aspects of my data analysis, interpretation, and communication of results. Dr. Baumgartner reviewed, revised, and edited multiple iterations of Chapters 3, 4 6, and 7, and my thesis as a whole.

Dr. Ellison Carter is an Assistant Professor in the Department of Civil and Environmental Engineering at Colorado State University. Previously, Dr. Carter was a post-doctoral fellow on the cookstove intervention study and oversaw the training of field staff, the implementation and organization of the baseline data collection campaigns, and laid the foundation for the post-intervention campaigns. Dr. Carter continued to advise me on the organization of the post-intervention campaigns, addressing logistical challenges during data collection, and provided ongoing feedback and support on the analysis of the stove use and air pollution data and interpretation of results. Dr. Carter also reviewed, edited, and revised, multiple iterations of Chapter 7, Chapter 4, and my thesis as a whole.

Dr. Alexandra Schmidt is an Associate Professor in the Department of Epidemiology, Biostatistics, and Occupational Health, at McGill University. Dr. Schmidt supervised the Bayesian statistical analysis of the intervention's impact on cardiovascular health, provided ongoing coding support, and multiple rounds of edits and revisions to Chapter 4.

Dr. Xudong Yang is a Professor in the Department of Building Sciences at Tsinghua University and is a Co-Principal Investigator on the project. His group lead the design, development, testing, and dissemination of the semi-gasifier cookstove and fuel intervention. Dr. Yang co-supervised my data collection activities in China and reviewed Chapter 7.

Dr. Ming Shan is a post-doctoral researcher at in the Department of Building Science at Tsinghua University. Under the supervision of Dr. Yang, he led the design and development of the semi-gasifier stove intervention and oversaw the construction of the village-level pellet factory. Both in China, and remotely, Dr. Shan provided key information and training on the engineering aspects of the stove intervention.

Dr. James Schauer is a Professor in the Department of Chemical and Environmental Engineering at the University of Wisconsin-Madison and the Director of the Wisconsin State Laboratory of Hygiene (WSLH) and is a Co-Principal Investigator on the project. Dr. Schauer directs the air pollution laboratory where all of the $PM_{2.5}$ personal exposure samples for this study underwent gravimetric, optical, and chemical analysis. Dr. Schauer provided expert advice on the treatment, transformation, analysis, and interpretation of the $PM_{2.5}$ and BC personal exposure data and gave general guidance on, and reviewed multiple drafts of, Chapter 7.

Dr. Majid Ezzati is a Professor of Global Environmental Health at Imperial College London, the Director of the Wellcome Trust-Imperial Centre for Global Health Research, and a Co-Principal Investigator on the Project. Dr. Ezzati provided general guidance on, and reviewed multiple drafts of, Chapter 7.

Dr. Subhrendhu Pattanayak is a Professor of Environmental Science and Policy at Duke University. Dr. Pattanayak advised on the statistical analysis of factors impacting intervention uptake and use and provided general guidance and reviewed multiple drafts of Chapter 7.

Dr. Marc Jeuland is an Associate Professor of Environmental Sciences and Policy at Duke University. Dr. Jeuland advised on the statistical analysis of factors impacting intervention uptake and use and provided general guidance and reviewed multiple drafts of Chapter 7.

Mr. Hongjiang Niu was the field site Project Manager in China. He supervised the field team and managed data collection activities in Sichuan, and assisted with logistics during my visits to China.

Dr. Ni Kun is a former PhD student under the supervision of Dr. Xudong Yang. Dr. Ni Kun helped set up the baseline data collection procedures at the field-site and the protocals for intervention implementation.

Dr. Christine Wiedinmyer is a scientist in the Atmospheric Chemistry Observations and Modelling Laboratory at the National Centre for Atmospheric Research (NCAR) and a Co-Principal Investigator on the project. Dr. Wiedinmyer provided general guidance and reviewed multiple drafts of Chapter 7.

Ms. Joy Tseng was a fourth-year undergraduate student at McGill University. She traveled with me to China for one month and assisted with data collection activities at the field site. She also translated the questionnaire on stove use and stove preference from English to Mandarin-Chinese. Ms. Tseng reviwed and edited Chapter 7.

Thesis organization

My thesis consists of an introduction (Chapter 1), stated research objectives (Chapter 2), two literature reviews (Chapter 3 and 6), two stand-alone manuscripts (Chapter 4 and 7), and a final discussion and conclusion (Chapter 8). My introduction introduces the reader to the global burden of cardiovascular disease as a result of exposure to air pollution from inefficient solid and biomass fuel burning, interventions of improved biomass stoves that can potentially reduce exposures to indoor air pollution and improve cardiovascular health, and the historical and current challenges facing improved biomass stove interventions in achieving high, sustained, and exclusive levels of use. My research objectives in Chapter 2 outline how I will evaluate the adoption of an advanced semi-gasifier cooking and water heating stove and pelletized fuel intervention in 12 rural villages in the Tibetan Plateau, southwestern China, and its impacts on indoor air pollution exposures and markers of cardiovascular heath. My literature review in Chapter 3 summarizes the current body of knowledge on the association between air pollution from inefficient solid fuel burning and responses in cardiovascular markers, and provides results on the potential improvements in blood pressure and other biomarkers of systemic inflammation and oxidative stress following previous improved biomass cookstove and fuel interventions. Following my review of the literature, Chapter 4 provides results on the impact of a high-performing and community designed semi-gasifier stove and pelletized biomass fuel intervention on vascular markers among 205 women in rural southwestern, China. Chapter 5 links Chapters 3 and 4 with Chapters 6 and 7 by introducing a major factor that has limited improved biomass cookstove and fuel interventions in achieving measureable health and air quality benefits for decades: a lack of uptake, adoption, and sustained and exclusive use. As such, Chapter 6 summarizes the global trends in improved biomass cookstove and fuel intervention use (as monitored with objective temperature sensors) and the multitude of factors that have been found to inhibit or promote adoption. Chapter 7 then quantifies the long- and short-term usage trends of the semi-gasifier stove intervention in southwestern China, and the individual, household, and community-level factors that were associated with difference stages of the adoption process, which include stove uptake, stove use, and duration of stove use. Finally, Chapter 8 situates the results from my thesis (specifically Chapters 4 and 7) into the global literature on the potential scalability and effectiveness of gasifier biomass stove interventions to reduce the global burden of cardiovascular disease.

List of abbreviations

BC: Black carbon

bDBP: Brachial diastolic blood pressure

BP: Blood pressure

bSBP: Brachial systolic blood pressure

cDBP: Central diastolic blood pressure

cfPWV: Carotid-femoral pulse wave velocity

CIMT: Carotid intima media thickness

cPP: Central pulse pressure

CRP: C-reactive protein

cSBP: Central systolic blood pressure

DBP: Diastolic blood pressure

EPA: US Environmental Protection Agency

HAP: Household air pollution

ICAM 1: Intercellular adhesion molecule 1

IL-6: Interleukin-6

IL-8: Interleukin-8

MDA: Malondialdehyde

$PM_{2.5}$: Particulate matter with aerodynamic diameter less than 2.5 um

RBP: Retinol-binding protein

RHI: Reactive hyperemia index

ROS: Reactive oxygen species

SBP: Systolic blood pressure

SES: Socio-economic status

SHS: Second hand smoke

SUM: Stove use monitor

THU stove: TsingHua University stove

TNF-alpha: Tumor necrosis factor-alpha

WHO: World Health Organizatio

Chapter 1. Introduction

Global consumption of biomass and coal (i.e., solid fuel) for household energy

Almost half of the world's population burns biomass fuel (i.e., wood, crop residues, and animal dung) and coal to meet their household energy needs, including cooking, space heating and lighting [1]. In many low-income and rural areas, electricity and gaseous fuels are often too expensive or inaccessible due to supply chain issues, whereas solid fuel is often more abundant and relatively lower-cost[2,3]. The majority of solid fuel users live in low or middle-income countries, with over half residing in India and China and a quarter in sub-Saharan Africa [1]. Between 1980 and 2010, the proportion of households relying on solid fuels decreased (62% to 41%), coinciding with rising national GDP's, household purchasing power, urbanization, and increased supply of electricity and gaseous fuels; however, the absolute number of homes using solid fuels remained approximately the same due to population growth [1].

Household air pollution from biomass-fuel burning

Biomass fuel is often burned in open fires or traditional stoves with large and often open combustion chambers. Thus, when biomass fuels are burned in these household stoves, people are exposed to high concentrations of air pollutants, which are released inside the home and into communities [4]. The resulting household air pollution (HAP) is a mixture of aerosols (e.g., fine particulate matter of different sizes and chemistry), gases (e.g., carbon monoxide), and volatile and semi-volatile organic compounds that are known teratogens, mutagens, carcinogens, and free radicals [4,5]. Particulate matter (PM) air pollution inherently produced with generation of HAP, is one of the most commonly researched and regulated airborne pollutants. PM can be generated from numerous sources and processes (e.g. combustion) and is currently the subject of numerous international and national air quality guidelines [6,7]. PM varies in shape and size [6]; however, PM_{10} and $PM_{2.5}$ (aerodynamic diameters < 10 μm and <2.5 μm, respectively) have received specific consideration for epidemiological studies as these size fractions are considered 'inhalable' [5]. PM_{10} has been shown to penetrate the lungs, and $PM_{2.5}$ is thought to be the particle size most strongly associated with health impacts as it is the largest size fraction that can reach deep into the respiratory tract and blood stream [8]. $PM_{2.5}$ exposures among individuals using traditional biomass stoves are typically 2-15 times higher than ambient conditions in even the most-polluted urban environments (e.g., weekly averages in Beijing range from 10 to 300 μg/m^3) [9]. Studies in Asia, Africa, and South America show that indoor $PM_{2.5}$ in households burning biomass fuel range from 50-1500 μg/m^3, exceeding the WHO 24-h interim indoor air quality target of 35 μg/m^3, and peak exposures during cooking can exceed 3000 μg/m^3 [10,11] .

$PM_{2.5}$ is a mixture of organic (e.g., organic carbon) and inorganic compounds (e.g., ions, metals) that combine and react to make PM mixtures of varying toxicity [12]. The composition of indoor-generated $PM_{2.5}$ varies by fuel type (e.g., wood, coal), stove type (e.g., open fire, advanced combustion), stove use practices, geography (e.g., type of minerals found in local environment) and climatic and atmospheric conditions (e.g., secondary atmospheric reactions produce compounds like sulphate) [13,14]. Black carbon (BC) and organic carbon (OC), two markers of incomplete combustion of fuels, comprise a large proportion of the PM exposure in settings of household solid fuel burning [14], with limited evidence showing that the relative contribution of these components to PM may be important for its health impact [15,16].

Climate impacts of inefficient biomass and solid fuel burning

Globally, $PM_{2.5}$ from household solid fuel burning is estimated to contribute to 12% of ambient $PM_{2.5}$ and, in countries like China, the proportion contribution reaches 39% [17,18]. Black carbon (i.e., soot) is the second leading anthropogenic factor forcing the climate to change [19], and a significant source of black carbon is as a component of PM generated from incomplete solid fuel burning. When the dark soot particles deposit on the surface of snow and ice, they absorb incoming and scattered heat from the sun (solar radiation). Due to black carbon's albedo reducing effects, it is a major contributor to glacial melting, particularly in high altitudes like the Tibetan Plateau [19,20]. Absorbing aerosols like BC can also heat the air and lower the levels of humidity in their locality, resulting in a positive radiative forcing effect [21]. Additionally, there is evidence that BC emissions can impact weather patterns, including decreasing cloud cover, and increasing draughts and flooding in Asia [22,23].

The health burden of exposure to HAP

HAP is a leading risk factor for the global burden of disease, currently contributing to an estimated 2.6 million premature deaths and 77 million disability-adjusted life years (DALYS) per year[24]. There is strong evidence that exposure to HAP is associated with decreased lung function, and increased incidence of respiratory infections, including pneumonia, tuberculosis, and chronic obstructive pulmonary disease, particularly among children under 5 years old for whom lower respiratory infections are a leading cause of premature death[25–27]. A limited but growing number of studies among children also suggest that exposure to HAP is associated with non-respiratory health outcomes, including low-birth weight, impaired neurodevelopment, and sleep apnea [28–31]. Among adults, HAP exposure has been linked to increased risk of respiratory infections, cataracts, certain cancers, and cardiovascular outcomes, including cardiovascular mortality, higher blood pressure, and carotid intima-media thickness [26,32–35].

HAP exposure and risk of cardiovascular disease

Strong and consistent epidemiologic evidence demonstrates a causal link between urban/traffic air pollution and tobacco smoking with increased risk of cardiovascular mortality and non-fatal events [36]. A small but growing number of studies have evaluated the associations between HAP exposure and increased cardiovascular risk. An prospective cohort study in Iran found that self-reported lifetime use of kerosene and diesel fuel for cooking was associated with an increased risk of cardiovascular mortality compared to natural gas users [37], though no association was found for biomass fuel use. Furthermore, a cross-sectional study in China found that use of solid fuels was associated with higher prevalence of coronary heart disease and diabetes [38]. The evidence for cardiovascular mortality and diseases attributable to HAP is largely based on prospective studies of outdoor air pollution and both second hand and active smoking. Using these data, Integrated Exposure-Response Curves (IERs) were developed to estimate the relative risk of cardiovascular events and mortality across a range of annual $PM_{2.5}$ exposures that includes HAP exposures [39]. Recent reviews call for better characterization of the association between exposure to HAP and CVD fatal and non-fatal endpoints [32,36].

Most evidence of HAP and cardiovascular disease is from studies of sub-clinical markers of cardiovascular health, including blood pressure, pulse pressure, and arterial stiffness [15,32,40–44], which are themselves independent risk factors for cardiovascular disease and mortality [45–48]. A number of cross-sectional studies from Asia, Latin America, and Africa found positive associations between exposure to HAP (measured pollution exposures and/or current or lifetime self-reported use of biomass fuel) and systolic and diastolic blood pressure, central pulse pressure, ST-segment depression, carotid intima-media thickness, and prevalence of hypertension [15,34,35,40–43,49–58]. Notably, several intervention studies of improved biomass or gaseous stoves (e.g., ethanol) in Latin America and sub-Saharan Africa found significant reductions in blood pressure (BP) among women who received the intervention stove compared with pre-intervention [10,59–61] and compared with women who did not receive the intervention [60,62], with larger effects among older women [59,63]. These studies indicate that measures taken to reduce exposure to HAP may reduce cardiovascular risk in HAP-impacted communities.

Clean fuels and high-efficiency cookstoves as household energy interventions

In the 1970's, mounting concern to protect forest resources from overharvesting of raw biomass for household energy use led to the design and distribution of more efficient biomass stoves that burned less wood fuel, though little attention was given to the air pollution emissions of these technologies and most stoves were no less polluting than the traditional models[64,65]. As air pollution reduction and subsequent health improvement became a larger priority, combustion scientists and engineers have worked to improve the thermal efficiencies and combustion processes of biomass stoves with the goal of reducing harmful pollutant emissions. Still, 'improved' biomass cookstoves that have resulted from these efforts range substantially in their design and emissions performance[66]. A high-performing stove in the laboratory often does not yield similarly high performance in the field under conditions of actual use [67–69]. A combination of technical (e.g., stove breakage) and behavioral factors (e.g, stove design is not robust to user needs and activities) can greatly impact the efficiency and emissions performances of 'improved' biomass stoves, and thus the use of a term like 'improved' should be interpreted with caution [66].

Millions of 'improved' biomass stoves have been distributed to households across most low- and middle-income regions [66,70–73]. Large-scale, top-down efforts have been championed by national governments, including the National Improved Stove Program (NISP) in China [70,72] (1980-1990, 200 million stoves) and the National Improved Chulha Program in India (NPIC) (1985, 28 million cookstoves) [71,74]. While both of these initiates resulted in the distribution of millions of stoves, their outcomes were substantially different; the national campaign in China has been considered to be one of the most successful in terms of widespread adoption of a biomass chimney stove with enclosed combustion chamber [70,72], while in India, millions of 'improved' efficiency biomass "Chulha" stoves were unused, have been discarded, or have broken [71,74]. Studies of improved biomass stove programs in Africa, Latin America, and Asia have shown sizeable reductions in kitchen concentrations of $PM_{2.5}$ ($\mu g/m^3$) (range of mean % reduction: -41, -63%) and CO (ppm) (range: -39, -68%)from baseline conditions, though post-intervention concentrations remain well above international targets[7,11,75,76].

Biomass-burning gasifier stoves have been proposed as an alternative to gaseous (e.g., LPG, ethanol) and electric stoves, which have the lowest (or no local) pollutant emissions, but can be limited by cost and supply chain issues [2]. Gasifier stoves burn processed biomass fuel in a two-stage process, separating the combustion of raw biomass from the combustion of gases, which results in a 'gas-like' flame [77]. Gasifiers have typically outperformed other types of biomass stoves in laboratory studies [67,78,79]; however, their performance is variable [80] and few studies have evaluated air pollution concentrations and exposures from these stoves under conditions of actual use in homes [11,68,81]. International organizations including the Global Alliance for Clean Cookstoves (GACC) and governments, including China, are promoting the distribution of gasifier stoves and processed biomass fuels (e.g., pellets, briquettes) for household energy even though the empirical evidence of their effectiveness in reducing air pollution and, ultimately, improving health outcomes, is very limited [77,82–86]. There is clearly a need for rigorous research that evaluates the effectiveness of gasifier and semi-gasifier stoves in reducing HAP and improving health.

Chapter 2. Research objectives

Globally, HAP is currently responsible for 2.6 million yearly premature deaths, approximately half which are attributable to cardiovascular diseases [24]. In China, an estimated 700 million people still cook and heat with solid fuels and an estimated 700,000 Chinese die prematurely from exposure to HAP [1,87,88]. Though hundreds of millions of 'improved' biomass stoves have been distributed in China and other countries, the population-level adoption of improved biomass cooking technologies has not always been high, emissions performances have been poor, and the evidence of their health benefits limited [59,62–65,89–95].

Advanced combustion gasifier stoves have consistently and sizably outperformed other 'improved' biomass stoves in laboratory studies of their air pollution emissions performance [67,78]. In China, rural energy policies indicate broadening support for the construction of village-level biomass processing factories which produce processed (pelletized) biomass fuel that are most efficiently burned in gasifier stoves [86,96]. However, very little is known about the potential scalability of gasifier stoves and pelletized biomass fuel interventions and their ability to deliver measurable benefits in air pollution exposure reduction and population health. **To fill this evidence gap, we conducted the first study to evaluate the adoption and use of an advanced semi-gasifier stove and pelletized biomass fuel intervention and its impacts on air pollution and cardiovascular risk in rural southwestern China**. We enrolled 205 rural women from 204 homes in 12 villages in Beichuan County, Sichuan Province, China into a 3-year, pre- and post-intervention study (Sept 2015 – Feb 2017), of stove adoption and use, air pollution, and cardiovascular health. The intervention was a high-performing and low-polluting semi-gasifier stove that burned pelletized biomass as fuel. The intervention was designed by engineer researchers at TsingHua University (referred to as the THU stove) over a 5-year iterative process that incorporated community preferences and attention to other energy needs like water boiling[97]. Following a year of baseline measurements, the intervention stove was distributed to homes in half of the study villages (~3/5 of the study homes) and dissemination occurred in two phases; 25% of intervention homes received stoves in the first phase (September 2015) and 75% in the second phase 3-4 months later (January 2016). At the end of the study, control homes received the intervention stoves.

The specific aims for my thesis research are two-fold:

1. Evaluate whether women receiving a THU semi-gasifier stove and pelletized biomass fuel intervention had changes in blood pressure, arterial stiffness, and central hemodynamics compared with women who did not receive the intervention (control);

    1a. Evaluate whether intervention women had changes in mean exposures to $PM_{2.5}$ and BC pollution compared to control women;

2. Quantify the uptake, adoption, and long-term use of a THU semi-gasifier stove and pelletized biomass fuel intervention, and the household and individual-level factors associated with these different metrics of stove use.

To achieve my research goals, I collected self-reported information from questionnaires, and objective measures of stove usage, air quality and exposures to $PM_{2.5}$ and black carbon, and subclinical cardiovascular markers including blood pressure, arterial stiffness, and central hemodynamics. Data were collected in the winter (heating) and summer (non-heating) seasons during five data collection campaigns, two pre- and three post-intervention.

Chapter 3. Literature review: Cardiovascular impacts of improved biomass stove and modern fuel interventions

To inform my first research objective, I conducted a literature review to summarize the current state of knowledge on (i) the associations between household solid fuel use and resulting air pollution exposures with CVD outcomes and (ii) the cardiovascular impacts of transition from traditional biomass stoves to ‘improved’ stove and fuel interventions.

To this end, I searched PubMed and Scopus databases for peer-reviewed journal articles. For objective (i), I used *“CVD” OR “blood pressure” OR “arterial stiffness” OR “ventricular” OR “CIMT” OR “plaque” OR “systolic” OR “diastolic” OR “pulse wave velocity” OR “pulse pressure” OR “inflammation” OR “biomarker” OR “oxidative stress” OR “endothelial”) AND (HAP OR “household air pollution” OR “biomass smoke” OR “biomass fuel” OR “solid fuel” OR “indoor air pollution”),* for objective (ii), I used (*“CVD” OR “blood pressure” OR “arterial stiffness” OR “ventricular” OR “CIMT” OR “plaque” OR “systolic” OR “diastolic” OR “pulse wave velocity” OR “pulse pressure” OR “inflammation” OR “biomarker” OR “oxidative stress” OR “endothelial”) AND (“cookstove” OR “cook stove” OR “household energy intervention” OR “improved stove” OR “ICS” OR “gasif*” OR “advanced combustion” OR “LPG” OR “biogas” OR “ethanol” OR “electricity”) AND (“indoor air pollution” OR “household air pollution” OR “smoke”);* I also reviewed the reference lists in identified studies. From my initial literature search, I retrieved 719 articles on CVD and HAP exposure and 135 articles on CVD and cookstove interventions of which I reviewed titles for inclusion into the review. I restricted the review to studies of adults (≥18 years old) exposed to pollution from household solid fuel burning since exposure ranges differ from ambient PM.

3.1 Associations between exposure to air pollution and CVD mortality and events

There is strong and consistent epidemiological and toxicological evidence that exposure to urban and traffic-related air pollution is associated with an increased risk of cardiovascular mortality and non-fatal events [36,98,99], which is further supported by a strong evidence associating tobacco smoking and cardiovascular risk [100,101]. Associations between exposure to environmental tobacco smoke (i.e., second hand smoke (SHS)) and CVD mortality and events have also been established from observational studies and from natural experiments that observed reductions in CVD events and mortality following smoking bans and other regulations [102,103].

3.2 Exposure assessment in epidemiological studies of HAP

Epidemiological assessments of HAP have generally used two different approaches to assess exposures: (1) a fuel-based approach, and a (2) pollutant-based approach [26].

Fuel-based approaches use information on current and/or historical use of solid fuel stoves. These approaches can potentially capture long-term exposure to HAP, are relatively inexpensive (per response) and non-invasive (e.g., interview, survey) to collect, and can thus lead to studies with a large number of responses and sufficient power to detect small effects. However, the data were collected from self-reported surveys and potentially subject to reporting biases, including social desirability bias (e.g., respondents may over-report the use of cleaner fuels), as well as recall bias (e.g., respondents may not remember the number of days they used different types of fuels in the past) [104]. As well, considering that exposures to air pollutants like $PM_{2.5}$ are influenced by many environmental, behavioural, household factors (e.g., temperature, humidity, personal time-activity patterns, kitchen characteristics, cooking times and practices, and other air pollution sources), attributing HAP exposures to fuel use categories is subject to misclassification and also cannot be used to evaluate exposure-response relationships [10,26].

Pollutant-based approaches capture real-time and time-resolved, 'integrated' measures of air pollution in communities, homes, and for personal exposures, and can be used to estimate exposure-response relationships. Measurement of integrated personal exposure to $PM_{2.5}$ using gravimetric analysis is considered the gold standard. However PM monitors are expensive, noisy, and bulky to carry, which limits the feasibility of large-scale and long-term measurement, particularly among children and other vulnerable populations[10]. Stationary measurements in homes, and particularly kitchens, have been widely used as an alternative to personal HAP exposure assessment, though their association with measured exposure has been shown to be poor in settings where both stationary and personal exposure measurements were conducted[10]. The evidence of measured personal exposures or indoor concentrations of HAP $PM_{2.5}$ and BC and responses in CVD sub-clinical indicators or biomarkers is thus limited by the lack of studies conducted in diverse regions of the world, small sample sizes due to the intensive nature of collecting personal exposure measurements, and the cross-sectional nature of study designs, which can lead to bias from reverse causality.

3.3 Associations between exposure to HAP and CVD events and mortality

There is limited direct evidence establishing a link between CVD events and mortality and exposure to HAP, which is largely due to the difficulty of setting up cohort studies in low-resource settings where populations may be transient but need to be followed over long observation periods (e.g., >10 years) to observe clinical CVD endpoints. Additionally, challenges of exposure assessment limit the sample sizes that can be obtained with sufficient power to detect an effect [32]. To date, just one prospective study has evaluated the association between household fuel use and CVD mortality, finding that lifetime use of kerosene or diesel fuel compared to use of natural gas was associated with an increased risk of CVD mortality in Iranian adults (10-year adjusted hazard ratio 1.11 [95% CI 1.06, 1.17]) [37], though no effect was found for use of biomass fuels. Aditionally, a cross-sectional study in China found that use of solid fuels was associated with self-reported coronary heart disease (Odds ratio (OR) 2.58 [95% CI 1.5, 4.3]) and diabetes (OR 2.48 [95% CI 1.6, 3.9]) [38], though the study did not adjust for level of urbanicity, geography (e.g., elevation, location), ambient temperature, features of diet, or physical activity.

