



Understanding the Impacts of Traditional Cooking Practices in Rural Madagascar and a Way Forward with Improved Cookstoves

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Abstract

Traditional biomass cooking practices pose a major threat to human health and the environment in Madagascar, where over 99% of the population relies on solid biomass fuels for energy. Biomass burning is a major contributor to household air pollution, which can impact the respiratory and cardiovascular health of primarily women and children. The need for fuelwood also places stress on the environment as a major driver of deforestation. This thesis quantifies the household air pollution and exposure measured in ~20 households in a village in the SAVA region of Madagascar, in addition to the amount of fuelwood extraction, and the time and health burdens on the local population. This thesis also presents an assessment of the improved cookstove landscape in the SAVA region and tests the efficiencies of several of these stoves to estimate the fuelwood reduction impact these stoves could have. Water boiling tests were performed on three wood-burning stoves and five charcoal-burning stoves sold in the region. It was found that household and individual exposure to particulate matter and carbon monoxide exceeded WHO standards and roughly 42% of individuals were found to have hypertension. Families are estimated to consume an average of 3,088 kg of fuelwood per year and walk an average distance of 3.3 kilometers, three times a week to collect. Of the improved wood stoves tested, two were found to require significantly less fuelwood (up to 1/3 less fuel by weight) than traditional methods. These findings emphasize the problems associated with traditional cooking and the potential for improved cooking technologies to mitigate these issues in energy-poor communities.

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I. Introduction

Across the globe, over 3 billion people use solid biomass fuels with inefficient stoves in environments with poor or limited ventilation (Sustainable Energy for All 2017). The biomass inputs required for this contribute to local landscape degradation, deforestation, and ecosystem destruction. The inefficient burning of these fuels requires significant time inputs from women, specifically, who are often responsible for the collection and processing of fuelwood in addition to the time spent cooking for their families. Such burdens are characteristic of “energy-poor” populations, caused by limited access to clean fuels like gas or electricity (Sovacool 2012). Perhaps the most dangerous result of open-fire biomass cooking is the air pollution generated and the health impacts this has on women and children. In this thesis, I will focus on the impacts of traditional cooking in one rural village in the SAVA region of Madagascar, evaluating forest loss (using fuel consumption as a proxy), time and lifestyle costs for families, and the effects of generated air pollution on human health and the environment. Lastly, I will explore efforts to mitigate these impacts through locally-made improved biomass cooking technologies.

1.1 Deforestation in Madagascar

Madagascar is undergoing a serious deforestation crisis, presenting resource constraints and posing threats to biodiversity and the natural environment. Madagascar has undergone a 40.4% loss in forest cover: a reduction from 16.0 million hectares in 1950 to 9.5 million hectares in 2000 (Allnutt et al. 2008). Some proclaim that Madagascar’s tropical forests should be of top priority for conservationists due to the high levels of endemic species living in these ecosystems (Myers et al. 2000). Drivers of deforestation include slash and burn agriculture (known as *tavy* in Madagascar), and harvesting wood for building materials and cooking fires (Scales 2014). Deforestation is typically accompanied by other environmental consequences including degraded

air and water quality, loss of habitat, less material for fuel and infrastructure, and increased erosion and runoff (Kramer et al. 1997).

1.2 Time and livelihood impacts of traditional cooking

The Malagasy spend an average of 2.2 hours every day collecting firewood and the energy needs for cooking and lighting account for about 6.1% of all household expenses (World Bank Group 2014). Compared to other Sub-Saharan African countries, Madagascar has some of the lowest levels of modern-fuel penetration and underdeveloped markets for improved cookstoves, demonstrated by Figure 1. Women and children disproportionately bear the costs of traditional biomass cooking through fuelwood collection and time spent in front of the cooking fire. They also face elevated risks of burns, injuries, and disease from poor air quality. It is estimated that women spend 2.7 hours actively cooking each day, although times of exposure to indoor air pollution are likely to be much higher, as women perform other in-kitchen activities while they are cooking. Traditional cooking creates serious fire risks, and causes physical damage to households from the accumulation of smoke and soot (World Bank Group 2014).