3.4 Estimating the exposure-response between HAP and CVD events and mortality

To estimate the potential CVD impacts of HAP in the absence of observational studies, Burnett et al (2014) estimated an exposure-response curve between $PM_{2.5}$ exposures and the relative risk of CVD mortality from stroke and ischemic heart disease based on numerous longitudinal studies associated CVD mortality with exposure to ambient air pollution, second hand smoke, and tobacco smoking [39]. The curve exhibits steep increases in the relative risk of CVD mortality at lower exposures (i.e., those typical of ambient air pollution in North America) and increases, but flattens out, at higher exposures (i.e., tobacco smoking), forming a supra-linear exposure-response relationship [39,98]. Consequently, reducing exposures to $PM_{2.5}$ at lower baseline levels (e.g., ambient pollution 0-50 $\mu g/m^3$) may have a greater impact on reducing health burdens then reducing the same magnitude of exposures but starting from higher baselines. Notably, the IER curves assume similarities in the toxicity of $PM_{2.5}$ from traffic and urban sources and $PM_{2.5}$ from biomass burning, which may not be the case [12] and levels of exposure to $PM_{2.5}$ in settings where biomass burning is common (~50-600 μg/m^3) generally fall between ambient air pollution and smoking [10].

3.5 HAP and sub-clinical cardiovascular markers

3.5.1 HAP and blood pressure, markers of atherosclerosis, and arterial stiffness

A number of HAP studies have evaluated the associations with sub-clinical cardiovascular markers like blood pressure and arterial stiffness, which are independently associated with increased risk of cardiovascular events but can be measured over the shorter-term and with smaller sample sizes [32,36]. Cross-sectional studies in Asia sub-Saharan Africa, and Latin America found that, compared with clean fuel users, women primarily using solid fuel had higher SBP (range 0.58-9.2 mmHg)[35,49,50,53,57], DBP (range 2.0-5.9 mmHg)[49,54], arterial pressure (2.0 mmHg) [54], and odds of hypertension (OR range: 1.07-1.4)[35,52,54]. In exposure-response studies conducted in Asia and sub-Saharan Africa, a 1-ln (μg/m^3) or 1 ppm increase in daily exposure to air pollutants ($PM_{2.5}$, BC, CO) was associated with 1.8-4.3 mmHg higher central and brachial SBP [15,34,40,41] and 0.4-1.3 mmHg higher DBP [15,34,40,41,58,105]. In a panel study of rural Indian women, acute increases in SBP (0.4-1.9 mmHg) were observed in the minutes following exposure to black carbon during cooking [42]. Notably, these exposure-response studies suggest non-linear associations where blood pressure levels rise steeply at lower levels of exposure, (e.g., $PM_{2.5}$ 0-50 μg/m^3), and flatten as exposures increase (e.g., $PM_{2.5}$ >50 μg/m^3) [15,40,41]. Studies that evaluated household concentrations of HAP and blood pressure were less consistent, potentially due to greater exposure measurement error [43,51,59]. Rural Indian women in homes where daily indoor $PM_{2.5}$ exceeded the WHO target of 35 μg/m^3 had higher SBP (7.1 mmHg, p-value=0.09) and DBP (4.7 mmHg, p-value=0.06) than women in homes where indoor $PM_{2.5}$ concentrations met or were lower than the WHO target [51] and reductions in household HAP was moderately linearly correlated with reductions in levels of SBP (mmHg) among women in Bolivia (r=0.59) [59], though a cross-sectional study in Nicaragua did not find an association between HAP concentrations and blood pressure levels [43]. Finally, limited evidence from Nepal, China, and Nicaragua suggests that older women and those with higher BMI may be more vulnerable to higher blood pressure from HAP exposure compared with younger women and those of healthy weight [15,40,43,55,56].

Indicators of arterial stiffness and atherosclerosis have also been positively associated with use of biomass fuels. In Peru, biomass users had 2-3 times higher odds of carotid artery plaques and greater (0.03 mm) CIMT compared with clean fuel users [50]. Just several small-scale studies assessed changes in measures of arterial stiffness (e.g., carotid-femoral pulse wave velocity (cfPWV), augmentation index (AIx) (%)), following exposure to woodsmoke; while these studies point to a positive association - for example in rural China women with higher exposure to $PM_{2.5}$ had higher augmentation index levels (2.8% difference [95% CI -1.6, 7.2]) compared to women with lower exposure - the precision in their estimates is limited due to small sample sizes. Larger-scale studies are needed to confirm these results [34,106].

3.5.2 HAP and biomarkers of oxidative stress, inflammation, endothelial function, and ventricular right pressure

Toxicological studies of human and animal cells have elucidated some of the potential pathological mechanisms by exposure to air pollution can result in CVD events and mortality (i.e., biological plausibility) [36]. The bulk of these studies point to a positive association between exposure to traffic and urban-related ambient air pollution and elevated levels of proinflamatory biomarkers (which are indicators of systemic inflammation), the over-production of reactive oxygen species (i.e., free radicals) [36], endothelial dysfunction, endothelial cell activation, and blood coagulation [3634,52,94,107–111]. The limited evidence from HAP studies corroborates these findings [34,52,94,107–111]. For example, cross-sectional studies in India observed that higher levels of indoor concentrations of $PM_{2.5}$ in biomass-burning homes was associated with higher serum concentrations of inflammatory markers including IL-6, CRP, TNA-α, and IL-8 among adult women (Odds ratio (OR) range: 1.3-2.2)[110]. Furthermore, longitudinal intervention studies in Canadian adults[109] and pregnant Nigerian women[94], observed that large decreases in HAP exposure (1-ln ($\mu g/m^3$) or median ($\mu g/m^3$) reduction in $PM_{2.5}$) following intervention was associated with 10-24% decreases in serum concentrations or counts of inflammatory biomarkers, such as IL-8, TNA-α and band cells. Similar positive associations were found for studies of HAP and markers of oxidative stress; among a cohort of adult Indian women, higher levels of exposure to HAP was associated with significantly higher levels, such as reactive oxygen species (ROS), oxidized low-density lipoprotein level in plasma (OR range 1.7-2.7) [52,110], and depletion in antioxidant enzymes (OR 1.3) [52,110]. Furthermore, endothelial dysfunction is one mechanism along the atherosclerotic disease pathway. In a rural woodsmoke-impacted community in Canada, reductions in HAP from the introduction of air filters resulted in a 9.4% (95% CI 0.9, 18%) increase in a biomarker of endothelial functioning (RHI), and in high-altitude Peru, biomass users compared to non-users had 10-15% increases in serum concentrations of some biomarkers of endothelial inflammation (e.g., VCAM, ICAM, E-selectin protein) [107,109]. There is also speculation that biomarkers of right ventricular pressure are also associated with HAP and are risk factors for the genesis of CVD events and mortality, though no HAP studies to date have found a statistically significant association [34,108].

3.6 Impact of improved biomass stoves or modern fuels on cardiovascular risk

Few studies have evaluated the CVD impacts of clean stoves or fuels following randomized, quasi-experimental, or non-randomized intervention (Table 1). To date, only six studies conducted in Africa (n=1), Asia (n=2), and Latin America (n=3) evaluated changes in sub-clinical vascular markers (e.g., blood pressure, ST-segment depression) or blood biomarkers of inflammation and oxidative stress: three had a randomized intervention design (three total studies, five published papers) [60–62,94,95] and three are non-randomized observational studies [59,63,93]. Most field campaigns assessed the effectiveness of an improved biomass burning stove (with or without a chimney) (e.g., rocket stove, Plancha chimney stove; improved Chulhas) (n=5) [59–61,63,93,95], and one campaign (two manuscripts) evaluated the impact of a fuel intervention (bioethanol) [62,94].

Table 1. Review of prospective intervention (randomized or non-randomized) studies evaluating the cardiovascular impacts (blood pressure, vascular functioning, and/or biomarkers) following improved biomass stove or fuel interventions in low- and middle-income countries.

Author (year of publica-tion)	Setting	Study design	n	Partici-pants	Interve-ntion	Intervention effect	Covariates evaluated
McCracken et al. (2007) [60]	Guatemala	**RCT**; ITT; Control group; Within and between-group comparisons;	120	Women 38-84 yrs	Plancha chimney biomass stove	Intervention vs control: **SBP**: **-3.1** mmHg [95% CI: -5.3, -0.8], and **DBP**: **-1.9** mmHg [95% CI: -3.5, -0.4] Pre- vs post-intervention: **SBP: -3.7** mmHg [95% CI: -	Age, BMI, SES, active smoking, SHS temperature, season, day of the week, time of day

		Controlled for confounders.				8.1, 0.6] and **DBP: -3.0** mmHg [95% CI -5.7, -0.4]	
Alexander et al. (2017) [62]	Nigeria	**RCT**; ITT; Control group; Within and between-group comparisons; Sub-group analyses.	324	Pregnant women	Bio-ethanol cookstove	Intervention vs control: **DBP**: -2.8 mmHg (p-value=0.04) and percentage of **hypertensive** women: 1.9% vs 6.4% (p-value=0.05) Intervention vs control: **DBP** +3.6 mmHg (p-value=0.03) and percentage of **hypertensive** women: 1.8% vs 8.8% (p-vaue=0.03) (among baseline kerosene users)	
Aung et al. in review (2018) [95]	India	**Randomized Intervention** ITT; Per-protocol; Control group; Within and between-group comparisons; Stratified analyses; Controlled for confounders.	222	Women ≥25 years old	Biomass 'Rocket' stove	Intervention vs control: **SBP** +1.2 mmHg [95% CI: -2.9, 5.4] and **DBP**: +0.6 mmHg [95% CI: -1.8, 3.1] Pre- vs post-intervention: **SBP:** +0.2 mmHg [95% CI: -2.5, 2.1] and **DBP:** -0.2 mmHg [95% CI: -1.9, 1.4]. Mixed stove users (intervention and traditional) vs control (traditional): **SBP:** +6.7 mmHg [95% CI: 1.4, 12.1] and **DBP:** +2.4 mmHg [95% CI: -0.8, 5.6]	Age, BMI, ambient temperature, betel nut chewing, self-reported health, and SES Stratified analyses: Age ≤40 or >40; BMI <18.5 kg/m^2, 18.5 kg/m^2 ≥ BMI < 23 kg/m^2; and ≥ 23 kg/m^2
McCracken et al. (2011) [61]	Guatemala	**RCT**; ITT; Control group; Within- and between group comparisons; Controlled for confounders.	119	Women 38-84 yrs	Plancha chimney biomass stove	Intervention vs control: **ST-segment depression**: OR 0.26 [95% CI 0.08,0.90] and **HRV** (SDNN difference*) - 2.0 msec [95% CI -6.5, 11.2] Pre vs post-intervention: ST-degment depression: OR 0.28 [95% CI 0.12, 0.63] and **HRV** (SDNN difference) 0.9 msec [95% CI -6.0, 8.3]	Age, BMI, ever smoking, SES, SHS, ownership of a wood-fired sauna, time of day
Olopade et al. (2016) [94]	Nigeria	**RCT**; ITT; Control group; Within- and between-group comparisons; Sub-group analyses.	271	Pregnant women	Bio-ethanol cookstove	Intervention vs control: mean change in **RBP** (mg/dl) (p-value=0.71), **IL-6** (pg/ml) (p-value=0.14), **IL-8** (pg/ml) (p-value=0.95), **TNF-α** (pg/ml) (p-value=0.24), **MDA** (pmol/ml) (p-value=0.11) Intervention vs control: **TNF-α:** −6.2 (pg/ml) (SE	Season (rainy vs dry)

						5.24) (intervention) vs 14.03 (pg/ml) (SE 5.89) (control) (p-value=0.01) among fire-wood users at baseline	
Clark et al. (2013) 63	Nicaragua	**Prospective cohort (no control)**; ITT; Within-group analyses; Stratified analyses.	74	Female cooks	Chimney biomass "Eco-stove"	Pre vs post-intervention: **SBP**: **-**1.5 mmHg [95% CI -4.9, 1.8], and **DBP:** 0.0 mmHg [95% CI -2.1, 2.1] Pre vs post-intervention: **SBP**: **-5.9** mmHg [95% CI -11.3, -0.4] and **DBP**: -1.8 mmHg [95% CI -5.4, 1.7] (among women over 40 yrs old)	Stratify model by age (≥40yr and < 40yrs) and weight status (Obese vs non-obese)
Alexander et al. (2014) 59	Bolivia	**Prospective cohort (no control)**; ITT; Within-group comparisons; Stratified analyses.	28	Female head-of-household	"Yanayo" chimney biomass stove	Pre vs post-intervention: **SBP:** -4.8% change (p-value=0.01) (pre-int mean: 114.5 +- 13.0 mmHg; post-int mean: 109.0 +- 10.4 mmHg) Pre vs post-intervention: **DBP:** -1.5% change (p-value=0.5) (pre-int mean: 71.2 ± 6.3 mmHg; post-int mean: 70.1 ± 7.8 mmHg) Stratified models: Women over 50 yrs (p-value =0.05), women of normal weight (p-value=0.09) and women overweight (p-value=0.08) had significant or slightly significant decreases in **SBP**	Stratified models by age (≥50 and <50yrs) and weight status (Underweight, normal weight overweight, and obese)
Jamali et al. (2016) 93	Pakistan	**Prospective cohort**; ITT; Control group; Between-group comparisons; Controlled for confounders.	605	Main cook in household	Improved biomass stoves (NPIC program)	Intervention vs control: **SBP** range 0.95 [95% CI -2.0, 5.0] to 0.02 [95% CI 3.4, 3.5] mmHg, **DBP** range -0.89 [95% CI -3.3, 1.5] to 0.74 [95% CI -1.8, 3.3] mmHg and **pulse** 1.47 [95% CI -2.2, 1.9] to 2.55 [95% CI -0.2, 5.3] beats/min	Age, education, husband/fathe education, monthly income, kitchen type, SHS

Definitions: RCT: randomized controlled trial, ITT: Intention-to-Treat; BMI: Body-mass index; SES: Socio-economic status; SHS: exposure to second hand smoke; SBP: Systolic blood pressure; DBP: Diastolic blood pressure; HRV: Heart rate variability; SDNN: Standard deviation of normal-to-normal intervals; IL-8: Interleukin-8; IL-6: Interleukin-6; MDA: Malondialdehyde; RBP: Retinol-binding protein; TNA-α: Tumor necrosis factor alpha

3.6.1 Randomized cookstove interventions

Three separate intervention studies with randomized allocation of the intervention, including improved biomass burning stoves (n=2) [60,61,95] or modern fuels (n=1) [62,94] , were conducted between 2002 and 2015 in Guatemala, Nigeria, and India to assess changes in sub-clinical CVD markers, including blood pressure, ST-segment depression, heart rate variability, and inflammatory biomarkers. In these studies, the introduction of intervention stoves changed air pollution exposures ($PM_{2.5}$) or household concentrations *between intervention and control groups* by -64% to +119% [60,61,95,112], and *within intervention groups* (i.e., pre- versus post-intervention) by -40% to +35% [61,95]. Furthermore, the introduction of (a) improved biomass stoves and (b) gas-fuel stoves were associated with *between group* differences in SBP ranging from (a) -3.1 to +1.2 mmHg [60,95] and (b) -1.3 mmHg (p-value=0.86) [62], respectively, and DBP ranging from (a) -1.9 to +0.6 mmHg [60,95], and (b) -2.8 mmHg [62]. *Within intervention women* changes over time showed similar trends with mean changes in SBP ranging from (a) -3.7 to +0.2 mmHg [60,95] and DBP ranging from (a) -3.0 to -0.2 mmHg [60,95]. For other vascular markers, in Guatemala, a chimney biomass stove intervention was associated with 0.26 [95% CI 0.08, 0.90] lower odds of 30-minute average ST-segment depression, but no association was found for heart rate variability [61]. Only one intervention study collected blood markers of systemic inflammation, which is a proposed biological pathway along the genesis of CVD events and mortality. In Nigeria, serum concentrations of TNA-α were significantly reduced for women receiving a bioethanol stove (-6.2 (pg/ml)) compared with control women who continued using wood stoves (14.03 (pg/ml)), though mean changes in other biomarkers including IL-6, IL-8, MDA and RBP were not statistically significant [94]. Notably, the studies in Nigeria and Guatemala saw the largest improvements in BP and markers of vascular functioning and also had high levels of sustained use of the intervention stove (>90% of days intervention used) [113,114] In India, women continued using their traditional stoves alongside the intervention stove and mixed stove use was associated with higher SBP +6.7 mmHg [95% CI 1.4, 12.1] and DBP +2.4 mmHg [95% CI -0.8, 5.6] compared with control women [95].

All studies included a control group for comparison and conducted Intention-to-Treat (ITT) analyses, with the India study additionally conducting a per-protocol analysis based on stove usage patterns [95]. Sample sizes were small to moderate, ranging from 119 women in Guatemala to 324 women in Nigeria. The randomized intervention studies in Guatemala and

India controlled for known confounders, such as age, BMI, SES, active and second hand smoking, ambient temperature, day of the week, time of day, self-reported health, and ownership of land, though these studies did not account for features of diet (i.e., sodium intake) or cooking methods (frying versus boiling), which may change with the introduction of a new cooking technology and also be associated with changes in cardiovascular risk [60,61,95]. The study in Nigeria only accounted for an indicator for the rainy/ dry season in their models, or conducted sub-group analyses among kerosene or firewood users at baseline. Thus, although the Nigeria study is a RCT, which comes with an assumption of measured and unmeasured covariates being controlled for in the randomization process, the moderate sample size (n=324) could threaten the 'assumed' balance of covariates between groups [62,94].

3.6.2 Non-randomized stove intervention evaluation studies

Two non-randomized intervention studies of improved biomass stoves conducted in Bolivia [59], and Nicaragua [63] found large reductions in household concentrations of $PM_{2.5}$ over time *within the intervention group*, ranging between -77 and -80% ($\mu g/m^3$) [59,63] and the introduction of the intervention was further associated with significant decreases in SBP (mmHg) *within* Bolivian women (-4.8% decrease, p=0.01) and women over 40 years old in Nicaragua (-5.9 mmHg [95% CI -11.3, -0.4]), with no observed affect for DBP. In Pakistan, among a subset of the study population (n=20 intervention, n=20 controls), the intervention group had a significantly (p<0.05) lower median concentration of $PM_{2.5}$ (78.4 $\mu g/m^3$ (IQR 45.4–164.1)) compared to the control group cooking with traditional biomass stoves (588 $\mu g/m^3$ (IQR 250.4–893.8)) [93], though the post-intervention mean levels of SBP, DBP, and pulse rate were not significantly different for intervention or control women [93].

Only the Pakistan study included a control group, such that natural changes that may have occurred over time in the study population and were independent of the intervention (i.e., seasonal changes in air pollution or cooking times) were not controlled for in the Nicaragua and Bolivia studies [59,63,93]. The study in Pakistan controlled for known CVD risk factors including age, SES, and exposure to second hand smoke, and the studies in Bolivia and Nicaragua stratified their models by age and categories BMI [59,63,93]. The studies that exclusively conducted *within-group* analyses (i.e., changes in BP over time among intervention women) [59,63] did not control for potentially influential time-varying confounders such as ambient temperature which has been shown to influence stove use patterns[115] and is strongly correlated with blood pressure[116]. Finally, sample sizes varied considerably between studies, as low as n=28 [59] women enrolled to as high as n=605 women [93]. Small sample sizes can reduce the statistical power in a study to detect changes in the outcome measures.

3.7 Conclusion

There is strong evidence of causal associations between exposure to smoking and ambient air pollution and an increased risk of CVD events and mortality, and mounting evidence that this relationship extends to short and long-term exposure to HAP from biomass fuel combustion. The majority of direct evidence is based on studies of exposure to HAP and sub-clinical indicators of CVD that are independently associated with increased risk of cardiovascular diseases, including vascular markers and blood markers of inflammation, oxidative stress, and endothelial functioning. Together, these studies suggest that the implementation of cleaner-burning biomass cookstoves and modern fuels may be interventions to reduce cardiovascular disease burden, though the few cookstove or fuel intervention studies to date have been limited by small sample sizes [59,60,62,63,94], a lack of control for confounders[59,63,94], a lack of a control group for comparison [59,63], a limited suite of evaluated cardiovascular markers, and none have evaluated the potential cardiovascular impacts of advanced gasifier or semi-gasifier cookstove designs. Given the emphasis on these stoves designs for future and planned interventions, there is a need for rigorous research that evaluates the effectiveness of cookstove and fuel interventions in reducing air pollution and improving health indicators that can be used to inform evidence-based energy policies in low- and middle-income countries burdened by HAP.

Chapter 4. Vascular impacts of a semi-gasifier stove and processed biomass fuel intervention in the Tibetan Plateau, southwestern China

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Abstract

Background: Household air pollution from biomass stoves contributes to over 1 million yearly premature cardiovascular deaths globally. We hypothesized that an advanced combustion semi-gasifier stove and pelletized biomass fuel intervention would reduce cardiovascular risk in rural Chinese women.

Methods: We conducted a three-year pre- and post-intervention study in southwestern China. Women in half of the study villages were randomly assigned to receive the intervention at no cost (n=125) and women in the remaining villages served as controls (n=80). Blood pressure, arterial stiffness, central hemodynamics, air pollution exposures, and key cardiovascular risk factors were measured on up to five visits. The effect of the intervention on vascular indicators over time and between intervention groups was assessed with mixed-effects multivariable linear regression models using Bayesian inference procedures.

Findings: Pre- to post-intervention, brachial and central systolic (bSBP, cSBP) and diastolic (bDBP, cDBP) blood pressure and central pulse pressure (cPP) decreased on average for intervention and control women, though reductions were slightly greater for the control group, resulting in positive non-signifcant intervention effects for bSBP (mean posterior effect 1.44 mmHg [95% posterior credible interval (CI^e) -2.5, 5.2]), cSBP (0.55 mmHg [95% CI^e-3.0, 4.1]), bDBP (1.73 mmHg [95% CI^e -0.2, 3.5]), cDBP (1.19 mmHg [95% CI^e -0.8, 3.1]), cPP (0.23 mmHg [95% CI^e -1.8, 1.1]), and no difference for arterial stiffness (carotid-femoral pulse wave velocity: 0.03 log-m/s [95% CI^e -0.03, 0.08]). Air pollution exposures also decreased for intervention (-28% to -56%%) and control women (-19% to -59%) on average.

Interpretation: As China and other countries create policies and promote interventions to reduce the burden of CVD caused by household air pollution, our study provides useful and timely information on the lack of an impact that a high-performing gasifier stove intervention had on vascular makers of CVD in a rural Chinese setting.

Keywords: Arterial stiffness, blood pressure, cookstove, household air pollution, pulse wave velocity

4.1 Introduction

Cardiovascular diseases are the leading contributors to disease burden globally [117] and in China [118], responsible for >17 million premature deaths in 2015 and posing substantial social and economic burdens [119]. Aging populations and shifts in lifestyle choices (e.g., smoking, diet, physical activity) are important contributors to this large and increasing cardiovascular burden [24]. Environmental risk factors such as air pollution and tobacco smoking have consistently shown strong associations with an increased risk of cardiovascular mortality and related non-fatal events (CVD), and the majority of deaths attributable to air pollution are related to cardiovascular diseases [36,117].

Cooking and heating with inefficient biomass and coal stoves, a daily practice for over 2.8 billion people globally, and ~700 million Chinese [1,88], emits high concentrations of air pollution into homes and communities[4]. Studies in Latin America, sub-Saharan Africa, and Asia have associated air pollution from biomass burning with higher blood pressure (BP), carotid intima-media thickness (CIMT), and left ventricular remodeling [38,40,42,49,50,58]. Among rural Chinese women who regularly cooked with biomass stoves, a 1-log-µg/m^3 increase in exposure to $PM_{2.5}$ or black carbon was significantly associated with a 2 to 4-fold increase in systolic BP (mmHg) and a 0.5 to 1.5-fold increase in diastolic BP (mmHg) [15,41]. While our understanding of the mechanisms by which inhaled particles may increase blood pressure and cardiovascular risk is not entirely clear, toxicological studies and bioassays of human and animal cells point to cellular oxidative stress and systemic inflammation as likely mechanisms [36].

Reducing exposures to household air pollution by distributing improved biomass stoves and fuels can potentially result in improvements in cardiovascular health [11,75]. In randomized trials in Guatemalan and Nigerian women, the introduction of wood chimney and ethanol stoves were associated with lowered BP and ST-segment depression compared with those who continued using traditional stoves [60–62,94]. Other non-randomized intervention studies found similar decreases in levels of systolic blood pressure among intervention women over time [59,63]. However, there are only a small number of improved stove and fuel trials [59,60,63,93–95] that are also limited by small sample sizes, in some cases a lack of a control group, and minimal adjustment for confounding covariates, which limits the conclusions we can draw from them. Additionally, a number of studies have assessed the impact of stove interventions on blood pressure, though none have evaluated the effects of stove interventions on arterial stiffness or central hemodynamics, which are known risk factors for CVD, independent of BP.

Advanced combustion gasifier stoves have been widely promoted by international organizations as a new generation of high-performing biomass stoves that may be more affordable and realistic alternative to LPG or electric stoves. In China, rural energy policies support the production of processed biomass pellets to burn in gasifier stoves and subsequent replacement of traditional, highly-polluting coal and biomass stoves[96]. Gasifier stoves consistently outperformed other advanced biomass stoves in laboratory and field studies of air pollution emissions, but have not been evaluated for their potential impacts on air pollution exposures and health in real-world settings [78]. Thus, we conducted the first field investigation of an advanced semi-gasifier stove and its impacts on blood pressure, arterial stiffness, and central hemodynamics in rural Chinese women, in an effort to generate and communicate fundamental evidence for policies on household energy interventions and their public health impact.

4.2 Methods

4.2.1 Study design and intervention

The study was conducted from May 2014 to January 2017 in 12 villages in Sichuan Province, China. A feasibility study was conducted to obtain the data needed to design the study measurements and determine the required sample size [34]. At baseline, all homes cooked with traditional biomass stoves with enclosed combustion chambers and chimneys that vented outdoors, and 39% of homes also regularly cooked with gas and/or electricity.

4.2.2 Participants

Women were invited to participate if they lived in the study villages, regularly used traditional biomass stoves, were not pregnant, had no history of smoking, and provided oral informed consent. We enrolled only women because they are the primary stove users and because most men were smokers (>60%). Of the 280 eligible women, 205 women from 204 households were enrolled (71% participation rate). Most of the 85 women that declined participation did so because they worked outside of the study villages. Ethical review boards at all investigator institutions approved study protocols.

4.2.3 Procedures

The intervention was a low-polluting semi-gasifier cooking and water heating stove (Figure 1) and a supply of pelletized biomass fuel that was offered to homes at no cost. The stove was iteratively designed through both laboratory and in-home evaluations, and classified into the best-performing tier for air pollution emissions [80,97]. It featured a stainless-steel water heater, automatic lighter and adjustable flame, and an external feeder for the biomass pellet fuel. A small-scale processing factory was constructed near the study villages to produce pelletized biomass fuel from hardwood locally available.

Women in half of the study villages were randomly assigned to receive the intervention after baseline assessment, forming groups of intervention (n=125) and control (n=80) women. Intervention women were offered the stove and fuel approximately one year after enrolment, between September 1 2015 and January 30 2016, and control homes were offered the stove upon study completion. Baseline (n=2) and post-intervention (n=3) campaigns were conducted in the winter and summer to capture seasonal differences in stove use and air pollution. In each campaign, trained staff traveled to participants' homes to perform health assessments, measure air pollution exposures, and collect information on energy and health-related behaviours. Data collection began on day 1 between the breakfast and midday meals (~9am-11:30am) and continued until the team conducted the second round of measurements at the same time on day 3. Data collection occurred seven days out of the week as participants behaviors on weekdays were similar to weekends in this setting.

Figure 1. Traditional biomass chimney stove and semi-gasifier cooking and water heating stove in study kitchens. In Plot A, a woman is frying vegetables on a traditional chimney stove;

in Plot B the semi-gasifier (left) and traditional (right) stoves are arranged side-by-side in the kitchen; in Plot C a woman is boiling a soup on the semi-gasifier stove.

4.2.3.1 Brachial and central (aortic) blood pressure and pulse wave analysis

Blood pressure, specifically systolic blood pressure, is predictive of cardiovascular disease events (e.g., Ischemic Heart Disease, Myocardial Infarction) and cardiovascular related mortality [120]. At each baseline and follow-up visit, trained field staff measured participants' brachial and central systolic (bSBP/cSBP) and diastolic blood pressure (bDBP/cDBP) using an automated device (Cardioscope II, PulseCor Ltd., New Zealand). Central pulse pressure was estimated by applying a physics-based model to the low-frequency suprasystolic waveforms measured at the brachial artery and validated with high agreement against invasive measurements of cBP [121,122]. Following 5-minutes of quiet rest, three measurements were conducted in supported arms. The average of the second and third measurements in the highest arm was used for statistical analysis. Central pulse pressure (cPP) was calculated as the difference between cSBP and cDBP and represents central hemodynamics which are predictive of cardiovascular disease, independent of blood pressure [123].

Following BP measurement, we measured participants' carotid-femoral pulsewave velocity (cfPWV) by pulse wave analysis using an oscillometric device (Vicorder, Smart Medical, UK). Carotid-femoral PWV provides an indication of the stiffening of the arterial walls, which is associated with increased risk of cardiovascular events and mortality [124]. Measuring cfPWV is currently considered the gold-standard non-invasive measurement for arterial stiffness. Appropriately sized cuffs were placed over the carotid (neck) and femoral (thigh) arteries, and we estimated the distance between the two arteries based on the length between the suprasternal notch and the mid-point of the thigh cuff, with women in the supine position. The average of at least 3 readings was used for statistical analysis. Carotid-femoral PWV is calculated as the time it takes for the pulse waveform to travel the length of carotid-femoral notch over the distance between notches (m/s). Detailed information on the studies cardiovascular marker measurements has been reported elsewhere [41].

4.2.3.2 Individual, household, environmental, and community covariates

At baseline, field staff administered a detailed questionnaire on individual and household demographics, kitchen characteristics, socioeconomic (SES) asset-based indicators, smoking behaviors, and stove ownership and fuel use [125]. Variables collected that were considered possible confounders were age, marital status, ethnicity (Han or Qiang), SES, presence of a smoker in the home, self-reported diagnosed chronic illness (i.e., hypertension, diabetes), and use of anti-hypertensive medication. An asset-based index of SES was derived using principle components analysis (PCA) [125]; inputs into the score included ownership of a DVD player, microwave, car, solar water heater, refrigerator, computer, electric water cooler/heater, electric induction hotplate, and the purchase and construction costs of their home. Education was collected but not considered for the models because China was immersed in rapid societal and cultural changes when the older women in our cohort were of schooling age. Thus, our education variable is strongly correlated with age.

During each campaign, 48-h information on diet (sodium intake (mg) per woman/day), physical activity (average daily number of steps), height (meters), weight (kilograms), waist circumference (cm), and medication use, was also collected [41].

Ambient temperature conditions were monitored in real-time using a local meteorological monitoring station that was located at a central location in the study area, and when measurements were unavailable, elevation-adjusted temperature were obtained from the U.S. National Oceanic and Atmospheric Association for the nearest monitoring site (Mianyang City, Sichuan) [125]. We also measured indoor temperature in the room where the health measurements took place using a handheld monitor (Tianjianhuayi Inc., Beijing, China). We measured relative humidity, but due to day-to-day and spatial homogeneity of values, was not considered for inclusion in the regression analysis.

4.2.3.3 Particulate matter and black carbon air pollution exposures and ambient conditions

Participants' 48-h integrated, gravimetric $PM_{2.5}$ (particulate matter <2.5 µm aerodynamic diameter) exposures were collected in each data collection campaign and occurred at the same time as health measurements. $PM_{2.5}$ was collected on 37 mm PTFE filters (VWR, USA, 2.0-um pore size) placed in Harvard Personal exposure monitors (H-PEMs; Harvard T.H. Chan School of Public Health, USA) with a d_{50} of 2.5-µm at 1.8 lpm (±10%) and attached to personal pumps (Apex Pro, Casella CEL, UK) [125]. The monitors were held inside small waist packs that participants wore for the entire 48-h monitoring period, but could place up to 1 meter away while sleeping, or up to 2 meters away when the activity made it impossible to wear (e.g., bathing).

Compliance in wearing the air samplers was monitored through staff visits and by placing small pedometers (Omron HJ321 TriAxis Alvita) inside of the packs. Field blanks were collected for 10% of filter samples.

Time-resolved (minute-by-minute) concentrations of ambient air pollution were measured throughout the study period using a laser photometer (DustTrack 8530, TSI) placed on the top of a building at a central location that was representative of outdoor air pollution in all study villages. Five-day integrated measures of ambient $PM_{2.5}$ samples were also collected on filters inside the dual-purpose DustTrack. Daily averages were calculated from the minute-by-minute real-time data, and corrected for the difference in the corresponding five-day mass-based gravimetric measurement.

Detailed information on $PM_{2.5}$ laboratory mass and black carbon analysis are in Appendix 1 (A1).

4.2.4 Statistical analysis

4.2.4.1 Intention-to-Treat (ITT) analysis

The effects of the stove intervention on vascular markers were analyzed using an Intention-to-Treat (ITT) framework where women were classified into intervention and control groups based on whether they were allocated to receive the intervention (n=125 women), or not (n=80 women) [126]. This analysis provides an indication of the potential population-level impact if the intervention were scaled up under similar conditions (and among similar populations) in a real-world setting where full compliance is unrealistic [126].

4.2.4.2 Summary statistics and balance of measured covariates between groups

Summary statistics, including arithmetic means, medians, 95% confidence intervals, interquartile ranges, proportions and counts, were generated for all dependent and independent variables evaluated in the statistical models. Differences in baseline characteristics between (i) intervention and control women and (ii) women who participated in at least one post-intervention campaign and women lost to follow-up, were assessed using two-sample difference in means tests and chi-squared measures of association.

4.2.4.3 Exploratory analysis for model building

To estimate the unbiased effect of the intervention on vascular markers, we assessed potential confounders by plotting the change in vascular markers as a function of age (yrs), socio-economic status (SES), body mass index (kg/meter^2) (BMI), ambient temperature (Celsius degrees), ethnicity (Qiang or Han), season (summer or winter), whether the participant lived with a smoker (SHS), waist circumference (cm), sodium intake (mg/woman day), physical activity (steps/24-h), indoor air temperature (Celsius degrees), and household location (UTM grid location), disaggregating plots by intervention status and campaign.. Ambient temperature, age, BMI, ethnicity, season, SES, and SHS appeared to be confounders and were included in the multivariable models. We also assessed the distribution of our outcome and independent variables for normality, and transformed them accordingly (e.g., log-transformed) to meet the model's assumptions.

4.2.4.4 Cardiovascular health model building

We added an interaction term for intervention status (i.e., intervention vs control) and time (i.e., pre- vs post-intervention), which we refer to as the *intervention effect*, into the model's in order to estimate what the difference is between intervention groups in their change in vascular makers over time. To additionally assess the within-group average changes in vascular markers over time, we conducted mixed-effects multivariable linear regression analysis for each dependent variable that accounted for the correlation of repeated measurements within individuals over time. Separate models were conducted for each marker (bSBP, cSBP, bDBP, cDBP, cPP, and log-cfPWV).

Statistical inference was made under the Bayesian paradigm and Markov Chain Monte Carlo approximations were obtained through the package JAGS in R[128] . Information on the model building process and estimation of missing values are provided in the Appendix 1 (A2, A3). Following the Bayesian paradigm, we assigned a prior distribution to the parameter vectors containing all the unknowns of the models. In general, we assumed vague, independent prior distributions to let the data drive the inference procedures. In particular, for the coefficients of the covariates we assign a zero-mean normal distribution with a reasonably large and known variance. The precision parameters followed a uniform prior distribution as suggested by Gelman (2006), and the variance of each woman's random effect followed a half-Cauchy prior distribution [127]. For each outcome, we ran two chains for 40,000 iterations, discarded the first

10,000 iterations as burn-in, and stored every 30th sampled value to avoid autocorrelations of the chains. Convergence of the chains was visually evaluated.

4.2.4.5 Pre- and post-intervention air pollution exposures

We summarized (arithmetic means and 95% confidence intervals) the pre-and post-intervention and intervention group exposures to $PM_{2.5}$ and BC disaggregated by season (heating season (winter) vs non-heating season (summer)) and then calculated yearly averages by applying weights to each seasonal mean that corresponded to the seasons duration (summer = 8 months, winter = 4 months). We also evaluated changes in ambient concentrations of $PM_{2.5}$ over time from a monitor set up at a central study site. A comprehensive evaluation of the intervention's effect on air pollution exposures, kitchen concentrations, and changes detailed chemical composition of $PM_{2.5}$, is forthcoming in a separate paper.

4.2.4.6 Sensitivity analyses

As sensitivity analyses, we conducted a per-protocol analysis, grouping women based on whether they accepted the intervention into their homes (intervention n=117; control n=88). We conducted the analysis without women taking antihypertension medication (n=31) and assessed whether the effect of the intervention on vascular outcomes was modified by age or BMI. Details in Appendix 1 (A4). Finally, we tested the assumption that missing outcome measurements were missing at random.

4.3. Results

4.3.1 Participation and follow-up

The women enrolled at baseline were of either Han (78%) or Qiang ethnicity and ranged in age from 27-86 years. The majority of women worked in subsistence farming (90%) and had a primary school education (83%) (Table 1). Following baseline assessment, 164 women participated in at least one post-intervention season (80%), 142 in the non-heating season, and 140 in the heating season (Figure 2). Reasons for non-participation in post-intervention campaigns included (i) temporary relocation to live or work (n=93 (w2), n=38 (s2), n=58 (w3)), (ii) refusal (n=21 (w2), n=21 (s2), n=23 (w3)), (iii) acute illness (n=5 (w2), n=3 (s2), n=4 (w3)), and (iv) death (n=1) (Appendix 1 Table A5).

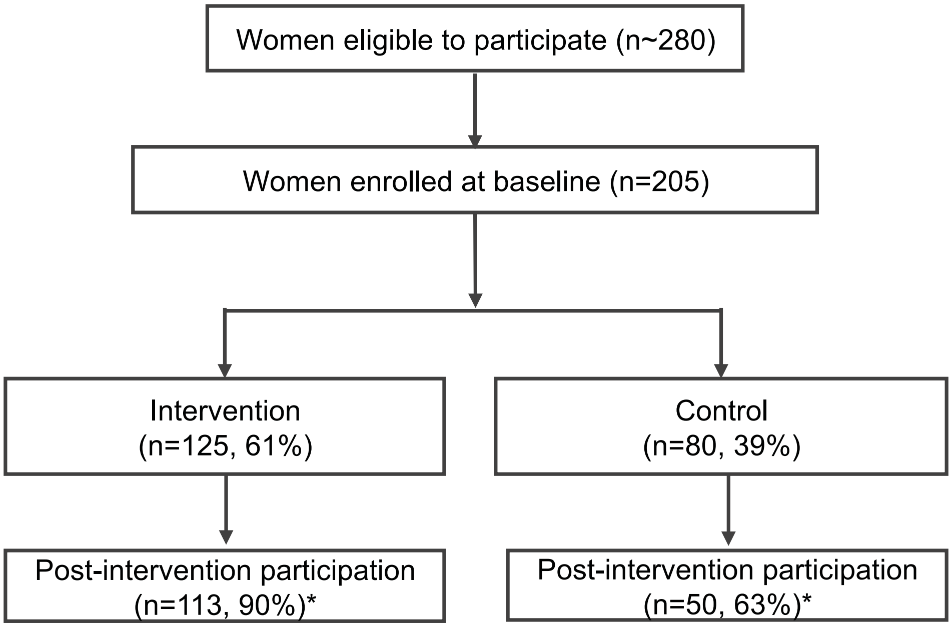

Figure 2. Baseline enrollment and follow-up after a semi-gasifier stove and fuel intervention. *Post-intervention participation was classified as participation in at least one post-intervention data collection campaign.

4.3.2 Balance of measured covariates between groups

Measured baseline covariates and vascular outcomes were generally balanced between (i) intervention versus control women and (ii) women who participated in a post-intervention measurement versus those lost to follow-up (Table 1). Baseline systolic BP significantly differed between intervention and control women, though these differences were controlled for by model design.

Table 1. Baseline characteristics of study participants (n (%), # (%), means [95% confidence interval], and medians (Interquartile ranges (IQR 25%, 75%)))

	Control (n=80)	Intervention (n=125)	Loss to follow up after baseline (n=42)
Age (years)	52.3 [49.6, 55.2]	51.6 [49.6, 53.6]	51.6 [47.7, 55.5]
Ethnicity			
Han	61 (76%)	100 (80%)	34 (81%)
Qiang	19 (24%)	25 (20%)	8 (19%)
BMI (kg/m^2)	25.4 [24.6, 26.1]	24.9 [24.2, 25.5]	24.9 [24.1, 25.8]

Height (centimeters)	153.1 [151.6, 154.6]	151.7 [150.6, 152.8]	152.3 [149.9, 154.6]
Socio-economic status (SES)			
Highest (top 33%)	21 (26%)	47 (38%)	10 (24%)
Middle (middle 33%)	25 (31%)	43 (34%)	12 (28%)
Lowest (lowest 33%)	34 (43%)	35 (28%)	20 (48%)
Education			
None	8 (10%)	21 (17%)	6 (14%)
Primary school completion	59 (74%)	93 (74%)	36 (86%)
Secondary school completion	2 (3%)	7 (6%)	0 (0%)
No response	11 (13%)	4 (3%)	0 (0%)
Number of inhabitants in the home	4.0 [3.7, 4.3]	4.1 [3.9, 4.3]	3.9 [3.5, 4.4]
Lives in a household with at least one smoker?			
Yes	48 (60%)	75 (60%)	23 (55%)
Physical activity (number of steps in 24-h) (Median & IQR)			
Summer	8474 (5323, 13391)	8441 (5302, 12220)	7870 (3994, 10295)
Winter	4370 (2046, 7761)	4746 (2417, 7216)	3250 (1959, 6204)
Sodium intake (g/day) (Median & IQR)			
Summer	3.15 (2.08, 4.95)	3.11 (1.92, 6.09)	3.18 (2.04, 4.78)
Winter	2.89 (1.41, 5.28)	3.02 (1.79, 6.14)	3.66 (1.35, 6.48)
Baseline brachial SBP (mmHg)			
Summer	126.7 [120.1, 133.4] *	117.5 [113.7, 1121.4] *	118.9 [111.1, 126.7]
Winter	131.3 [126.2, 136.3] *	125.1 [121.9, 128.3] *	128.1 [120.8, 135.4]
Baseline central SBP (mmHg)			
Summer	120.5 [114.2, 126.9] *	112.8 [109.1, 116.4] *	111.5 [103.8, 119.2]
Winter	125.1 [120.2, 129.9] *	119.1 [115.9, 122.2] *	121.4 [113.9, 128.9]
Baseline brachial DBP (mmHg)			
Summer	76.6 [73.3, 79.9]	71.8 [69.9, 73.5]	73.2 [69.3, 77.1]
Winter	79.7 [76.9, 82.4]	77.0 [75.3, 78.7]	79.3 [74.8, 83.7]
Baseline central DBP (mmHg)			
Summer	78.3 [74.8, 81.8]	74.0 [72.2, 75.8]	75.2 [71.1, 79.4]
Winter	81.2 [78.3, 84.1]	78.6 [76.8, 80.4]	81.0 [76.4, 85.6]
Central pulse pressure			
Summer	40.8 [37.7, 43.9]	37.1 [35.2, 39.0]	35.9 [32.5, 39.5]
Winter	41.9 [39.4, 44.6]	39.3 [37.6, 41.0]	38.5 [34.6, 42.3]
Carotid-femoral pulse wave velocity (m/s)			
Summer	7.7 [7.3, 8.0]	7.3 [7.1, 7.5]	7.4 [6.9, 7.9]
Winter	7.7 [7.3, 8.1]	7.8 [7.6, 8.1]	7.7 [7.0, 8.4]
Currently taking hypertension medication?			
Yes	14 (18%)	17 (14%)	7 (16%)

BMI, body mass index; DBP, diastolic blood pressure; SBP, systolic blood pressure

* difference is statistically significant between intervention and control women: p-value <0.05

§ difference is statistically significant between women who participated post-intervention and women who did not (women who participated post-intervention not included in table due to space constraints): p-value <0.05

4.3.3 Interventions effect on cardiovascular makers in adjusted regression models

In adjusted models, mean brachial and central BP and cPP decreased for the entire study population pre- to post-intervention. Mean systolic BP reductions of -4.12 mmHg [95% CI^e -7.4, -0.9] (bSBP) and -3.72 mmHg [95% CI^e -6.8, -0.6] (cSBP) were observed for the control group, and -2.68 mmHg [95% CI^e -9.9, 4.2] (bSBP) and -3.2 mmHg [95% CI^e -9.8, 3.5] (cSBP) for the intervention group (Figure 3). DBP significantly decreased for control women (-2.00 mmHg [95% CI^e -3.6, -0.47] bDBP and -1.84 mmHg [95% CI^e -3.5, -0.2] cDBP) but not for intervention women. Mean cPP decreased for both intervention (-2.05 mmHg [95% CI^e -5.8, 0.5]) and control (-2.28 mmHg [95% CI^e -4.0, -0.6]) women. Log-cfPWV did not change over time for either group (control: -0.03 m/s [95% CI^e -0.07, 0.01]; intervention: 0.00 m/s [95% CI^e -0.09, 0.09]).

There was not a statistically significant *intervention effect* on any of the six vascular markers (Figure 4). The mean difference between intervention and control women in their mean change in vascular markers over time was slightly positive for bSBP (mean posterior effect 1.44 mmHg [95% posterior credible interval (CI^e) -2.5, 5.2]), cSBP (0.55 mmHg [95% CI^e-3.0, 4.1]), bDBP (1.73 mmHg [95% CI^e -0.2, 3.5]), cDBP (1.19 mmHg [95% CI^e -0.8, 3.1]), cPP (0.23 mmHg [95% CI^e -1.8, 1.1]), and no difference for log-cfPWV (0.03 log-m/s [95% CI^e -0.03, 0.08]), though in all cases the 95% credible intervals crossed zero.

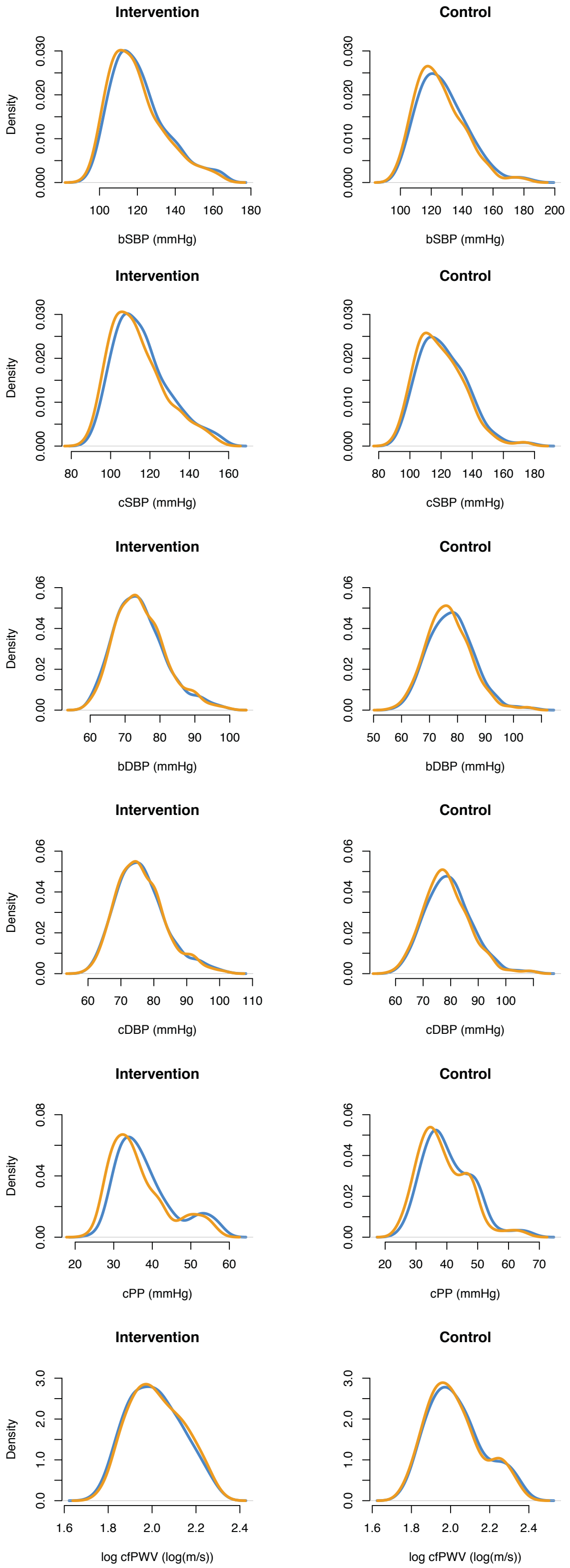

Figure 3. Smoothed densities of posterior model fitted bSBP, cSBP, bDBP, cDBP, cPP, and log-cfPWV for 205 women in southwestern China, pre- and post- a semi-gasifier stove and

pelletized biomass fuel intervention. Orange lines represent post-intervention densities and blue lines pre-intervention densities.

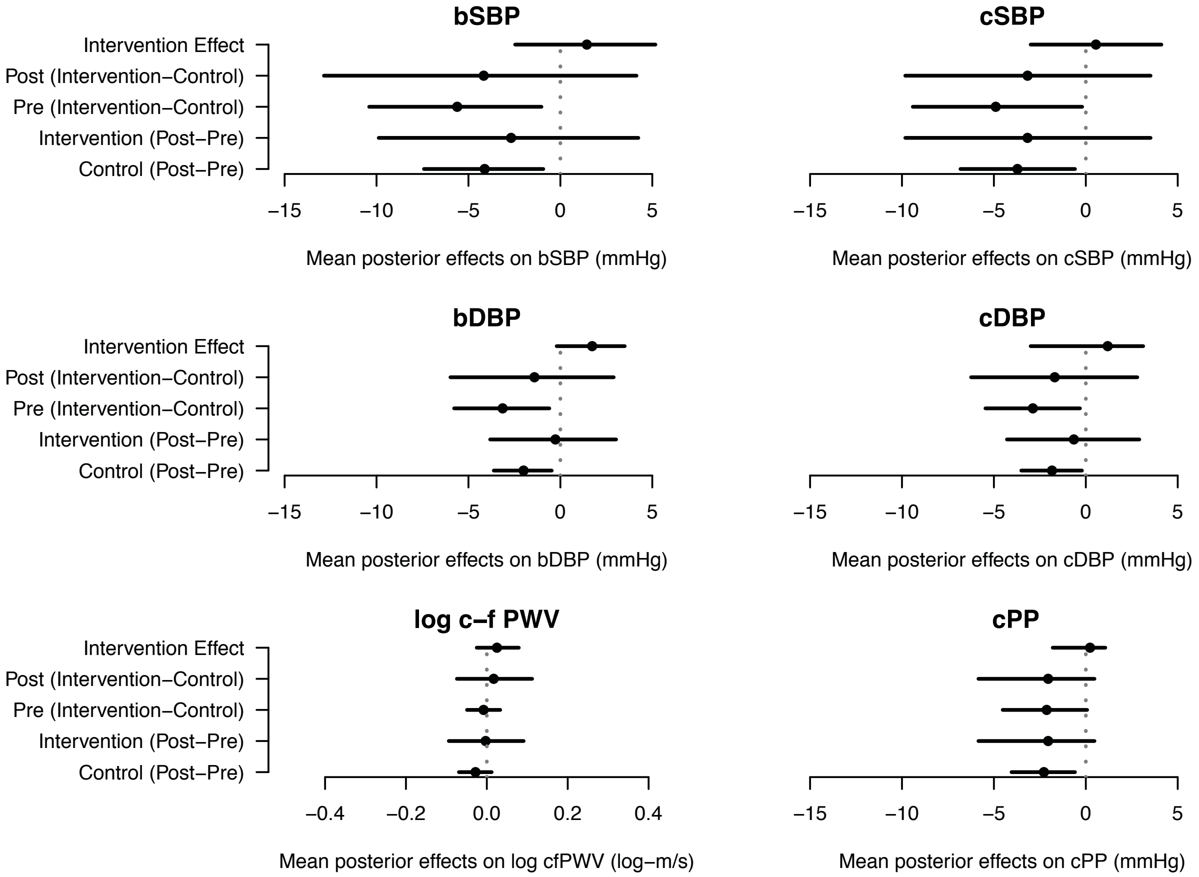

Figure 4. Posterior marginal means and 95% credible intervals of the intervention effect on BP, cPP, and log-cfPWV in rural southwestern Chinese women, before and after a semi-gasifier stove intervention. All models controlled for within-subject random effects and age, ethnicity, SES, BMI, outdoor temperature, secondhand smoking, and season (SI 6). **Legend:** *Control* **(***Post-Pre)* is the mean change over time among control women; Intervention (*Post-Pre)* is the mean change over time among intervention women; *Pre* (*Intervention-Control)* is the mean difference between intervention and control women in the pre-intervention season; *Post* (*Intervention-Control)* is the mean difference between intervention and control women in the post-intervention season; and *Intervention effect* is the mean difference between intervention and control women in their mean change over time. Posterior summaries of mean effects and 95% credible intervals for covariates included in the ITT models are in the supplementary materials (Appendix 1, A6). *Note the reduced y-axis scale for log-cfPWV.

4.3.4 Within and between group air pollution exposures

Average 48-h personal exposures to $PM_{2.5}$ and BC decreased for the entire study population from pre- to post-intervention. There was a 19% decrease in mean $PM_{2.5}$ for control women (pre: 179.8 μg/m^3 [95% confidence interval (CI) 134.8, 224.7]; post: 145.2 μg/m^3 [95% CI 101.1, 189.2], and a 28% decrease for intervention women (pre: 127.6 μg/m^3 [95% CI 108.8, 146.3]; post: 91.6 μg/m^3 [95% CI 76.7, 106.3]). Similarly, there was a 59% decrease in mean BC for control women (pre: 8.9 μg/m^3 [95% CI 5.7, 12.1]; post: 3.6 μg/m^3 [95% CI 1.8, 5.3]), and a 56% decrease for intervention women (pre: 4.6 μg/m^3 [95% CI 2.9, 6.1]; post: 2.0 μg/m^3 [95% CI 1.7, 2.3]). Personal exposures to $PM_{2.5}$ and BC were consistently higher in the heating seasons (winter) compared to the non-heating seasons (summer). Pre- to post-intervention, mean exposures decreased in the non-heating season for both intervention and control women, and in the heating season, decreased for intervention women, but stayed the same for control women. (Figure 5).

Average daily outdoor $PM_{2.5}$ concentrations ranged from 0.95 μg/m^3 to 85.6 μg/m^3 (mean: 21.4; median: 19.4) and the pre-intervention season (mean [95% CI]: non-heating: 20.8 μg/m^3 [16.7, 24.9]; heating: 19.6 μg/m^3 [16.6, 22.6]) was comparable to the post-intervention season (mean [95% CI]: non-heating: 12.0 μg/m^3 [8.60, 15.4]; heating: 32.6 μg/m^3 [28.4, 36.8]).

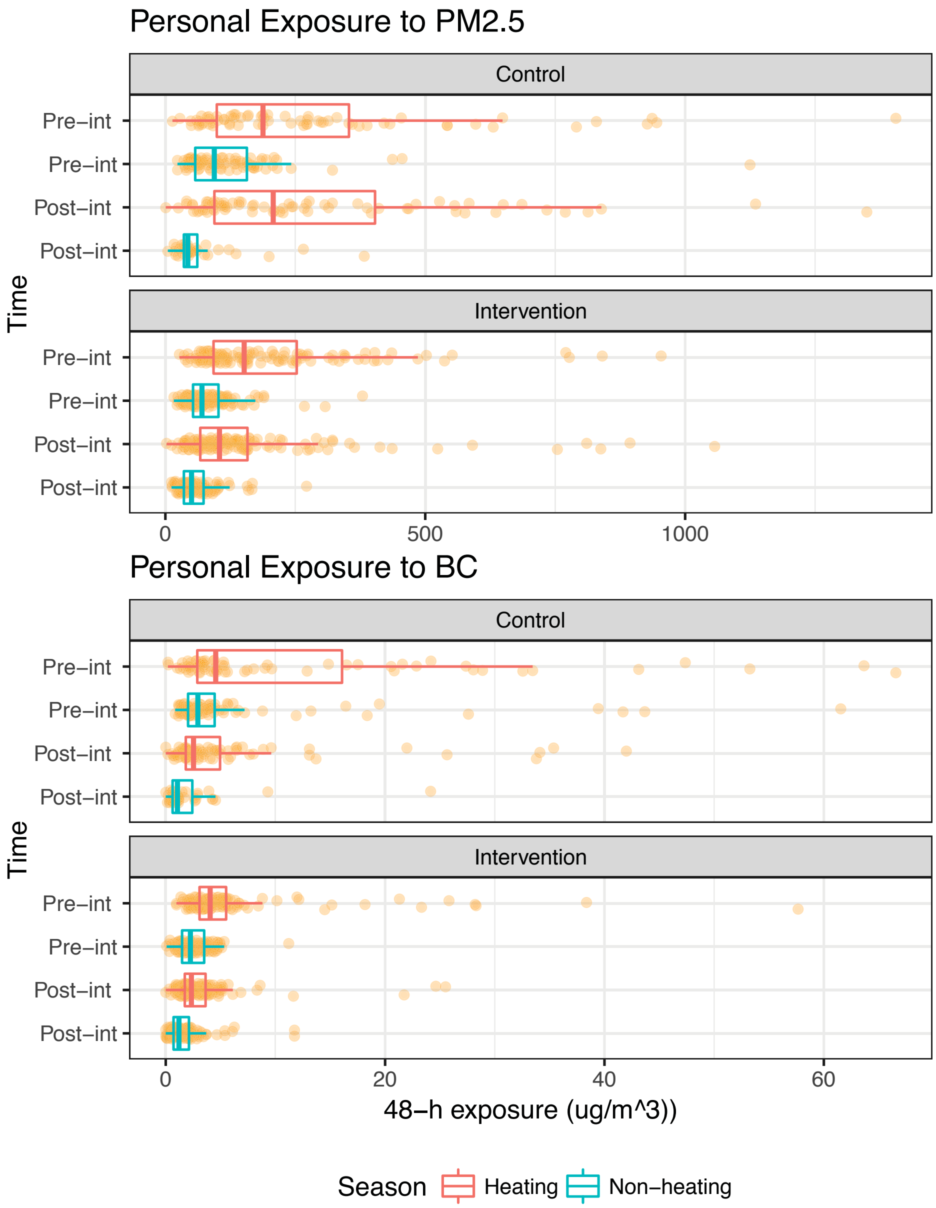

Figure 5. Pre- and post-intervention medians and inter-quartile ranges (IQRs) of 48-h personal exposure ($\mu g/m^3$) to $PM_{2.5}$ and black carbon in the non-heating (Summer) and heating (Winter) seasons in southwestern China. Orange points are the data points; Pre-int: Pre-intervention; Post-int: Post-intervention. Note: X-axis for $PM_{2.5}$ was limited to 1500 ($\mu g/m^3$) for enhanced visibility though highest measured value (outlier) was 1868 $\mu g/m^3$ and BC x-axis was restricted to 70 ($\mu g/m^3$) though the highest measured value (outlier) was 139 ($\mu g/m^3$).

4.3.5 Sensitivity analyses

Parameter effect estimates were similar between ITT and per-protocol analyses (per-protocol results in Appendix 1, A7 and A8). The mean posterior parameter estimates and fitted outcome values between our final full models and reduced models where only 57 women who participated in all data collection campaigns were similar. As well, the mean parameter estimates between our final full models that assumed the missing outcomes were missing at random, and the models that assumed the missing outcomes were not missing at random, were similar. These results exhibited evidence that non-participation of women in any given data collection campaign or instrument failure and estimating their outcome values from the full posterior distribution, did not introduce selection bias into our models. When we included all study women into the models (full models) and excluded women who reported taking antihypertension medication at baseline (n=31 women), modelled parameter estimates were similar. These results indicate that by including women with a higher risk of CVD into the full models, it does not introduce selection bias. Running separate models for (d) women older, and younger, than 50 years old, and (e) BMI ≤25 kg/m^2 (normal) or ≥25 kg/m^2 (overweight), yielded similar effect sizes of the covariates to the final full models.

4.4 Discussion

Average exposure to air pollution and both brachial and central SBP and DBP decreased over time for the entire study population. Considering that BP decreased among women in the intervention group (though the 95% credible intervals crossed zero), our results generally support trends observed in previous biomass stove intervention studies in Bolivia [59], Guatemala [60], and Nicaragua [63] (before-and-after study designs). However, intervention studies in Nicaragua and Bolivia [59,63] did not have a control group and thus could not account for natural changes that might have occurred in the levels of blood pressure over time, which we observed in our control group in this study. Thus the difference in the change in BP between our two groups (i.e., intervention effect) was inconclusive, similar to what was observed in intervention studies in India and Pakistan [93,95].

Ours is the first study to evaluate the impact of an improved cookstove intervention on cPP and measures of arterial stiffness, such as cfPWV. We found that cPP decreased over time for everyone, but log cfPWV generally remained the same. A previous study of this population found a significant exposure-response relationship between personal exposure to air pollution and cPP, but no association between air pollution exposure and cfPWV [41].

Our observed mean reductions in BP for both groups could be explained by a general shift to greater use of LPG, biogas, and electric stoves that coincided with moderate use of the semi-gasifier stove in the intervention group (~40% of days over 5-months) [130]. Specifically, 23% of intervention homes and 24% of control homes were observed exclusively using higher-preforming biomass and/ or modern fuel stoves (e.g., LPG, biogas, electric) post-intervention [130]. This shift could have been the result of general awareness around cleaner cooking generated as a result of the intervention study, but also likely reflects recent economic and infrastructure development in the region, including improved roads to transport clean fuel to homes, and a country-wide transition away from solid fuels for cooking over the last few decades [1,78]. Our within-group mean BP reductions are consistent with a recent fuel-switching randomized trial among pregnant mothers in urban Nigeria that observed a decrease in bDBP (-2.8 mmHg) among intervention subjects who received an ethanol stove compared with controls [62]. This same study also found that among users of firewood before the trial started, intervention women had significant decreases, and control women increases, in levels of tumor necrosis factor alpha (TNF-α), a biomarker of systematic inflammation [94], pre-to-post intervention.

Personal exposures to air pollution decreased for intervention women, indicating a possible air quality benefit of the intervention. However, controls had similar reductions which provides evidence that other changes may be occurring within these communities that contribute to exposures, such as the observed shift to greater use of clean fuels. However, we cannot disentangle to what extend use of the intervention, use of clean fuels, or a combination of these, contributed to reductions in exposures to $PM_{2.5}$ and BC given the prevalence of mixed stove use. Similar to our results, two pilot studies of gasifier stove interventions in India [131] and central China [132] found that personal exposures to $PM_{2.5}$ decreased with use of new gasifier stoves, however they still remained well above the WHO's interim 24-h target. Among our intervention group only, the *within-group* percentage decreases in mean exposures to $PM_{2.5}$ fell within the range of reported percentage decreases from previous improved (non-gasifier) biomass cookstove interventions (before-after study designs) in South America (range: 19.4% to 86.5% decreases) [11,75], though, given the similar reductions in personal exposures within our control group, it is clearly imperative for studies to track trends in a control group when making inference about the contribution of interventions to changes in air pollution.

The lack of an observed vascular benefit may also be explained by the high levels of post-intervention exposures to $PM_{2.5}$ (Figure 6). Previous exposure-response studies show non-linear associations between $PM_{2.5}$ from biomass burning and blood pressure, where the association is steep at lower concentrations below 50 $\mu g/m^3$ and then flattens out, and in our study, post-intervention mean group exposures to $PM_{2.5}$ ranged from 92 to 145 $\mu g/m^3$ [40,41]. Although the stove was designed to reduce $PM_{2.5}$ to levels that were at or below international targets, exposures were likely influenced by improper and non-exclusive use of the intervention (77% of intervention homes continued using traditional stoves) [130] , and by alternate sources of pollution exposures (e.g., exposure to dust or traffic emissions) [14].

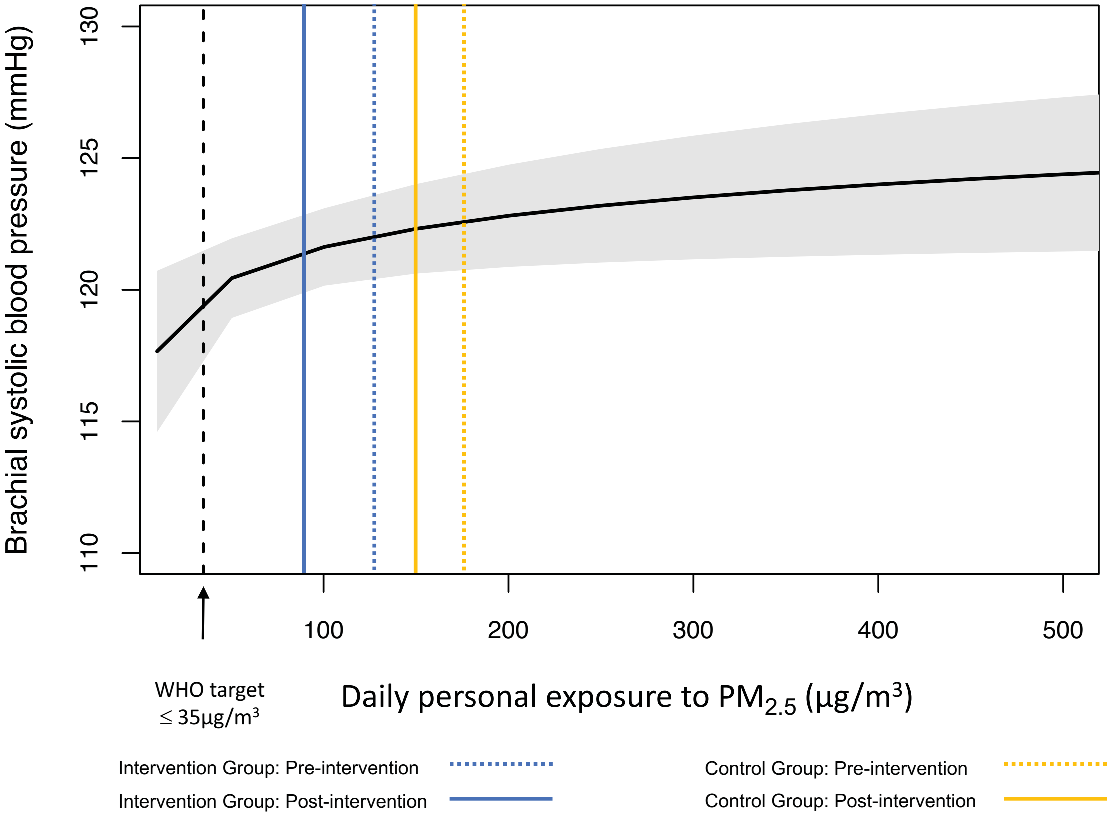

Figure 6. Estimated exposure-response curve for daily personal exposure to $PM_{2.5}$ ($\mu g/m^3$) and brachial systolic blood pressure (mmHg) based on a pooled analysis of rural southwestern Chinese women cooking with biomass fuels [40,41]. Exposure-response models controlled for age, body mass index, socioeconomic status, sodium intake, physical activity, and

ambient temperature. The y-axis shows the adjusted levels of brachial systolic BP (mmHg) and the x-axis shows personal exposure to $PM_{2.5}$ (μg/m^3) over a 48-h period. The vertical solid and dashed blue and orange lines show this study's mean 48-h personal exposure to $PM_{2.5}$ for intervention and control groups, pre- and post- semi-gasifier stove intervention. The vertical black dashed line is the interim WHO indoor air quality target for mean $PM_{2.5}$ personal exposure (μg/m^3).

Our study is the first to estimate the cardiovascular health impacts of a high-performing, and community-designed, semi-gasifier stove and pelletized biomass fuel intervention in a real-world setting. Our study benefits from the number of vascular markers measured and the range of cardiovascular risk factors controlled for in the models. We were also able to test models that assumed different temporal and hierarchical correlation structures within the data and iteratively fit missing outcome values within the modelling process by following the Bayesian paradigm. Our study is limited by the lack of randomized design, though we did randomly select half of the villages to receive the intervention in order to control for exposure spillovers from adjacent homes. While this may have introduced community-level latent influences into our models, accounting for correlations within communities with random-intercepts did not change the model parameter estimates or improve fit. We also had incomplete follow-up of ~20% of participants due to higher than expected migration to nearby towns, resulting from very recent infrastructure investment in the region. However, measured covariates between participants that participated post-intervention and participants that did not were balanced (Table 1), and models that were run on women who participated in all 5 campaigns provided similar results. It is also possible that our study raised general awareness about air pollution and health, and lead to a greater than expected increase in clean fuel use in the control group.

4.5 Conclusion

Our intervention study in rural southwestern China found that blood pressure, pulse pressure, and arterial stiffness were not improved as a result of the distribution of a high performing semi-gasifier stove and supply of pelletized biomass fuel. A combined set of factors, including low levels of sustained and exclusive use of the semi-gasifier stove [130], reductions in air pollution exposures for the entire study population (including controls), and insufficient reductions in average personal $PM_{2.5}$ exposures below international targets, were likely contributors to our null finding. Improved biomass stoves may be designed with the potential to make a significant contribution to the global burden of cardiovascular diseases, and gasifier stove designs in particular are currently promoted as the next generation of ‘clean-cooking’ technologies in China and elsewhere. However, their effectiveness in real-world settings needs to be more carefully understood, quantified, and communicated.

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Chapter 5. Beyond the lab: Behavioral factors impacting improved cookstove effectiveness in field-based settings

The evidence of a positive association between CVD sub-clinical indicators and exposure to HAP is growing, and suggests a possible cardiovascular health benefit from reducing HAP with interventions such as improved biomass cookstoves or fuels. There are only a handful of studies that have evaluated the cardiovascular health benefits of these interventions in low- and middle-income countries. Taken together, these studies form a complex story, one complicated by variable intervention effect sizes and directions, and a host of limitations hindering their results, such as small study sample sizes, missing control groups, or a lack of control for confounders [59–63,93–95]. For my thesis, I conducted the first field-based evaluation of the potential cardiovascular health impacts of an advanced semi-gasifier stove and pelletized biomass fuel intervention, and the first in a rural Chinese setting. I used multi-level Bayesian models that controlled for known confounders to estimate the relationship between the intervention and a suite of sub-clinical cardiovascular markers, including brachial and central systolic and diastolic blood pressure, pulse pressure, and markers of arterial stiffness. In the adjusted models, the intervention was not significantly associated with any of the sub-clinical cardiovascular markers. However, over time, group mean levels of blood pressure and arterial stiffness did appear to improve for the entire population, likely due to the influence of other time-varying factors affecting this study population. Mean exposures to $PM_{2.5}$ and BC were reduced for both the intervention and control groups over time (range: -19%, to -59% decrease), though levels still remained well above the WHO's interim target for 24-h exposure [76].

Since the 1970's, interventions of older-generation improved biomass stoves have been hindered in their efforts to reduce HAP by poor emissions performance, low levels of adoption, and persistent, concurrent use of highly polluting traditional stoves and unprocessed solid fuels. [64,65,135,136] Advanced combustion stove interventions, such as semi-gasifiers, are currently being promoted as the next generation of stove interventions, particularly in China [83,84,86,96,137], though little is known about their acceptance and use in real-world settings [90–92,138,139], or how patterns of use may impact the capacity of these interventions to reduce HAP levels and improve cardiovascular health. A group of engineer researchers at Tsinghua University tried to overcome these multiple barriers by iteratively designing a semi-gasifier stove (THU stove) in the lab over a

5-year process, achieving ISO Tier 4 status for emissions performance (highest tier), and testing the stove in communities taking villager preferences and cooking needs into account [80,97].

In our field-based evaluation of the THU semi-gasifier stove and pelletized biomass fuel intervention in rural China, markers of cardiovascular health did not improve. Thus, for the second manuscript in my thesis (Chapter 7), I estimated the population-level uptake, adoption, and long-term use, of the THU semi-gasifier stove and pelletized biomass fuel intervention, and evaluated the enablers and barriers that influenced these processes. Chapter 7 is the first study to evaluate the adoption process of an advanced semi-gasifier stove in a Chinese context, and the first to evaluate the individual, household, and community-level factors that influence different stages of the stove adoption process, such as initial use, choice of use, and intensity of use.

Chapter 6. Literature review: Enablers, barriers, and trends in improved biomass stove and fuel intervention adoption in low- and middle-income settings

I conducted a literature review to summarize the current state of knowledge on i) methods used to monitor cookstove and fuel intervention programs, ii) trends in uptake, adoption, and sustained use of cookstove and fuel interventions in low- and middle-income countries, and iii) demand and supply-side factors which enable or inhibit cookstove and fuel intervention adoption. To this end, I searched the Scopus database for peer-reviewed journal articles with the search terms (a) *("cookstove" OR "cook stove" OR "household energy intervention" OR "improved stove" OR "gasifier" OR "advanced-combustion" OR "LPG" OR "biogas" OR "electricity" OR "ethanol") AND ("SUM" OR "stove use monitor" OR "temperature sensor")* as well as (b) *("cookstove" OR "cook stove" OR "household energy intervention" OR "improved stove" OR "gasifier" OR "advanced-combustion" OR "LPG" OR "biogas" OR "electricity" OR "ethanol") AND ("adoption" OR "uptake" OR "sustained use") AND ("enabler" OR "barrier" OR "behaviour" OR "factors" OR "demand" OR "supply").* I also reviewed the reference lists of identified studies. From my initial literature search, after restricting to low- and middle-income settings and peer-reviewed articles, I retrieved 417 (string of terms (a) and 462 (string of terms (b)) articles of which I reviewed titles and abstracts for inclusion in this review. Due to the high volume of articles that could fit within my defined review goals, I relied heavily on previously published systematic reviews that summarized a large proportion of the body of research.

In the 1970's, large-scale efforts to distribute higher efficiency biomass cookstoves to households in lower-and middle income countries began as an effort to protect forest resources from overharvesting [64,65]. Improving the efficiency of biomass stoves was the main goal, as compared with switching to gaseous fuels, due to the large rise in oil prices during the petroleum crisis [135]. Following decades of large-scale energy intervention efforts, low levels of adoption and use along with poor or inconsistent emissions performance have limited the success of most improved stove programs in achieving their intended health and environmental goals [64,65,135]. Renewed interest in rural energy has led to several large-scale national and international initiatives to distribute higher-efficiency biomass stoves [70,73,85,140], even though a number of studies document low demand and modest levels of use following free or subsidized distributions [90–92,136,141,142].

6.1 Methods to quantify and monitor cookstove and fuel intervention adoption

Early evaluations of cookstove intervention programs were primarily in the form of interviews and focus groups, case-studies, and household surveys, and they were used to assess the compliance and acceptance of the new technologies [64,65,81,135,143–148]. These early evaluations informed researchers, implementers, funding agencies, and policy makers what was needed to accelerate the adoption and use of these new technologies, beyond the initial distribution of the stoves [64,65,135]. Evaluations conducted with surveys or interviews benefitted from the depth of information that could be acquired, but the self-reported outcomes risked systematic bias if respondents' answers were influenced by social expectations (i.e., what they thought the interviewer wanted to hear) or if they changed behavior due to an awareness of being observed (i.e., 'Hawthorn Effect') [104,139,149]. Furthermore, many of these early evaluations used cross-sectional study designs or case-studies to quantify usage patterns that could not capture the fluidity of both the household and community technology adoption processes, which can change over time [150].

More recently, stove evaluation programs have relied on more objective measurements of stove adoption including the use of small temperature sensors [151]. These temperature sensors, also known as Stove Use Monitors (SUMs), measure real-time stove use by recording temperature fluctuations of stove surfaces (used to identify cooking events)[113]. The monitors are robust for extended monitoring periods (e.g. up to several months autonomously) and relatively unobtrusive (some are as small as a penny), which makes their presence less likely to influence regular cooking behaviors [149]. Limitations of the sensors, leading to measurement error, can arise from weak temperature signals associated with poor placement on stove surfaces, poor sensitivity for lower-temperature stoves, and low specificity of the automated programs used to identify cooking events from the temperature data (i.e., non-events which may just be natural temperature fluctuations are classified as cooking events) [139,152,153].

6.2 Use of SUMs to monitor short- and long-term ('sustained') use of improved biomass stove and fuel interventions

In the following section, I summarize the studies that utilized objective methods to monitor the short- and long-term usage patterns of improved biomass or modern-fuel stoves. Even within this sub-set of studies, large heterogeneity exists in the way that these stove use data were summarized and presented (Table 1). For example, the different metrics used to describe stove usage patterns included the mean proportion of days that stoves were in use, mean proportion of daily meals that stoves were in use, proportion of households with exclusive use of stoves during the monitoring period, and the proportion of households that used stoves over a certain amount of days, among others.

Overall, the use of cookstove interventions in 9 studies conducted in Asia, Latin America, and Africa were generally low to moderate (Table 1) with several notable exceptions. In Guatemala, for example, locally-produced Plancha biomass chimney stoves had high initial uptake and, among these homes, very consistent use (mean 92% of days' stoves in use [95% CI 87%, 97%], mean 2.6 daily meals [95% CI 2.4, 2.7]) over a 32-month monitoring period [113]. Similarly, a bioethanol fuel and stove intervention in urban Nigeria was similarly successful with 90% of days in use in the 1-4 months following intervention [114]. However most studies reported low and declining levels of improved biomass cookstove use over time [90–92,138,139,153–155]. Natural draft, 'Rocket'-style stoves with insulated combustion chambers struggled to achieve high or exclusive periods of use in Kenya, Rwanda, and Uganda [92,139,153,155]. In Kenya and Uganda the stoves were exclusively used on just 13-47% of days over short-term periods of evaluation ranging from 2-5 weeks [92,153], and in Ghana, the stoves were used on just 29% of days [139]. Advanced combustion stoves, such as gasifiers (e.g., Phillips models, Oorja, Ecochula), are more efficient and typically emit less air pollution than other biomass stoves [78–80], but a lack of end-user interaction has limited their effectiveness in reducing air pollution exposures and indoor concentrations in 'real-world' settings [91]. For example in Ghana [139], gasifiers were used on 14% of days during a year monitoring period, and in Kenya [92] and India [90], only 18%-38% of homes had high (≥80% of days in use) or exclusive levels of gasifier stove use. The average number of daily meals that gasifiers were used was also highly variable across studies, ranging from 0.34 times per day in Malawi (2 years after intervention) to 3.3 times per day in Kenya at 2-weeks post-intervention [68,91,138].

Table 1. Short- and long-term monitoring of improved cookstove and fuel intervention use with objective temperature sensors

Study	**Stove type/ fuel intervention**	**Monitoring period**	Mean % of **days** in use [95% CI]	Mean number of **meals** per day (SD) [95% CI]	% of **homes** with exclusive or high levels of use[ς] (≥80% of days in use)
Improved biomass and chimney stoves[Π]					
Guatemala (Ruiz-Mercado 2013) [113]	Plancha Biomass Chimney stove	32 months	92% [87, 97]	2.56 [2.40, 2.74]	
Kenya (Lozier 2015; Pilishvili 2016) [68,92]	Rocket stove(s) (EcoZoom, EnviroFit, Prakti)	2 weeks		3.3 to 3.75**	13% to 33%
Rwanda (Thomas 2013) [155]	Rocket stove	2 weeks		1.10 (1.10)	
Ghana (Piedrahita 2016) [139]	Rocket stove (Gyapa)***	1 year	28.8%		
Uganda (Hankey 2015) [153]	Rocket stove	1 month			47%
Gasifier and semi-gasifier stoves					
Kenya (Lozier 2015; Pilishvili 2016) [68,92]	Gasifier(s) (Phillips, Ecochula)	2 weeks		3.05 to 3.3**	24% to 38%
India (Mukhopadhyay 2012) [138]	Gasifier(s) (Oorja, Phillips)	12 weeks		0.67 (0.76) to 2.13 (0.58)	
Malawi (Mortimer 2016) [91]	Gasifier (Phillips)	2 years		0.51 (0.55) year 1; 0.34 (0.40) year 2	
India (Pillarisetti 2014) [90]	Gasifier (Phillips)	60 weeks			[ς]18% to 29%
Ghana (Piedrahita 2016) [139]	Gasifier (Phillips)***	1 year	14%		
Gaseous stoves					
Nigeria (Northcross 2016) [114]	Bioethanol stove	4 months	90%		

*Mean: Arithmetic mean; CI: Confidence interval; %: Proportion; SD: Standard deviation; range: # to #.

**Divided 48-h number of cooking events as reported in Pilishvili et al. 2016 by 2 to approximate daily.

*** Two Gyapas or Phillips given to each household.

[Π] Darfur study (Wilson et al 2016) was omitted from table. While Wilson et al. 2016 used SUMs to elicit trends in stove use, they classified users as adopters (at least 10% of days the stove was in use) vs non-adopters. They found that 71% of their study population in an internally displaced persons camp were adopters [154].

6.3 Household stove use patterns in the context of improved cookstove and fuel interventions

Equally as important as generating demand and acceptance of improved cookstoves and fuels is reducing the desirability and use of traditional stoves [156,157]. The classic fuel switching paradigm of a linear energy ladder – where, as households rise in economic and social affluence, they also transition to exclusive use of modern fuels and efficient stoves - has been largely discredited through empirical research [157]. Field assessments of cookstove interventions confirm that households often using cleaner stove technologies alongside traditional ones, even as incomes increase, commonly referred to as 'stove or fuel stacking' [92,138,139,153,157,158]. For example, 41% of Ugandan households used both the intervention stove and traditional open fires [153] and in India, only 6% of households exclusively used the new gasifier stove [90]. A recent modeling study by Johnson & Chiang (2015) found that air pollution exposures would not meet the WHO's interim indoor air quality target of 35 $\mu g/m^3$ unless use of the traditional stoves were largely suspended and the intervention stove was very low-polluting (e.g., gaseous fuel stoves) [159]. Similarly, field assessments of six improved biomass and gasifier stoves in Kenya [92] and a high-performing semi-gasifier stove in rural China [134], found that combined use of both the improved and traditional stoves on the same day resulted in similar and often higher household concentrations of $PM_{2.5}$ compared with exclusive use of the traditional stove.

6.4 Demand and supply side factors impacting intervention stove and fuel adoption

Early reviews of the enablers and barriers of improved biomass stove adoption in the 1980s highlighted a myriad demand and supply side factors that impacted the adoption and use improved cookstoves at household and community scales [64,65,135]. These reviews largely relied on case-studies of cookstove interventions and researchers' personal experiences [64,65,135]. However, the factors identified in these early studies are just as relevant for intervention programs today [145,158,160,161]. The factors described below are not necessarily discussed in each individual study, but were highlighted in reviews as being important across the spectrum of studies.

6.4.1 Demand-side factors

Age: Generally, age has been found to be negatively associated with adoption of improved biomass stoves [161]. That older cooks are less likely to adopt interventions is perhaps unsurprising since cooking behaviors and habits become entrenched over time, and older cooks may be less inclined to modify these long-developed behaviors [160–162].

Household composition: The impacts of household size and the gender of the household head have been widely included in studies of improved stove and fuel adoption. The impact of household size remains unclear; however, most studies found that households with a female head were more likely to adopt cleaner fuels [161].

Income and Education: The willingness and capability of households to adopt improved stoves and fuels is impacted by socio-economic status (such as household income or measures of households assets) and education of adults in the home [64,135,144,145,158,160,161,163]. Generally, households with greater income and education were more willing to invest in new biomass stoves or modern fuels [158,160,161]. While higher income can be an enabler to adoption, the lack of income has also been found to be a major barrier [158,160,161]. The relatively high upfront cost of biomass stoves and gaseous fuels is one of the most frequently reported barriers to household energy transitions. As well, a major barrier associated with the sustained use of modern fuels is the cost of refilling fuels [158,160].

Geography: Compared with rural areas, the adoption of modern fuels is accelerated in urban areas, where biomass is less abundant, clean fuels and electrity supply are more consistent, and time-savings may be valued more[145,158,160,161,164]. As well, in higher altitude or latitudinal regions where the climate is colder, improved cookstoves may be multi-functional and are valued for their ability to address other home energy needs, such as space heating, cooking for animals, or specialty tasks (e.g., smoking meat) [160].

Social factors: A less understood but potentially influential factor on stove adoption and use is the impact of social pressure (e.g., village or community leader support) and peer effects (e.g., neighbor) [164–167]. These effects have been evaluated for toilet and water filter interventions, but less so for cookstove interventions [168]. Researchers in Uganda found that when villages knew that a prominent member of the village also owned an improved stove, it increased the odds that they also favored the stove, although favoring the improved stove did not necessarily translate into purchasing one [167].

6.4.2 Supply-side factors

Stove design: It is generally agreed upon that offering and marketing culturally appropriate stove designs that allow users to cook their traditional foods is imperative for sustained use [139,141,145,147,158,160,161]. Designing multi-faceted or multiple technologies that not only meet, but exceed, the services of traditional stoves and fuels is critical for securing replacement of these alternative higher-polluting options [156]. Furthermore, stoves designs need to be durable and have a sufficient life-span so that households have enough time to acclimate to their functioning and use, as well as beyond that point [160,163]. Efficient burning of biomass with improved stoves or burning biomass in processed forms (e.g., pellets) can lead to fuel savings and thus reduced monetary costs to households and has been widely found to be an enabler to adoption [158,160]. Reductions in fuel use can also lead to decreases in the amount of time allocated to harvesting, collecting, and processing biomass fuels and allow more time to pursue other economic generating activities [2,147,158,161]. Using an improved biomass stove or modern fuel can also translate into time savings during the cooking process through greater heat transfer and automated ignition and temperature controls [158,160].

Distribution and supply networks: The instability of gaseous fuel supply networks, particularly in areas where transport trucks need to travel long distances and over poor quality roads, has been found to be a major barrier to the adoption of modern fuels in some contexts [135,158]. Instability of gas-fuel supply leads to fluctuations in fuel availability and thus, a continued reliance on raw solid fuels and increased levels of stove- and fuel-stacking [158].

Subsidies, economic incentives, and loans: Governments and civil society can assist households in overcoming the initial financial barriers to investment in improved cookstoves and fuels by providing village or household-level subsidies [158,160,169], though, studies have also found that reducing initial costs too much may result in a reduction in the perceived value of the technology and lead to dis-adoption over time [158]. Additionally, providing price incentives (such as payment installments) or micro-loans have also shown to be effective in helping households overcome the initial barrier of improved stove or fuel uptake [158,160].

Market development and programmatic mechanisms: Creating local demand for improved cookstoves and modern fuels is important for initial stove and fuel uptake, and particularly for sustained use [160]. Media (e.g., radio advertisements) and educational campaigns (e.g., presentations to end users) are several mechanisms commonly used to promote improved stoves and fuels. Hosting training days, product demonstrations, doing door-to-door promotions, and spreading the news via word-of mouth are also effective promotion measures [158,160,170–172]. For example, stove programs that provide face-to-face interaction with implementers, hands-on training, and continued post-implementation support, are generally more effective in increasing sustained use of stoves than programs that drop stoves off at households and/ or provide a user manual [160]. Conversely, a lack of interaction with target communities during the stove design and implementation phase, and a lack of user training, can be barriers to long-term adoption and use [160].

6.4.4 Necessary but not sufficient

While the above-mentioned factors are necessary for improved cookstove and modern fuel adoption, none alone are sufficient. Programs need to consider all domains and tailor intervention designs, distributions to the target communities, and provide continued follow-up and support to ensure that these factors are addressed [160].

6.5 Limitations of the current body of research

Studies over the past few decades identify a range of individual, household, community, and state-level factors that can influence the new stove adoption. However, key gaps in our knowledge exist, particularly on the factors that impact specific stages of the stove adoption process, such as initial uptake, choice of use, and the intensity of use. This offers opportunity for new areas of inquiry that can directly inform planned and ongoing policy initiatives and intervention programs. Furthermore, relatively few studies have evaluated the adoption and long-term use of advanced combustion stoves like gasifiers, even though several governments, including China, and many non-governmental organizations are actively promoting these stoves as a next generation of promising household energy interventions[84,96,136,137].

Contemporary reviews [158,160,172] defined intervention **adoption** as the initial purchase or acquisition of an improved stove or fuel, the initial use, and the continued use (up to one-year post acquisition) in some capacity, and **sustained use** as the continued use of improved cookstoves and fuels at least one or two years following acquisition. These reviews vaguely defined adoption to include a larger suite of studies and diversity of definitions. However, it is important to note that the factors that influence different stages of the stove adoption process, such as initial purchase or acquisition, continued use, and the intensity of use (i.e., how often, for how long), are likely to differ, and were not systematically quantified as separate processes. It is generally understood what factors are important to consider when promoting improved cookstoves and fuels (e.g., income, education, stove design); however, there is relatively little empirical evidence on the factors that influence the stove adoption process over time **after** stoves have been distributed or purchased by households [91,136,138,139]. For example, peer-effects (e.g., a neighbor uses an improved cookstove) may influence another household to try out the same improved cookstove, however, after interacting and cooking with the stove, that household may choose to dis-adopt it over time. There is also limited understanding of what factors influence the **intensity** of improved cooktove or modern fuel use (e.g., number of meals cooked per week, duration of minutes' stove in use) [161,173]. Understanding what drives the intensity of using improved cookstoves or fuels is important because an 'adopter' who uses the intervention once a week and continues to use their traditional stove may have different levels of HAP exposure, and potentially no health benefit, compared to an 'adopter' who uses the intervention exclusively every day of the week.

6.6 Conclusion

Numerous qualitative and quantitative studies have assessed the levels of cookstove adoption and the factors that influence this process. Factors including the initial investment, costs of equipment repair and fuel refilling, inadequacy to meet local cooking needs, and household characteristics and demographics have been barriers for households to purchase or accept new stoves and modern fuels across settings and intervention types. Objective monitoring of cookstoves has shown that the short or long-term sustained use of these interventions has been modest, even with free or subsidized distribution, and that traditional stove use often continues. However, little is known about the factors that influence the different stages of the cookstove and fuel adoption process (different stages such as initial uptake, daily choice of use, and intensity of use), and few studies have evaluated the adoption and use of high-performing biomass stoves (such as gasifiers or semi-gasifiers) [90–92,138,139] or modern fuel stoves (such as LPG or biogas)[114], interventions. Thus, we aimed to evaluate the uptake and usage trends of a high-performing semi-gasifier stove and pelletized biomass fuel intervention in rural southwestern Chinese villages, and evaluate the factors that influenced different stages of the adoption process, including the initial uptake, choice of use, and intensity of use.

Chapter 7. Adoption and use of a semi-gasifier cooking and water heating stove and fuel intervention in the Tibetan Plateau, China

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Abstract

Improved cookstoves and fuels, such as advanced gasifier stoves, carry the promise of improving health outcomes, preserving local environments, and reducing climate-forcing air pollutants. However, low adoption and use of these stoves in many settings has limited their benefits. We aimed to improve the understanding of improved stove use by describing the patterns and predictors of adoption of a semi-gasifier stove and processed biomass fuel intervention in southwestern China. Of 113 intervention homes interviewed, 79% of homes tried the stove, and the majority of these (92%) continued using it 5-10 months later. Over five-month period following intervention, semi-gasifier stove use was modest (40.4% [95% CI 34.3, 46.6] days in use), and further declined up to 13-months. Homes that received the semi-gasifer stove in the first batch used it more frequently over a five-month period (67.2% [95% CI 42.1, 92.3] days in use) than homes that received it in the second batch (29.3% [95% CI 13.8, 44.5] days in use), likely because of stove quality and user training. Household stove use was positively associated with reported cooking needs and negatively associated with age of the main cook, household socioeconomic status, and the availability of substitute cleaner-burning stoves. Our results show that even a carefully engineered, multi-purpose semi-gasifier stove and fuel intervention contributed modestly to overall household energy use in rural China.

Keywords: Adoption, cookstove, China, energy, household air pollution, solid fuel, stove stacking, uptake

7.1 Introduction

Household burning of biomass and coal remains the primary energy source for cooking, heating, and other needs for billions of people [1]. This widespread practice is an important source of indoor and outdoor air pollution, and is associated with an estimated 2.8 million yearly premature deaths [87] and both global and regional climate change [19,174]. As a growing body of literature documents, the last four decades have seen many efforts by governments, non-governmental organizations, and for-profit companies to replace traditional biomass fuel stoves with higher efficiency fuels and biomass cookstoves [64,65,72,85,91,140,175]. Early stove programs focused on fuel supply and forest protection whereas more recent ones emphasized air pollution reductions and health. Unfortunately, low levels of adoption and poor emissions performances have limited the success of most clean stove programs in achieving their intended environmental and health goals. Reviews of stove intervention programs point to a number of technical, cultural, and socio-economic constraints that limit both the adoption of new stoves and the suspension of traditional stove use [160,161,176].

Advanced combustion semi-gasifier stoves are part of a next-generation of household energy technologies that have consistently outperformed other biomass stoves in laboratory studies, with some designs performing similarly to gaseous fuel stoves [67,78,79]. The acceptability of semi-gasifier stoves in field settings is still largely unknown [160], with only a few studies objectively monitoring their use in different settings [90–92,138,139], none of which evaluated the household or individual factors predicting use. Current rural energy policies in China support the production of processed biomass fuels (e.g., pellets or briquettes) [86,96], which are most efficiently burned in gasifier and semi-gasifer stove designs [77,177]. While the supply of processed biomass fuel in China is promising, the widespread acceptability and effectiveness of semi-gasifier interventions amongst China’s rural population are largely unknown.

This study quantified the uptake, adoption and long-term use of a semi-gasifier cooking and water heating stove (TsingHua (THU) stove) and processed biomass fuel intervention in rural China, and evaluated the enablers and barriers of use. Notably, the THU stove underwent extensive laboratory and field testing in homes during a novel, iterative stove design process described elsewhere [97]. We conducted our study in China because it houses one-fifth of the world's solid fuel users and the government is actively involved in the development and promotion of advanced stoves [1].

7.2 Methods

7.2.1 Study location and population

The study site covers approximately 6.2 km^2 in rural Beichuan County, Sichuan Province and includes 12 natural villages with ~280 households. Prior to intervention, all enrolled households cooked and heated their homes using wood and agricultural residues in traditional chimney stoves, though many also used liquefied petroleum gas (LPG), biogas, or electricity. Details on the study population and their energy use practices are presented elsewhere [34,125]. These villages were selected for study because of a planned energy intervention program supported by China's Ministry of Science and Technology and the Ministry of Agriculture.

Eligible households cooked regularly with a traditional biomass stove and lived in one of the participating villages. We enrolled 205 primary female cooks from 204 homes into the study [125]. Most of the 85 eligible women who declined participation (71% participation rate) did so because they worked outside of the village and participation was logistically difficult. Participants provided verbal informed consent prior to participating, and were reminded at each follow-up visit that they could withdraw at any time. The study protocol and its consent procedures were approved by ethical review boards at McGill University (#A01-E01-14A), the University of Minnesota (#1304S31002), Tsinghua University, and the University of Wisconsin-Madison (#2014-0006).

7.2.2 Semi-gasifier stove and processed biomass fuel intervention package

The intervention package included a semi-gasifier stove (THU) for cooking and water heating and a two-year supply of pelletized biomass fuel. The stove was designed in an iterative way, undergoing extensive laboratory and field testing in village homes throughout the five-year stove development process [97]. The stove featured an automatic ignition system and a small fan that produced a synthetic 'gas-like' flame that could be adjusted by the user. The adjustable flame varied the firepower and pot surface temperatures, and thus accommodated multiple styles of cooking (e.g., flash frying or slow simmer). Its other key features included a large cooking pot, stainless-steel water heater, galvanized iron chimney that vents outside the home, and an external pellet feeder that allowed the cook to add fuel during use (Figure 1). The stove was classified as IWA-ISO Tier 3 with respect to thermal efficiency (41% +/-2%) and Tier 4 with respect to pollutant emissions and safety (the best performing tier) [97]. A small-scale biomass processing factory was constructed at the study site in 2012 to produce pelletized biomass fuel using locally available hardwood and agricultural waste. Additional information on the stove's design and development process, technical features, energy efficiency, and pollutant emissions performance in the laboratory and field are provided elsewhere [97].

Following two seasons of baseline (pre-intervention) environmental measurements, villages were cluster-randomized to either receive the intervention during the study period (intervention group) or at the study end (control group). Several homes in intervention villages were controls because stove supply ran out (n=5), they were not present to receive the stove (n=5), or preferred to receive the intervention with control homes (n=1). In intervention villages, 125 homes were approached to receive the intervention. Stoves were distributed in two phases: September-October 2015 (Phase 1, n=27 homes) and January 2016 (Phase 2, n=98 homes). Households were offered the intervention at no cost. Prior to stove installation, local technicians took home measurements to inform chimney length and stove installation location. Phase 1 households received stove use training during stove installation, while those in Phase 2 received training one month after installation due to the Spring Festival holiday (8-22 February 2016). Local technicians provided ongoing stove maintenance and repair, delivered fuel replacement, and offered ongoing training on stove use to cooks.

7.2.3 Study design and data collection

The main cook in each study household completed a baseline questionnaire that included questions on household demographics, socioeconomic status (asset-based index, SES), and energy use practices [125]. A second questionnaire was administered to primary cooks at 9-10 months and 5-6 months' post-intervention for homes in Phase 1 and Phase 2, respectively. Cooks were asked about stove uptake (i.e., "Did the household try cooking with the stove at least once?") [150] and stove adoption (i.e., "Did the household permanently stop using the stove after they first tried it?") [178], and the number of stove repairs needed since installation. Households were also asked about the most and least desirable features of the intervention and traditional stoves, and the types of local dishes typically cooked on both. Questions were adapted from previous rural energy surveys [169,179], iteratively field-tested and adapted prior to implementation, and administered by field staff in the local dialect of Mandarin-Chinese.

We measured 48-h stove use in 108 intervention homes and in 32 control homes at 9-10 or 5-6 months' post-intervention. In a random sample of 38 intervention homes, stove use was continuously monitored immediately following intervention installation for 13-months and for 5-months for homes in implementation Phase 1 and Phase 2, respectively. In seven of these homes, traditional stoves were monitored for at least a week prior to intervention. Stove use was objectively measured using real-time temperature data loggers, namely Thermochron iButtons (Models DS1922L/DS1921G, Berkeley Air, USA) and Tsinghua University Temperature Sensors (Tianjianhuayi Inc., Beijing, China). Field staff placed the temperature sensors on stoves and programmed them to record surface temperature every 10 minutes; pilot data showed that measurements at 5, 10, or 20 minutes did not change the number of combustion events detected (Appendix 2 Table A1). Sensors were placed on all household stoves during 48-h monitoring and on the THU semi-gasifier and traditional stoves in the 38 homes with long-term monitoring. We placed control sensors on kitchen walls to measure room temperature fluctuations that were unrelated to stove use.

The number and duration of stove combustion events were identified from the temperature data using an algorithm adapted from Ruiz-Mercado et al (2013) and described in the appendix (Appendix 2 Paragraph A2). Briefly, a 'stove combustion event' was defined as a time period over which the stove surface temperature exceeded the wall control temperature by ≥10°C and met other conditions of peak shape to distinguish it from room temperature changes. If multiple combustion events were identified within a 60-minute period, they were classified as a single 'cooking event', which was the metric we used in the analysis. Stove use metrics applied to the short and long-term monitoring data are defined in Table 1.

7.2.4 Statistical analysis

We first examined the distribution of questionnaire and stove use data using summary statistics (means, proportions, and 95% confidence intervals [95% CI]) and graphical plots. To evaluate the enablers and barriers to intervention uptake and use, we defined outcomes as (1) *uptake* as "tried ever (yes/no)", (2) *use* as "stove was used at least once during 48-h monitoring (yes/no)", and (3) *duration of use* as the number of minutes that the stove was in use during 48-h monitoring. We then examined associations of these stove use outcomes with a number of independent variables selected based on the stove adoption literature. These variables included demographic characteristics of the household and primary cook, household SES [125], pre-intervention stove practices, stove implementation phase, and the number of dishes typically cooked on the intervention stove. We tested the unadjusted bivariate associations using t-tests and χ^2 (Chi-squared) tests. Co-linearity between independent variables was evaluated using Pearson and Spearman correlations. A multivariable probit regression model with a random intercept for natural village was used to model the association between uptake (yes/no) of the intervention and the selected independent variables. We next evaluated the association between 48-h stove use (yes/no), duration of use (minutes), and the independent variables using a hurdle model that was robust to clustering of standard errors within villages [180]. In this model, the determinants of household stove use ($p(y>0)$) and the total time (minutes) of stove use during the 48-h measurement period, conditional on use ($E(y|\ y>0)$), were modeled using probit and linear regressions, respectively. Model fit was assessed by visually inspecting model residuals. We also tested for influential variables which may have driven the observed associations by iteratively inserting and removing them from the models and looking for a change >25% in the covariate effects.

7.3 Results

Household demographics were similar between intervention and control homes, between homes that participated in the post-intervention measurements and homes that did not, and between homes that received the intervention in Phase 1 versus Phase 2 (Appendix 2 Tables A3 and A4).

Post-intervention interviews were conducted in 113 of the 125 intervention homes (90%) and 34 of the 79 control homes (43%) (Figure 2). Reasons for loss to follow-up were household relocation to an urban area (n=7 intervention, 24 control), refusal (n=2 intervention, 18 control), illness (n=2 intervention, 1 control), and death (n=1 intervention, 1 control). Complete 48-h stove use information with SUMs was obtained from 108 intervention homes (86%) and 32 control homes (41%).

7.3.1 Intervention uptake and adoption

Uptake and adoption are defined previously as whether a household tried the stove at least once (uptake), and whether they had not permanently stopped using it at the time of the survey (adoption). Among intervention homes interviewed, 79% (n=89) reported using the THU stove at least once (uptake) (Appendix 2 Figure A5) and, among these, 92% (n=82) reported still regularly cooking on the stove 5-10 months' post-installation (adoption). Homes in Phase 1 had higher uptake and adoption of the THU stove compared with homes in Phase 2 (88% vs 77% (uptake) and 100% versus 90% (adoption), respectively). The percentage of homes that reported stove repairs was less frequent among Phase 1 homes than Phase 2 homes (27% versus 48%). The most commonly reported repair need was the stove's automated ignition (Appendix 2 Table A6).

7.3.2 Frequency and patterns of stove use among adopters

Prior to intervention, all study homes regularly (three or more times a week) cooked with a traditional chimney stove and 39% also regularly cooked with an electric (induction) or gaseous stove (Figure 3). Post-intervention, the percentage of homes that used electric or gaseous stoves during 48-h of stove monitoring was 40% for intervention homes and 59.5% for control homes. Exclusive use of electric and gaseous stoves increased from 0% (pre-intervention) to 11% of intervention homes and 23% of control homes, which may reflect a shift to cleaner stoves that was independent of the intervention. While 43% of intervention homes used the THU stove during 48-h post-intervention monitoring, only 4% used it exclusively and the rest combined use with other stoves. Further, the majority of intervention homes (77%) continued to use traditional stoves in the post-intervention 48-h monitoring period.

Desirable features of the THU stove reported by cooks included its ability to reach high temperatures (51% of women), its ease of operation (43% of women), and that less smoke was generated from the cooking pot (40% of women). Desirable features of the traditional stove included the larger pot size and ability to cook more food (85% of women), and the taste of food (71% of women). Cooks also reported that the THU and traditional stoves were used to prepare different local dishes: 54% and 46% of cooks reported using both stoves to prepare fried dishes and stews, respectively, while 62%, 62%, and 70% reported using the traditional stove for porridges, soups, and steamed dishes, respectively. Less than 3% of participants reported using the THU stove to cook the latter set of foods (Appendix 2 Figure A7).

7.3.3 Long-term stove use monitoring with temperature sensors

Among intervention homes, the average percentage of days that THU and traditional stoves were in use over a five-month post-intervention monitoring period was 40.4% [95% CI 34.3, 46.6] and 45.2% [95% CI 38.3, 52.0], respectively (Figure 4), with a small decline in traditional stove use from pre-intervention levels (63.0% [95% CI 43.8, 82.2] days in use). The average proportion of THU stove use differed for homes in the Phase 1 and Phase 2 implementation groups (67.2% [95% CI 42.1, 92.3] and 29.3% [95% CI 13.8, 44.5] of days, respectively), though the rates of decline in use from the first to fifth month post-intervention were similar (-6.7% and -6.0% days in use, respectively). When used, the intensity of use was identical for the THU and traditional stoves (1.7 [95% CI 1.6, 1.7] meals per day, on average). The average daily number of cooking events on the THU stove was similar when it was used exclusively (1.7 events [95% CI 1.6, 1.7]) or on the same day as the traditional stove (stove-stacking) (1.7 events [95% CI 1.6, 1.7]). We found a moderate to high degree of correlation between our 48-h short- and long-term measures of stove use (Appendix 2 Paragraph A8)

Among homes in Phase 1, the average proportion of days the THU and traditional stoves were in use over a 13-month period was 51.4% [95% CI 45.1, 59.8] and 45.6% [95% CI 36.7, 36.7], respectively (Figure 4). However, THU stove use declined considerably from one (74% of days) to 13 (39% of days) months post-intervention.

7.3.4 Socio-demographic and behavioral predictors of THU stove uptake and use

The multi-level multivariable probit model did not identify any variables that were significantly associated with intervention uptake. However, the proportion of homes with uptake was not randomly distributed across the study region and, rather, clustered in certain villages (p-value from likelihood ratio test of standard and multi-level probit model difference = 0.05; intra-class correlation coefficient = 0.13). In contrast, a number of factors were associated with 48-h intervention use (yes/no) and the duration of use (minutes per 48-h) (Table 2). If a cook reported that the THU stove was suitable to cook one or more local dishes, the probability of stove use in the home increased significantly ($p<0.01$). If the stove was implemented in Phase 2, the THU stove was less likely to be used ($p=0.05$). Conditional on the THU stove being used, age of the primary cook ($p<0.01$), household SES ($p=0.05$), and ownership of either a gaseous or electric stove at baseline ($p<0.01$), were all negatively associated with minutes of THU stove use.

In robustness checks, we evaluated the proportion of daily meals cooked on the THU gasifier stove as an alternate outcome to duration of use, and estimated two-part models that assumed independence in each stage of the model, and standard truncated models (tobit). The results were similar across models. The hurdle model was selected for the main analysis because the estimations of stove use and duration of use were most in line with the process from which the data arose, and it had the lowest Akaike Information Criterion value [181]. We also calculated the degree of correlation between 48-h average cooking events during periods of 48-h observation and those of non-observation in a random sample of 17 homes, and did not find evidence of observer bias (Appendix 2 Paragraph A8).

7.4 Discussion

Though hundreds of millions of improved cookstoves have been disseminated globally [72,140], low levels of uptake and sustained exclusive use have limited their effectiveness [64,90–92,138,139,143]. We found that even a high-performing cookstove and fuel intervention, designed to meet local cooking needs and preferences, failed to replace traditional stoves or reach the uptake and use levels needed to achieve measureable air pollution reductions [159]. Compared with recent improved stove evaluations, the level of uptake in our study (79% of homes) was similar to that observed in Guatemala with a chimney biomass stove [113], in Malawi and India with Philips HD4012 gasifier stoves [91,138], in India with an electric stove [169,179], and in Ghana and Rwanda with rocket stoves [139,182]. The percentage of days the THU stove was in use over a 5-month period was modest (~40% of days in use per month), and gradually declined over time, similar to what was observed in studies of ISO Tier 3 and Tier 4 gasifier stoves in India and Sub-Saharan Africa [81,90–92,138,139].

While most study homes continued to cook with their traditional stoves, increased periods of exclusive use of modern-fuel stoves was observed from pre- to post-intervention. For example, pre-intervention, none of the study homes exclusively used modern fuel stoves, such as electric or gaseous stoves, to meet their energy needs but 14% exclusively used them during post-intervention 48-h stove use monitoring. At baseline, all study homes regularly cooked with solid fuels in traditional stoves, but only 77% used them during post-intervention monitoring. This trend in increased electric and gaseous stove use, independent of the intervention, may be partly attributable to recent economic growth and development (i.e., improved roads and other infrastructure) in the study region during recent post-earthquake reconstruction, and also reflects the gradual shift away from solid fuel cooking occurring throughout China [1,78,157,183]. A similar trend occurred during an intervention study in India when, compared with the intervention advanced biomass stove, more study homes gained access to and adopted LPG due to improved fuel availability and decreased costs during the study period [136].

In contrast to the laboratory-based design process of most biomass stoves, the THU stove was iteratively engineered through a process where local cooking requirements and user preferences informed each stage of its design [97]. Still, a third of cooks (38%) reported that they regularly did not use the THU to cook many local dishes, and this variable was a significant predictor of stove use in the two-stage hurdle regression model. Further, most participants preferred the taste of food prepared on a traditional stove and its capacity to prepare larger quantities of food than the THU stove. These results further highlight the challenge of designing contextually appropriate stoves that adequately meet or exceed the functionality of traditional cookstoves that, in most settings, have been used for lifetimes [142,147,162,184].

Overall adoption and use of the THU stove were considerably higher among homes in Phase 1 compared with Phase 2, despite similar household and primary cook demographics (Appendix 2 Table A4). Notably, the timing of stove use training and stove repair needs were different between the Phases, though not originally planned. In Phase 1, the number of intervention homes receiving stoves was smaller (n=27 versus n=98) and households received training on stove use immediately after installation. Also, the Phase 2 group received stove use training a month after installation due to the Spring Festival holiday. The need to provide training on stove use within a critical time window of installation is important for adoption [141,145,185]. In addition, stoves implemented in Phase 2 were manufactured as a separate batch and under different company management, which appears to have impacted stove quality; in particular, stove breakage was considerably more common. The nuisance of constant repairs likely inhibited reliance on, and confidence in, the THU stove to meet household energy needs [145,160].

Households that never tried the intervention (no uptake) were significantly clustered in certain villages. Because we lacked statistical power for village level analysis, we cannot identify what village-level factors were associated with the clustering. Previous studies from low and middle-income countries identified village-level peer effects and influence from leader's opinion as important drivers of adoption [165,167,185]. Other studies in Guatemala and Mexico found that differences between individual preferences for improved cookstoves were greater than the differences between communities [144,162]. It is also possible that residents of the same village were more similar in behaviors and other characteristics, and that this clustering was due to peer effects [186].

That older cooks used the intervention less is perhaps not surprising, considering that cooking behaviors and habits become entrenched over time, and that older cooks may be less inclined to modify these long-developed behaviors [160–162]. The negative association between household SES and intervention use is inconsistent with the literature [145,161,173]. However, since households were provided the stove at no charge, cost may not drive our results because there are lower returns from intense use for wealthy households who are already using improved fuels. This might also explain why households that already owned and used other cleaner stoves (i.e., LPG, biogas, electricity) did not use the intervention stoves as intensely – there is no novelty or additional benefit to use.

Our study has a number of limitations to consider for future studies on this topic. First, recent peri-urban development in our study region caused increased migration and a higher than expected loss to follow-up. Though, baseline socio-demographic and energy use characteristics were similar between homes that remained in the study and those lost to follow-up, indicating that the intervention adoption behaviors may have been similar for homes that left the study. Second, self-reported information on stove preferences and use can be subject to recall bias if participants felt inclined to respond in a systematically more positive or negative way [104,139]. However, our field staff continually encouraged participants to report their true experiences and, overall, self-reported information on stove adoption and use was consistent with objectively measured stove use metrics, suggesting that recall bias did not impact our results. Finally, traditional stoves have large surface areas and highly insulated combustion chambers that made it difficult to distinguish traditional stove use from room temperature change in a small number of cases (n=5). While traditional stove use may thus be slightly underestimated [152,153] as a result, we tried to avoid incorrect classifications by visually analyzing these cases.

7.5 Conclusion

Low-polluting gasifier stoves have the potential to fill critical clean cooking needs, particularly in places where raw biomass is abundant and where access to gaseous fuel or electricity is limited. We found that a low-polluting semi-gasifier stove and fuel intervention, designed to meet the local community's preferences and energy use needs, failed to replace traditional stove use in a rural Chinese setting. Though most households tried the stove and many continued cooking with it for at least 5-13 months' post-intervention, the levels of use were modest and likely insufficient for achieving large air pollution reductions. Factors including stove breakage, delayed user training, and the inability of the stove to meet household's diverse cooking needs were associated with lower levels of use. These results can inform future stove design and implementation programs, and assist researchers, stove developers, and practitioners in prioritizing efforts to formulate and test hypotheses about how to promote and accelerate exclusive use of clean technologies because household energy transitions have typically occurred over long periods [183]. In the very near term, clean-burning LPG and electric stoves may be most suitable for replacing traditional biomass cookstoves since they are the least polluting cooking stoves and already exclusively used by millions of rural homes in China [169,183,187].

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Tables and figures

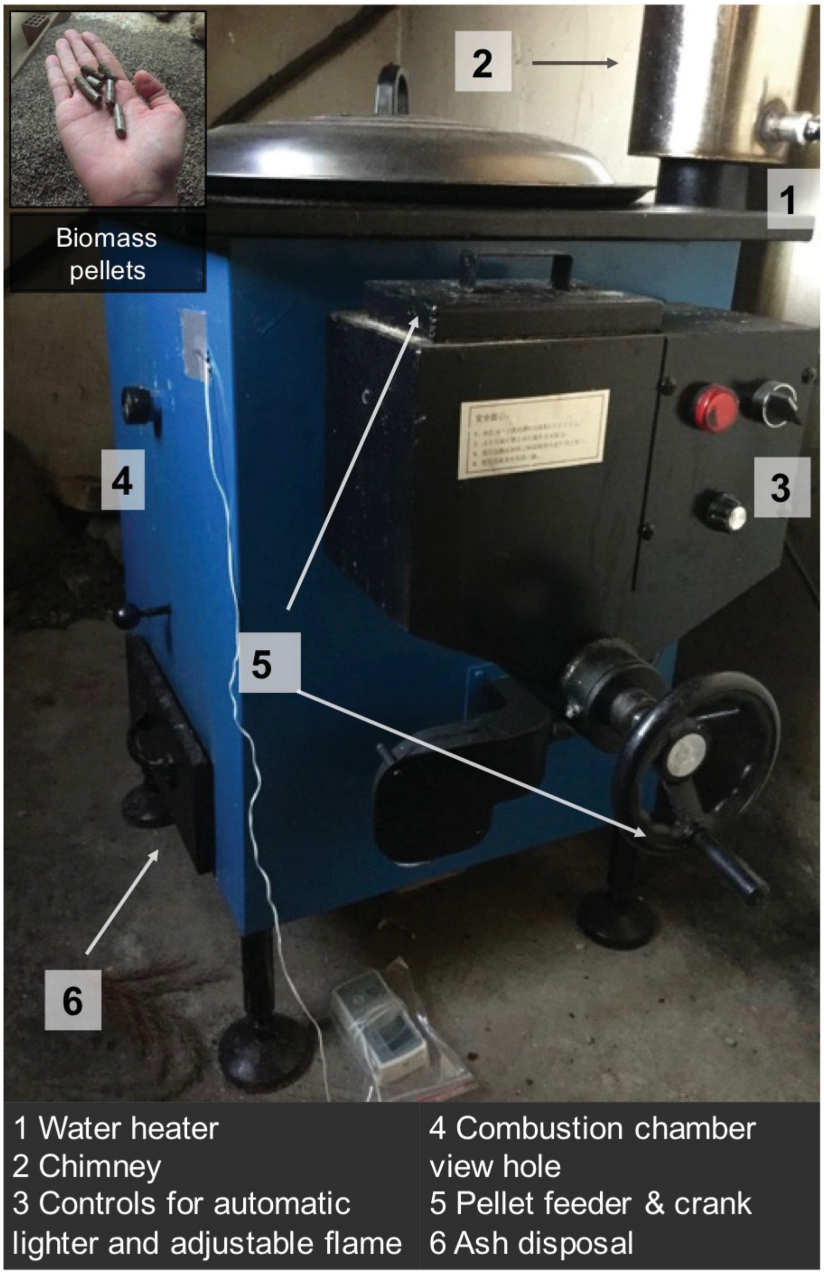

Figure 1. Key features of the Tsinghua designed THU semi-gasifier stove.

Table 1. Metrics of short- and long-term stove use using real-time temperature data [90,92,113].

Metric	Definition	48-h monitoring (n=108 intervention homes)	5-13-month monitoring (n=38 intervention homes)
Proportion of meals cooking with the stove	Total cooking events on each stove type was divided by the total number of meals reported by the main cook over the monitoring period	X	
Duration of cooking time	Total number of minutes that the stove was in use over the monitoring period	X	
Stove stacking	Use of more than one stove type during a 48-h monitoring period	X	
Monthly proportion of stove use	Total number of days per month when a stove was used at least once, divided by the total number of stove monitoring days in that month		X
Intensity of stove use	The average number of meals cooked on a stove in a given day, restricted to days that the stove was used		X

Figure 2A

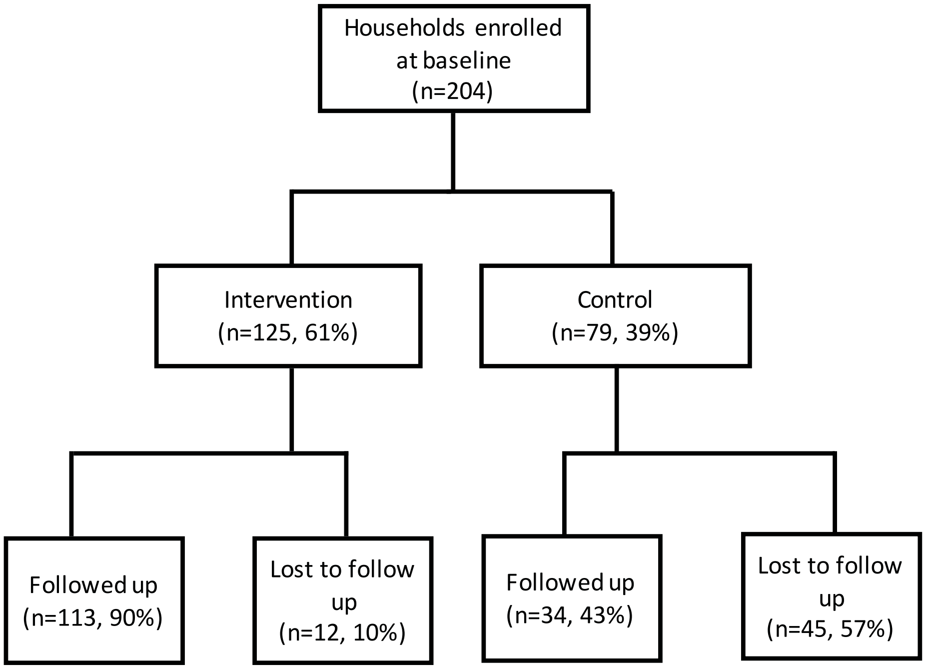

Figure 2B

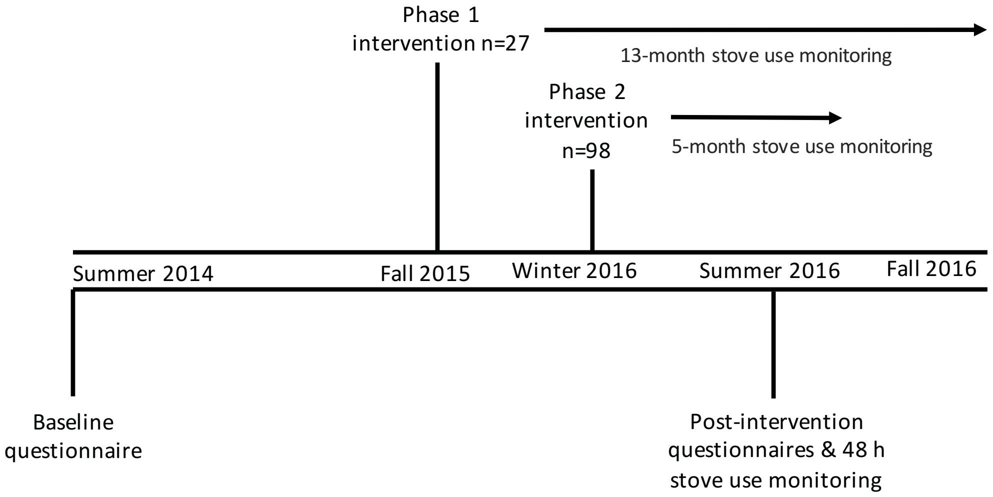

Figure 2 (a). Flow diagram of participation by intervention and control households, and (b) study timeline. Note: In the stove adoption manuscript (Chapter 7), women were classified as being in the intervention group is they were assigned to receive the semi-gasifier stove and fuel (n=125), though in the intervention health manuscript (Chapter 4), women were classified as being in the intervention group if they actually received the intervention (n=117).

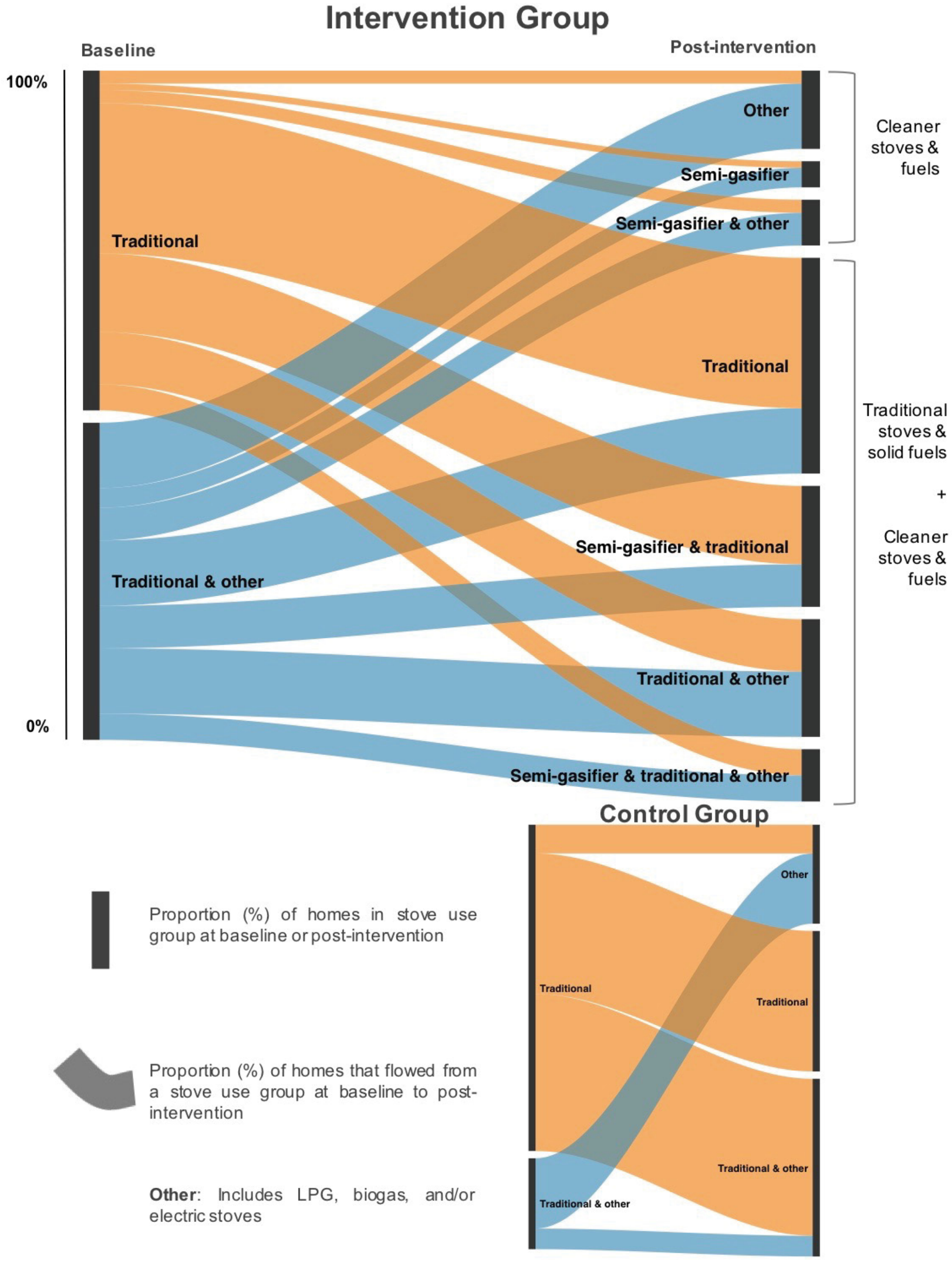

Figure 3. Proportion of homes using different stoves and stove combinations, before and after intervention. The y-axis represents the proportion of homes that regularly used different combinations of stoves, either at baseline or post-intervention. Stove use at baseline was classified as self-reported regular (3 or more times per week) use of stoves and post-intervention

if the stove was classified to be in use at least once in the 48-h period of stove use monitoring. The flows from baseline to post-intervention stove use are proportional and include all homes. Estimates are from 80 intervention and 31 control homes that were followed up post-intervention with stove use monitoring on all household stoves.

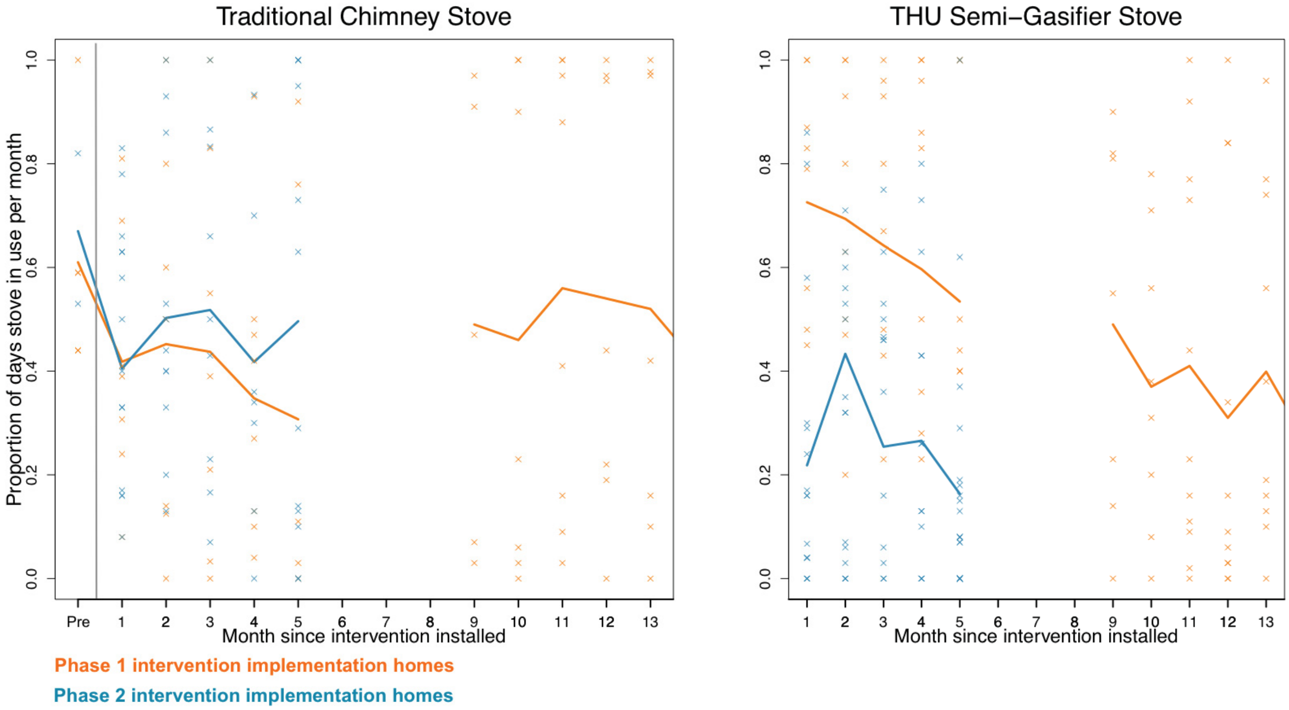

Figure 4. Average monthly proportion of days that the intervention and traditional stoves were used, pre- and up to 13-months post-intervention, in a random sample of 38 homes. Individual data points (x's) represent the proportion of days that the stove was used per month for each home. Lines represent the monthly average across all homes. Seven homes contributed to pre-intervention traditional stove estimates (pre). Days were omitted if homes did not have fuel, the stove needed repairs, participants were temporally living outside of the village, or the sensors failed.

Table 2: Results from the multivariable hurdle regression model[a] of THU semi-gasifier stove use, and duration of use (minutes), from 48-h stove use monitoring.

	Stove use					
	Probit regression (Use>0)			**Linear regression (E(Time in use | Use>0))**		
Individual and household characteristics	Mean change in probability of stove in use	95% confidence interval	p-value	Mean change in minutes of stove use over 48-h	95% confidence interval	p-value
Age of primary cook at baseline	0.00	-0.01, 0.01	0.48	-3.85	-6.29, -1.39	<0.01
Household socioeconomic status	-0.01	-0.06, 0.04	0.60	-34.92	-73.27, -1.23	0.05
Number of inhabitants	0.01	-0.03,0.06	0.59	16.72	-15.82, 49.25	0.31
Own LPG, biogas, or electric stove?						
No	Ref			Ref		
Yes	0.11	-0.18, 0.39	0.47	-86.20	-142.54,-29.86	<0.01
Adult child living in home?						
No	Ref			Ref		
Yes	0.08	-0.04, 0.19	0.19	26.23	-68.91, 121.34	0.59
Stove implementation phase[b]						
Phase 1	Ref			Ref		
Phase 2	-0.11	-0.22, 0.00	0.05	5.73	-60.55, 72.01	0.86
Able to cook one or more local dishes with the semi-gasifier stove?						
No	Ref			Ref		
Yes	0.41	0.31, 0.51	<0.01	30.43	-11.23, 72.34	0.52

[a] Standard errors of the model were robust to clustering of the outcome within natural village (n=12)

[b] The variable indicating if the THU stove needed repairs ever (1) or never (0) was removed from the model due to co-linearity with stove implementation phase

Chapter 8. Discussion and conclusion

8.1 Discussion

My thesis examined the adoption of a semi-gasifier stove and pelletized biomass fuel intervention and its impact on air pollution and cardiovascular health. My thesis was the first to evaluate the air pollution and health impacts of a high performing, low-polluting, semi-gasifier stove that was iteratively and carefully engineered to take into account community needs and preferences throughout the stove design process. My thesis was also the first to use Bayesian statistics to model the health impacts of a cookstove intervention and included a comprehensive suite of sub-clinical cardiovascular markers as outcomes, including central and brachial systolic and diastolic blood pressure, carotid-femoral pulse wave velocity, and central pulse pressure. Finally, my thesis was also among the few intervention studies to use objective measures of stove use (temperature sensors) to track the short- and long-term adoption trends of an improved cookstove and the first to quantify the individual, household, and community level factors that impacted different stages of the stove adoption process, which include initial uptake, daily choice of use, and intensity of use (e.g., duration). The results from my thesis are timely as Chinese rural energy policies suggest expanding development of biomass processing factories and gasifier or semi-gasifier stoves to burn this type of fuel efficiently and cleanly. [86,96] National governments additional to China (e.g. Rwanda) and international agencies (e.g. World Health Organization, Global Alliance for Clean Cookstoves) are promoting these interventions in places where exposures to HAP and the associated health burdens are high [73,83,84,86,96,137].

My literature review in Chapter 3 highlighted that there is growing and compelling evidence to suggest that exposure to HAP from inefficient combustion of solid fuels increases levels of CVD sub-clinical markers, independent of other known cardiovascular risk factors, such as daily temperature, age, education, and socio-economic status, among others [37–39,87]. Considering that half of the world's population is regularly exposed to HAP from cooking or heating with coal or biomass fuels, the potential cardiovascular health benefits from interventions to reduce HAP exposures could be substantial at the population-level.

In addition to our intervention study reported in Chapter 4, there are only a handful of randomized interventions or observational studies that have evaluated the cardiovascular health impacts of interventions of improved biomass cookstoves or fuels in low- and middle-income countries [59–63,93–95]. Positive, albeit often weak, benefits to sub-clinical markers of CVD were observed among intervention groups compared to control groups in Guatemala [60,61]and Nigeria [62,94], and among intervention women only (no control groups) in Nicaragua [63], Bolivia [59], though our results are similar to the null cardiovascular health findings observed among interventions in Pakistan [93] and India [95]. The evidence is further complicated by the fact that the majority of the intervention studies are limited by a lack of control for influential confounders, [59,62,63,94] and sometimes the lack of inclusion of a control group for comparison [59,63].

Chapter 6 highlighted that increasing adoption and attaining exclusive use of improved biomass stove interventions has been a persistent challenge for decades, and a lack of end-user interaction with the interventions has been a key barrier in their ability to deliver air quality and health benefits. We reported in Chapter 7 that the THU semi-gasifier stove intervention in China was only used on average ~40% of days each month (1-5 months following intervention), and the traditional stove was not replaced. In contrast, uptake of the intervention and usage trends over time were much higher in the Nigeria and Guatemala studies that also observed significant mean improvements in levels of blood pressure, ST-segment depression, and blood inflammatory markers for intervention women compared with controls [60–62,94].

While we did observe a sizeable mean reduction in personal exposure to $PM_{2.5}$ (-25%) and BC (-51%) for intervention women, post-intervention $PM_{2.5}$ and BC exposures (mean $PM_{2.5}$: 91.6 $\mu g/m^3$, mean BC: 2.0 $\mu g/m^3$) still remained well above WHO's interim target for indoor air quality [7], and control's who did not receive the semi-gaisifer stove had similar reductions in air pollution exposures. Furthermore, if the exposure-response function is indeed supra-linear as previous studies suggest [39–41,188,189], then even with sizeable reductions in $PM_{2.5}$, we might expect only modest reductions in levels of CVD sub-clinical indicators since baseline exposures are high and we are modelling the flat line of the curve.

An increasingly well-documented critique of past improved cookstove programs is that the selected stove designs were insufficiently tailored to people who were most likely to adopt the technology [64,160,162,172]. In contrast to the laboratory-based design process of most biomass stoves, the semi-gasifier stove evaluated in the present set of studies was iteratively engineered through an interactive process where local cooking requirements and user preferences informed each stage of its 5-year design [97]. However, following the introduction of the semi-gasifier stove into communities, we observed patterns of 'stove-stacking' as opposed to 'stove-switching'. The traditional wood chimney stove was not fully replaced by the semi-gasifier and was often used in combination other clean fuels and stoves (i.e., LPG, biogas, electric) to meet the entirety of a household's energy needs. The linear fuel switching paradigm - that as households climb the economic or affluence ladder, they also linearly switch from inefficient traditional fuels (e.g., wood, crop residues), to cleaner energy (e.g., LPG electricity) [157,190], has been challenged by recent field-evaluations showing that even in the midst of rising incomes and affluence, households accumulate and combine use of modern stoves and fuels with traditional ones [157]. My thesis corroborates this large body of field-based evidence that highlight the prevalent activity of 'stove-stacking' in the context of improved cookstove or fuel interventions and the potential threat that this activity poses to the expected benefits of these interventions [90,92,134,139,150,165]. The few field-based studies that assessed actual patterns of exclusive and mixed stove use and the resulting levels of air pollution showed that on days when intervention and traditional biomass stoves were used in tandem, household concentrations of $PM_{2.5}$ were similar to, or exceeded, household $PM_{2.5}$ concentrations on days of exclusive traditional stove use [92,134]. Thus, as gasifier stoves are promoted as less polluting than other improved biomass stoves, and as a potential alternative to LPG [83], programs need to accept the likelihood that stove-stacking may occur, and the implications this has for reductions, or potentially even increases, in household pollution.

The implementation of the THU semi-gasifier stove intervention differed for homes that received the stove in the first phase as compared to the second. Timing of education on proper usage and semi-gasifier stove quality differed by implementation phase; these factors may have limited household adoption of the intervention. Little is known about the effectiveness of different education or training programs that can potentially boost household demand for cleaner cookstoves [172,191]. A study in India found that behavior change promotion combined with door-to-door personalized demonstrations and information pamphlets increased the purchase of improved stoves; and when presented as options together, electric stoves were preferred over improved biomass stoves [172]. From the field of economics, we know more about whether and how economic incentives (i.e., rebates, subsidies) and strategies to employ these economic tools boost demand (i.e., purchase) of cleaner stoves and fuels, but we know very little about the impact that economic strategies have on sustained, long-term use. A recent pilot study in Cambodia (n=59 households) coupled capital-cost subsidies with rebates, and found that households responded to the rebates by purchasing (i.e. adopting) the improved stoves at higher rates and by using the stoves more frequently than the control homes over a one month period [191]. Considering that millions of improved cookstoves have been distributed globally, but many remain unused or discarded, I believe we need to conduct more research on the effectiveness of different economic incentives, social marketing, and educational techniques that can boost and accelerate the purchase and sustained use of improved biomass stoves.

8.2 Conclusion

Advanced gasifier stoves and processed biomass fuels have the potential to fill an important clean cooking gap in places where raw biomass is abundant and LPG and electricity are less accessible. My thesis showed that the adoption of a high-performing and low-polluting semi-gasifier stove and pelletized biomass fuel intervention among rural Chinese women was modest, usage declined over time, and use of traditional wood stoves continued. Further, I found that blood pressure, pulse pressure, and arterial stiffness were not improved as a result of stove distribution. Factors including the low levels of intervention adoption and non-exclusive and unsustained use impacted the semi-gasifier stove's effectiveness in meeting the WHO's interim indoor air quality target, and were likely barriers to improving measures of cardiovascular health.

Gasifiers are currently promoted around the world, and particularly in China, as the next generation of improved biomass cookstove technologies. However my thesis along with a limited number of other studies highlight how gasifiers are facing a number of behavioral and technical barriers from achieving high levels of adoption, reductions in air pollution exposures, and improvements in measured health outcomes, in real-world settings.

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Appendix 1

Paragraph A1: Air Pollution Laboratory Analysis

Filters with deposited $PM_{2.5}$ were stored in a freezer and cold chain transported to the Wisconsin State Laboratory of Hygiene for analysis. Filters were weighed three times using a microbalance (Mettler Toledo, MX5, Ohio USA) after 24-h of conditioning in a temperature and humidity controlled room. Filters were pre-weighed before deployment and post-weighed after sampling in the field; the net weight of uncorrected $PM_{2.5}$ mass (μg) was the difference between the average pre- and post-deployment weights. Uncorrected filter weights were then subtracted by the average season-specific field-blank mass and divided by the sampling volume to obtain a concentration (μg/m^3).

In the analysis of $PM_{2.5}$ personal exposures, we restricted our sample to those that reflected daily levels of exposure. In instances when pumps failed to run ±20% 48-h, or as a back-up ±20% 24-h, estimation methods detailed in Ni et al. 2016 [125], were applied.

Black carbon (BC) was analyzed on the PTFE filters using a SootScan (Model OT21) Transmissometer. Optical BC is an imperfect measurement of elemental carbon (EC), which is typically analyzed through thermal analysis on quartz filters. However, equipment and budget constraints restricted the study from collecting and analyzing EC on a full sample of quartz filters. Thus, in a random subset of homes in the baseline season (~1/3rd), 48-h stationary kitchen samples of $PM_{2.5}$ were co-located with cyclones holding quartz filters. We built a calibration curve with a linear spline model with one knot at 35 μg/cm^2 (BC) from the relationship between optical BC and EC and reported elsewhere [41]. After applying the calibration curve to the optical BC measurements, the corrected BC mass loadings (μg/cm^2) were converted to mass concentrations by multiplying the mass (μg/cm^2) by the area of the filters (9.03 cm^2), field blank correcting (10% representative sample), and dividing by the corresponding sampling volume (m^3).

Paragraph A2: Bayesian inference procedures:

We collected repeated measurements for each woman over time, and so it was expected that measurements collected on the same women would be correlated. We thus assumed three types of different woman-specific random effect structures: (i) a fixed within-subject random effects model that had a temporally constant prior mean random effect within each woman, (ii) a seasonal (winter versus summer) within-subject random effects model that had a seasonally varying prior mean random effect for each woman, and (iii) a time-varying within-subject random effects models which had a time-varying prior mean random effect for each woman, sequentially decaying in correlation over time (i.e., autoregressive).

We compared models with outcomes log and not log-transformed and with each of the aforementioned temporal correlation structures. We chose the best fitting models, which were defined as those with the lowest deviance information criterion (DIC) values. We also evaluated residual plots for any particular patterns and compared the fitted and observed values.

Paragraph A3: Estimating missing information

Our study was subject to participant loss to follow-up; however, given the reasons for non-participation, we assumed that participants were missing at random[129] . Under this scenario, the missing data become parameters of the model, and are estimated from their posterior predictive distribution (Figure A3). The estimation of the missing values and of the parameters are performed under a single framework, and uncertainty about these estimates are incorporated into the final posterior summaries. In order to fit values to our missing outcomes, the models needed complete information for all independent variables. We had complete information for all women on intervention status, age, exposure to second hand smoke, socioeconomic status, and ethnicity, as these were collected at baseline for all participants. If information on body mass index (BMI) was missing for any given campaign, we used the woman's measured BMI from the previous campaign. Similarly, we used the village- and campaign-specific average ambient temperature as a surrogate of measured outdoor temperature for women with missing measurements. In this way, we modeled blood pressure on the full sample of women in our study over all data collection campaigns (1025 total observations) and modelled arterial stiffness on the full sample of women in our study over four data collection campaigns (820 total observations; the final campaign was omitted due to instrument breakage).

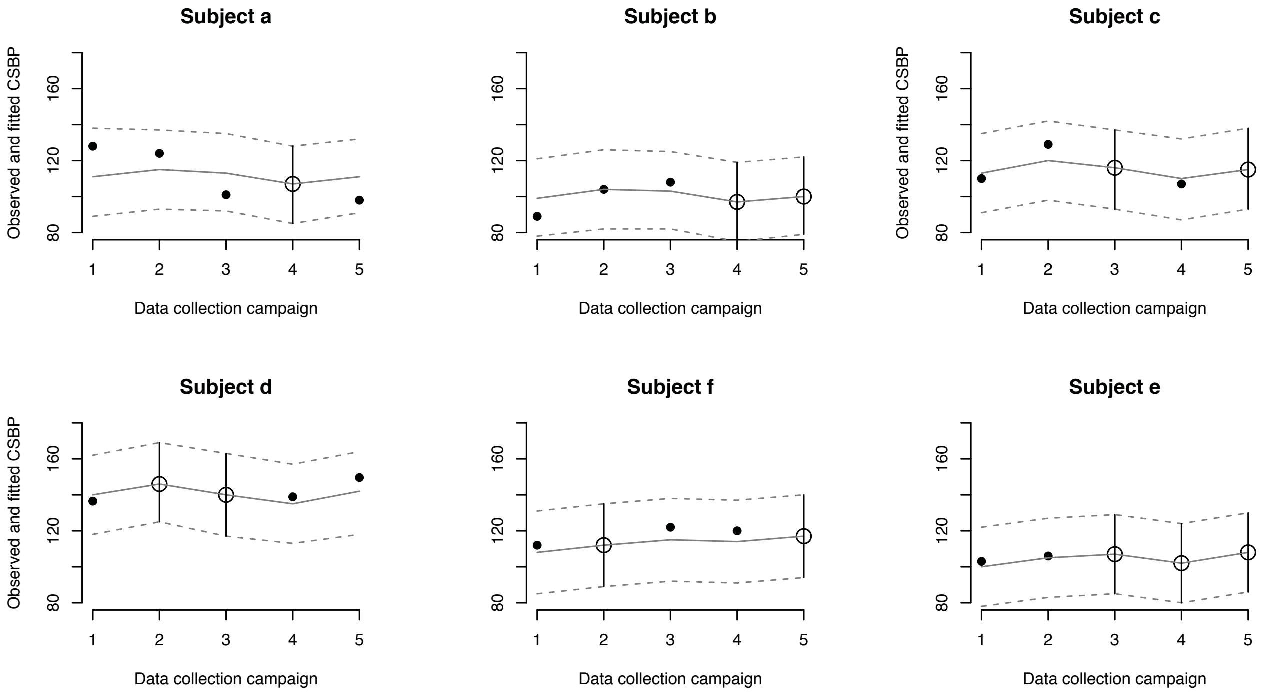

Figure A3. Observed and fitted values of cSBP for six randomly chosen subjects over five data collection campaigns. Solid lines represent the model's predicted values, open circles represent the fitted values when the subject had missing values for that data collection campaign, the solid black circles are observed values, vertical solid lines are the 95% credible intervals around the fitted values when the subject had missing values for that data collection campaign, and the dashed lines are the 95% credible intervals around all of the fitted values.

Paragraph A4: Methods for sensitivity analyses

We conducted multiple sensitivity analyses to check the robustness of our models and stability of our parameter estimates: we tested our (1) assumption that missing outcome measurements were missing at random, (2) whether including or excluding women on antihypertension medication changed the estimation of modeled parameters, and (3) whether the effect of the intervention on the outcomes was modified by age and BMI.

(1) To test our assumption that outcome measures were missing at random, we compared our modelled parameter estimates and predicted outcome measures between our final full model (presented in the paper) with a reduced model that only included the 57 women who participated in all 5 data collection campaigns. We additionally compared model parameter estimates between our final full model, which assumed that outcome measures were missing at random, with a second model which assumed dependence between the outcome measures and whether the outcomes were missing

or not. More specifically we modelled the probability of missing as a function of the cardiovascular outcome and other covariates.

(2) We compared modelled parameter estimates between our final full models, and reduced models where women who reported taking hypertension medication at baseline were omitted (n=31 women).

(3) We compared modelled parameter estimates between our final full models, and stratified models where (a) women below and above 50 years old, and (b) women with BMI below and above 25 kg/m^2. Cut points chosen based on what was commonly reported in the literature.

Table A5: Reasons for loss to follow-up

Table A5. Summary of reasons for loss-to follow (n=42 women)

	Temporarily relocation	**Refusal**	**Reoccurring acute illness**	**Died**
Post-intervention	N=20 (48%)	N=18 (43%)	N=3 (7%)	N=1 (2%)

A6: Posterior summary of the effects of covariates in the <u>Intention-To-Treat (ITT)</u> analyses of blood pressure, central hemodynamics, and arterial stiffness.

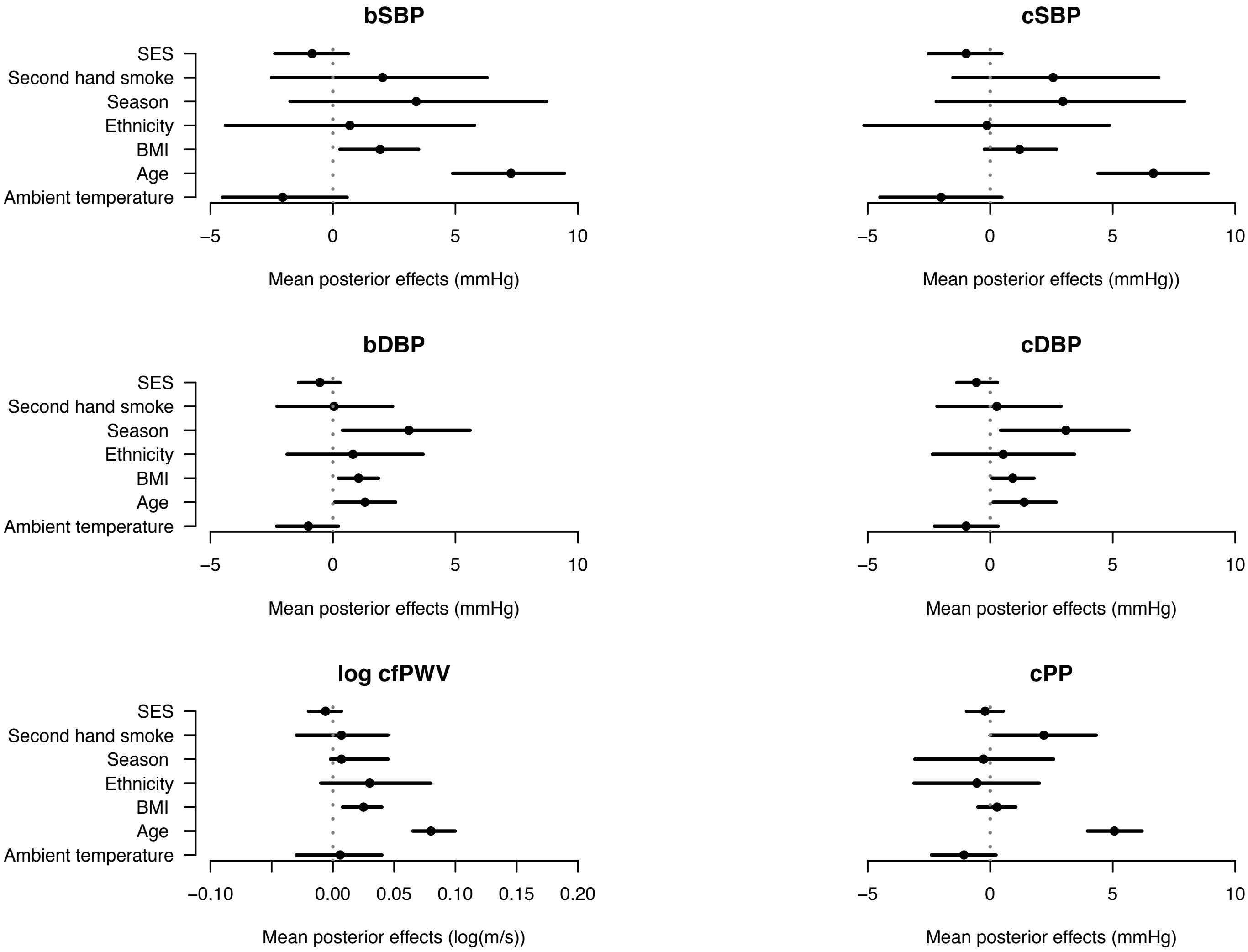

Figure A6. Posterior summary (solid circles: posterior mean; solid lines represent 95% CI) of the effects of covariates (excluding *intervention effects*) on blood pressure, central pulse pressure, and log-carotid-femoral PWV from the ITT models. Age, ambient temperature, and BMI were standardized by subtracting the variable means and dividing by each corresponding variable's standard deviations.

A7: Posterior marginal means and 95% credible intervals of the *intervention effect* on BP, cPP, and log-cfPWV from <u>per-protocol analyses</u>.

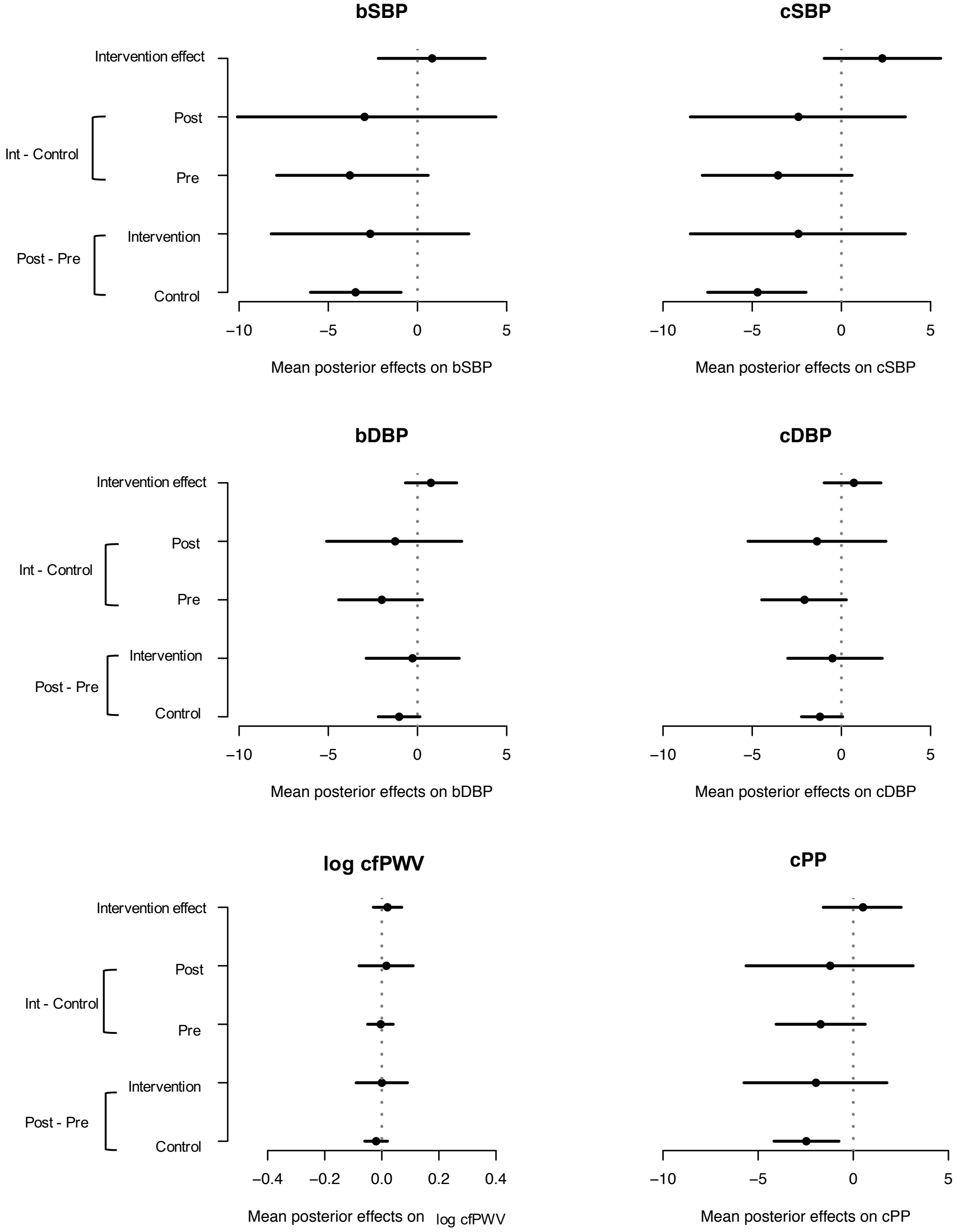

Figure A7. Posterior marginal summaries (solid circles: posterior mean; solid lines represent 95% CI) of the intervention effect on BP, cPP, and log-cfPWV in rural southwestern Chinese women, before and after a semi-gasifier stove intervention, from per protocol analyses. All models controlled for within-subject random effects and age, ethnicity, SES, BMI, outdoor temperature, secondhand smoking, and season. Intervention women were those that accepted the stove into their home (n=117), and control women were those that were assigned not to receive the stove or did not accept it into their home (n=88). **Legend:** *Post-Pre (Control)* is the average change over time among control women; *Post-Pre (Intervention)* is the average change over time among intervention women; *Int-Control (Pre)* is the average difference between intervention and control women in the pre-intervention season; *Int-Control (Post)* is the average difference between intervention and control women in the post-intervention season; and *Intervention effect* is the average difference between intervention and control women in their average change over time. *Note the reduced y-axis scale for log-cfPWV.

A8: Posterior summary of the effects of covariates in the per-protocol analyses of blood pressure, central hemodynamics and arterial stiffness.

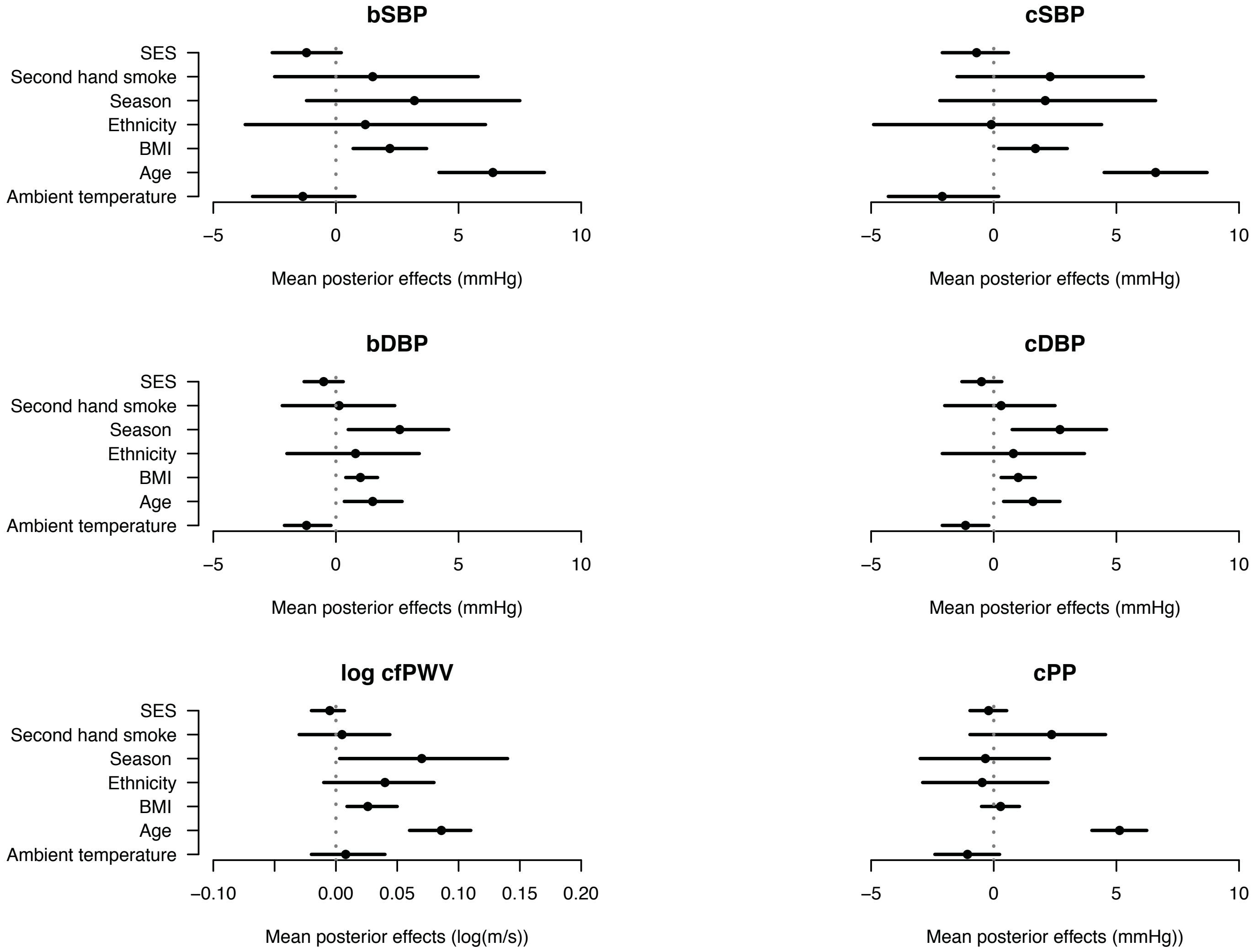

Figure A8. Posterior summary (solid circles: posterior mean; solid lines represent 95% CI) of the effects of covariates (excluding *intervention effects*) on blood pressure, central pulse pressure, and carotid-femoral pulse wave velocity from per-protocol analyses. Age, ambient temperature, and BMI were standardized by the mean and standard deviations. *Per-protocol:* women who accepted the intervention stove into their home (intervention) or not (control).

Appendix 2

Table A1. 8-day visual analysis of temperature peaks (cooking events) for semi-gasifier, traditional wood-burning chimney, and LPG, stoves and a rice cooker at 5-, 10-, and 20-minute data logging frequency, collected from one home in May 21-28th 2014 (baseline season).

	Total number of peaks at 5 minutes	Total number of peaks at 10 minutes	Total number of peaks at 20 minutes	Number of peaks missed between 5 and 10 minutes	Number of peaks missed between 5 and 20 minutes
Semi-gasifier	6	6	6	0	0
Traditional	4	4	4	0	0
Rice cooker	14	14	14	0	0
LPG	24	24	23	0	1

Paragraph A2. Explanation of the algorithms used to identify cooking events and cooking time duration from temperature data loggers.

Quantifying stove combustion events: An algorithm was developed to quantify the number of cooking events per day, per stove and per household from the temperature sensor data. Overall, the dataset included information on both stove surface and wall temperature measurements, which were matched on household, day, and time. Wall measurements served as controls for background changes in indoor ambient temperature. If the wall temperature was not monitored in a household due to a lack of sensor availability, the minimum temperature recorded on that stove in that household for that day was used as the control.

Stove combustion events were defined according to a step-wise analysis of the temperature profile:

1) The stove surface temperature had to be greater than the control temperature by at least 10 degrees Celsius to realistically be classified as a stove combustion event, as it had to be differentiated from natural diurnal temperature fluctuations.
2) The absolute stove surface temperature could not be less than 20 degrees Celsius because none of the stoves we were monitoring would realistically be below this temperature while fuel was being burnt.

3) We calculated the first derivative of the temperature profile, smoothing over a moving 80-minute interval, to evaluate the running slope. A change in the sign of the smoothed slope from positive to negative signaled a cooking event (peak in the data).

If two or more combustion events were identified within a 60-minute window, indicated by the location of their highest (peak) temperature, they were grouped together as one *cooking event*. The algorithm was coded in the open source statistical computing software R, Version 3.

In a validation study using the stove use data from a random sample of 6 homes conducted over two weeks; 90% of combustion events identified through visual analysis of the data were successfully classified by the algorithm; this compares well with other approaches in the literature [151,152].

Quantifying duration of cooking events: The duration of *cooking events* with the semi-gasifier stove was calculated from the short-term 48-h stove use monitoring data in the Summer (n=108 homes). A cooking event classified as starting when the temperature increased by at least 5 degrees Celsius from time-1 to time-2 and classified as ending when the temperature began to decrease from its maximum temperature achieved. A cooking event had to have temperatures exceeding 20 degrees Celsius and at least 10 degrees Celsius above wall temperature (same as above). All classifications were visually verified. For each home and 48-h monitoring period, the duration of individual cooking events was summed across all cooking events measured on the semi-gasifier stove to estimate the total 48-h cooking time with the semi-gasifier stove.

Table A3. Baseline characteristics of the primary cooks and households in the intervention and controls groups.

	Intervention group (n=125)		Control group (n=79)	
	N (%)	**Mean [95% CI]**	**N (%)**	**Mean [95% CI]**
Total	**125 (100%)**		**79 (100%)**	
Age		51.4 [49.4-53.3]		52.4 [49.6-55.2]
Ethnicity				
Qiang	25 (20%)		19 (24%)	
Han	100 (80%)		60 (76%)	
Highest education level obtained				
No formal education	23 (18%)		10 (13%)	
Primary school	95 (76%)		67 (85%)	
Junior high	7 (6%)		2 (2%)	
Senior high or university	0 (0%)		0 (0%)	
Occupation				
Unable to work, unemployed	1 (1%)		2 (3%)	
Housework	55 (44%)		20 (25%)	
Farming	59 (47%)		48 (61%)	
Factory, construction, craftsman, professional, civil servant, self-employed	10 (8%)		9 (11%)	
Asset-based relative wealth score (SES)				
Lowest SES tertile	35 (28%)		33 (42%)	
Moderate SES tertile	43 (34%)		25 (32%)	
Highest SES tertile	47 (38%)		20 (26%)	
Owns a computer				
Yes	92 (74%)		66 (85%)	
No	33 (26%)		12 (15%)	
Owns a car				
Yes	98 (78%)		63 (81%)	
No	27 (22%)		15 (19%)	
Total number of inhabitants in household		4.1 [3.8-4.3]		4.1 [3.6-4.4]
Main fuel used for cooking				
Wood	104 (87%)		66 (91%)	
LPG or biogas	15 (12%)		6 (8%)	
Electricity	1 (1%)		1 (1%)	
Main fuel used for heating				
Wood	80 (67%)		57 (83%)	
Wood-charcoal	34 (28%)		9 (13%)	
Electricity	6 (5%)		3 (4%)	

*CI: confidence interval, N: Number of observations, %: Proportion, Mean: Arithmetic mean

Table A4. Comparison of demographics statistics between intervention homes in the first (Fall 2015, n=27) and second (Winter 2016, n=98) stove implementation phases.

	Phase 1 group (n=27 HH)		Phase 2 group (n=98 HH)	
	%	**Mean [95% CI]**	**N %**	**Mean [95% CI]**
Demographics				
Education				
Illiteracy	19%		18%	
Primary school	70%		78%	
Junior high	11%		4%	
Senior high	0%		0%	
University	0%		0%	
Age		48.7 [44.5-52.8]		52.2 [49.9-54.4]
Ethnicity				
Qiang	11%		22%	
Han	89%		78%	
Occupation				
Unable to work	0%		1%	
Unemployed, not looking	0%		0%	
Unemployed, looking	0%		0%	
Housework	44%		46%	
Farming	48%		46%	
Non-farm	4%		2%	
Non-farm factory or construction	4%		4%	
Non-farm skilled craftsman	0%		0%	
Professional	0%		0%	
Civil servant	0%		0%	
Self-employed	0%		1%	
Other	0%		0%	
Marital status				
Married	96%		89%	
Divorced	0%		0%	
Separated	0%		0%	
Widowed	4%		10%	
Single	0%		1%	
Total number of inhabitants in household		4.1 [3.7-4.6]		4.1 [3.8-4.3]
Collect firewood for fuel?				
No	4%		6%	
Yes	96%		94%	

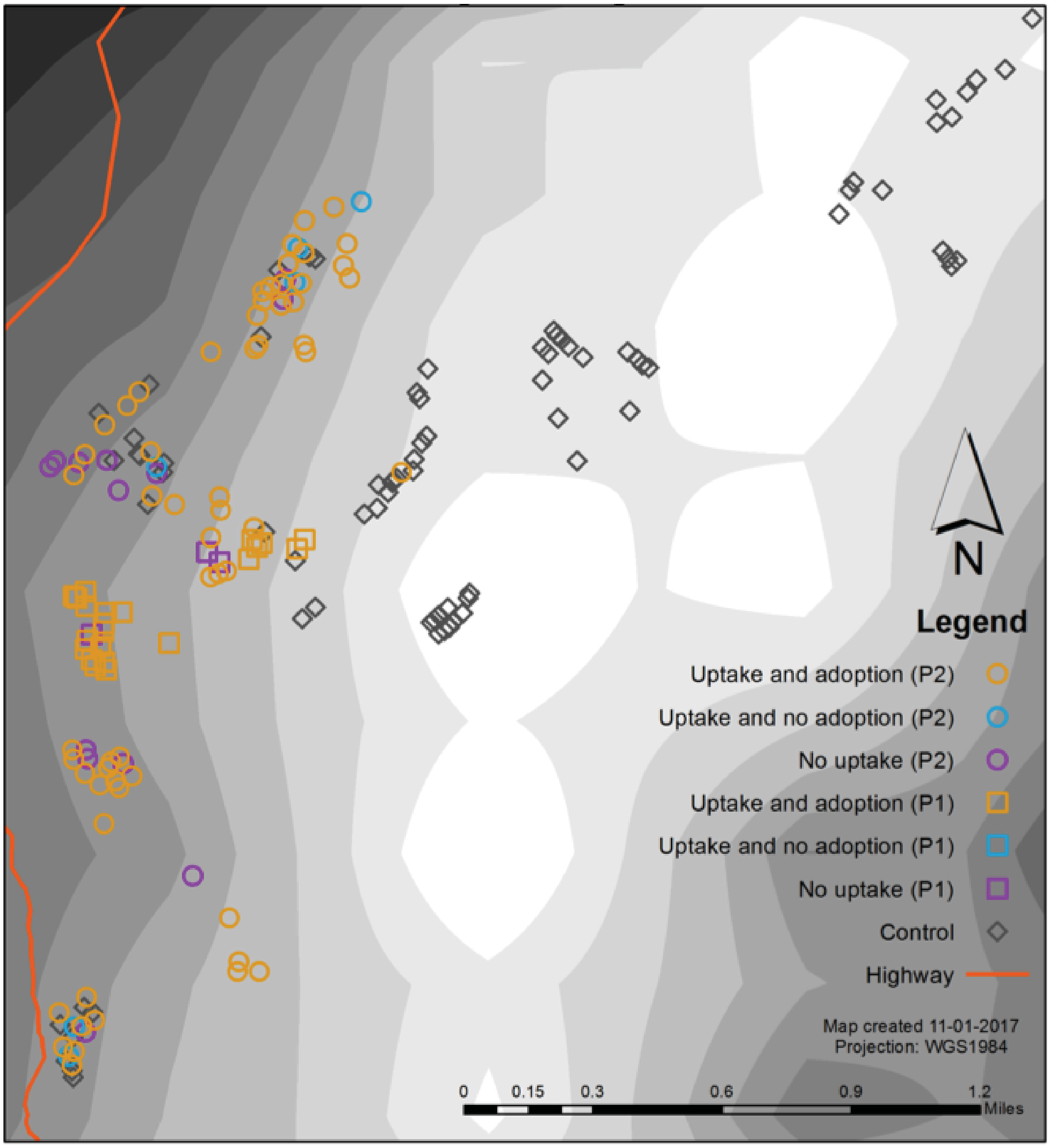

Figure A5. Map of participating study homes that were followed-up at 5-10 months post-intervention and their reported uptake and adoption of the intervention. P1 and P2 refer to homes in Phase 1 or Phase 2 stove implementation groups. The grey-scale gradient represents changes in elevation, with lighter colors representing increased elevation above sea level. Using printed maps of household locations, households were digitally geocoded into Google Earth as KML files (© 2012 Google Inc.). The resulting Google Earth files were converted into ArcGIS (Esri Inc., Redlands, California) shapefiles, mapped using the WGS 1984 coordinate system, and linked with questionnaire data.

Table A6. Uptake, adoption, and repair needs of the THU semi-gasifier stove for interviewed homes in Phase 1 and Phase 2 stove implementation groups.

	All homes	Phase 1 homes	Phase 2 homes
Intervention homes surveyed	n=112	n=25	n=87
Uptake: Household accepted the THU stove and tried using it at least once	89 (79%)	22 (88%)	67 (77%)
Sample of surveyed homes with uptake	n=89	n=22	n=67
Adoption: Household reported still using the THU stove at least five months post-installation	82 (92%)	22 (100%)	60 (90%)
Repair needs: Did the household report that the THU needed repairs at least once?	39 (43%)	6 (27%)	32 (48%)
Repaired once	22	3	19
Repaired two or more times	16	3	13

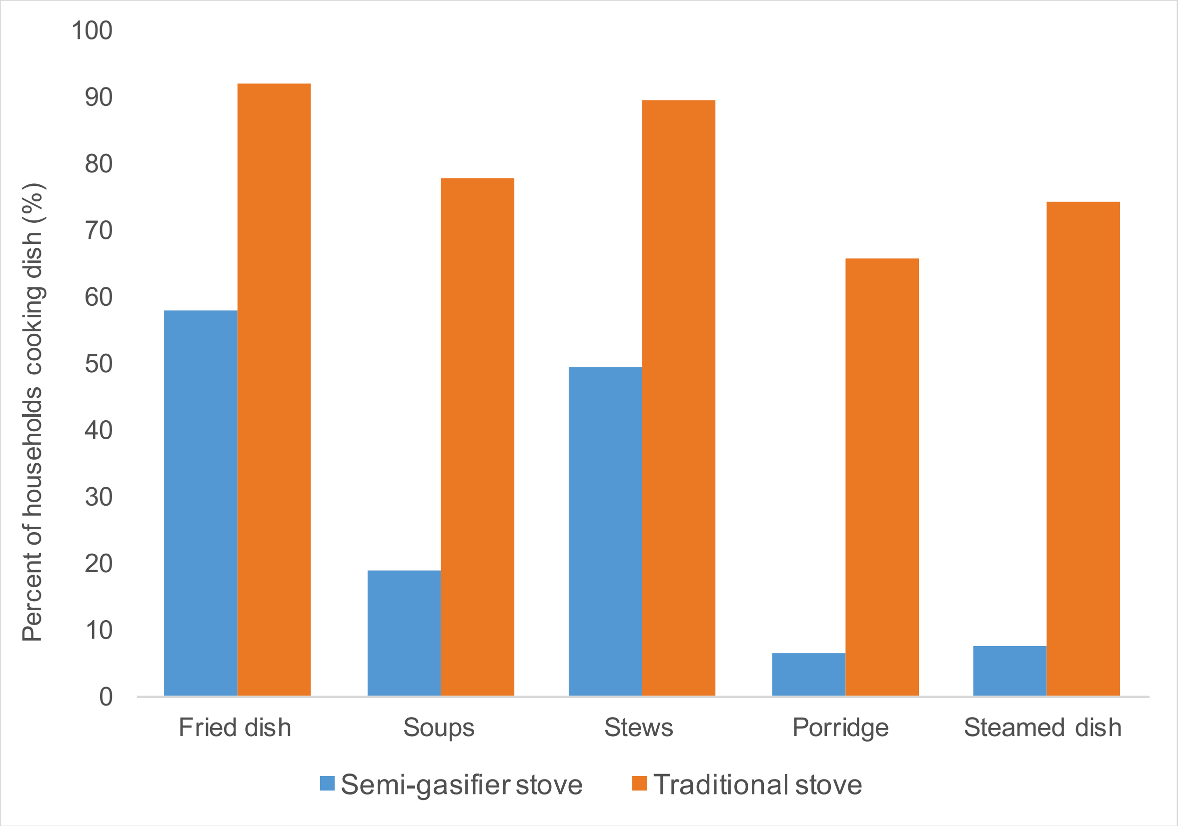

Figure A7. Proportion of intervention homes that chose to prepare five different local dishes on the THU semi-gasifier and/or the traditional stoves on a regular basis.

Paragraph A8. Did short-term patterns of stove use predict long-term use, and was there a Hawthorn Effect of cooking patterns during period of observation?

Methods of our sensitivity tests

Did short-term average daily cooking events reflect long-term averages? We used short-term (48-h) measures of stove use in our predictive model assuming that the data reflected average long-term patterns of use. We conducted a series of sensitivity tests from a subset of homes (n=38) where we had both short-term (48-h) and long-term data (five months). We correlated short- and long-term average daily cooking events on the semi-gasifier and the traditional stoves.

Did cooking behaviors change during periods of observation (Hawthorn Effect)? To test our assumption of no observer bias (Hawthorn Effect), during 48-h of stove use monitoring (which were collected at the same time as air quality and health data measurements), we left SUMs on stoves for an additional 48-h post-data collection in a subset of 17 homes. We then calculated the correlation between household average duration of total 48-h cooking time on the semi-gasifier stove (min), during 48-h of observation, and 48-h post-observation. We first calculated the Pearson correlation coefficients among the 17 homes with 48-h observation/ 48-h post-observation data. We further restricted the data, and calculated the Pearson correlations, among homes that (a) used the semi-gasifier stove at least once (omitted zero values) and (b) used the semi-gasifier stove at least once (omitted zero values) and removed an extreme outlier that may have been driving the observed relationship.

Results of sensitivity tests

Short- and long-term cooking event association. We found a moderate degree of correlation between short- and long-term averages (semi-gasifier stove r=0.55; traditional stove r=0.56) and a higher degree of correlation between one-month and 48-h average daily cooking events collected within the same calendar month (semi-gasifier stove r=0.80; traditional stove r=0.62). Traditional stoves were used slightly more frequently during 48-h monitoring compared with the long-term average.

Hawthorn effect. Average total duration of 48-h cooking events was highly correlated with the semi-gasifier stove use during and after the observation period when (a) all observations were used, and (b) when zero values representing no cooking events (0 minutes) were excluded ((a) r=0.98, (b) r=0.98). However, when an extreme outlier was omitted, the correlation between average total duration of 48-h cooking events and semi-gasifier use remained high (r=0.85), reflecting a high degree of within-household variation in cooking behaviors.