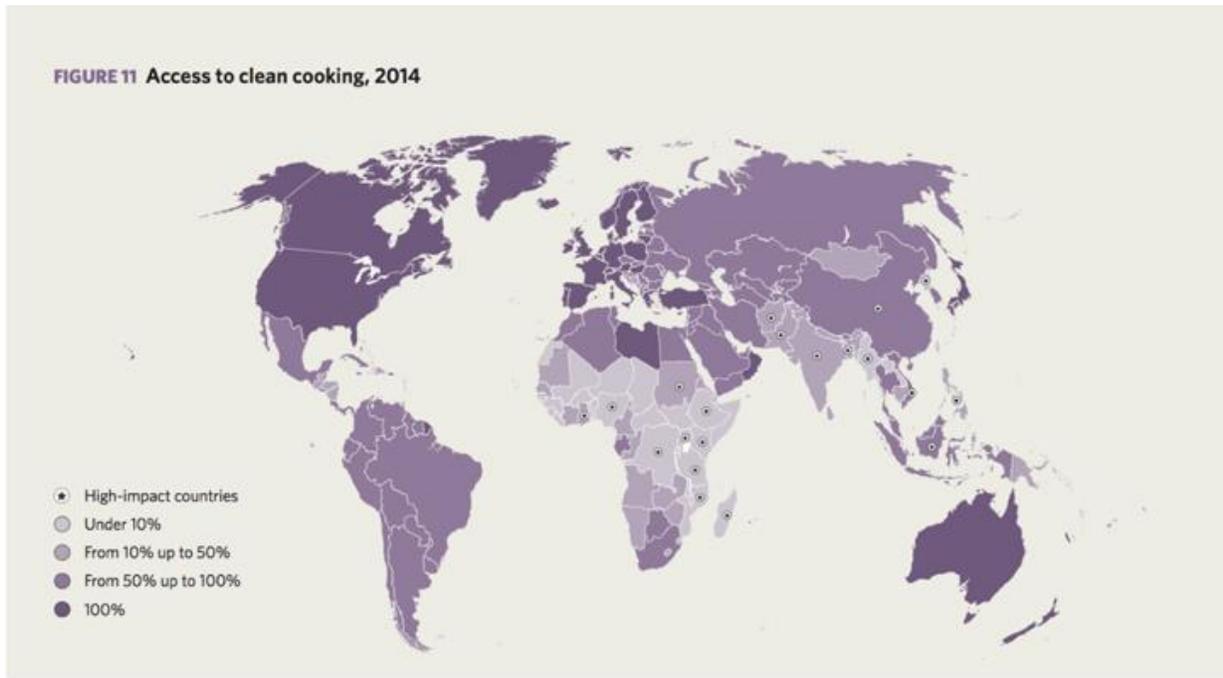


Figure 1: Percentage of the population with access to clean cooking fuels and technologies (Sustainable Energy for All Global Tracking Framework)

1.3 Household air pollution

Household air pollution (HAP) from solid biomass fuels is estimated to cause 3.5 million premature deaths annually and account for 16% of global particulate matter pollution (Kankaria and Nongkynrih 2014). In Madagascar, HAP is the second leading cause of disease and more than 99% of households rely on solid biomass fuels for cooking (Dasgupta, Martin, and Samad 2015). Poorly ventilated kitchens may exacerbate the effects of HAP, and in Madagascar, only about 17% of the population cooks outdoors (World Bank Group 2014). HAP carries with it serious health consequences including hypertension, asthma, lung cancer, bronchitis, and other respiratory and cardiovascular illnesses. The inefficient burning of solid biomass fuels and poor ventilation worsen these threats to human health and contribute to ambient air pollution. It is estimated that there is a loss of 37 DALYs (disability adjusted life years) per 1,000 in Madagascar due to HAP. Recent data suggest that HAP will soon become the leading regional risk factor for mortality, surpassing childhood malnutrition and high blood pressure (World Bank Group 2014).

1.4 Benefits of improved cookstoves

Improved cookstoves (ICS) may help to mitigate the health, livelihood, and environmental consequences associated with traditional cooking practices in Madagascar. Improved cookstoves facilitate more efficient combustion of biomass fuels which reduces indoor air pollution, fuel consumption, and time spent cooking and gathering fuel (Shankar et al. 2014). This additional time can be used to start small business ventures, pursue an education, start home gardens, develop familial and communal bonds, or for leisure. Improved cookstoves could plausibly play a role in alleviating energy poverty among rural communities and aid in the transition from traditional, open-fire cooking to clean cooking with electricity or liquefied petroleum gas (LPG). At least one study, however, failed to find evidence for this (Van der Kroon, Brouwer, and Van Beukering 2014). Garland et al. (2017) suggests that the reduction of black carbon emissions from ICS adoption could have meaningful effects on mitigating climate change, particularly via implementation of improved charcoal stoves (Garland et al. 2017). Owning an improved cookstove may also be socially empowering for individuals in energy-poor communities, particularly when consumers are provided with a range of products to choose from (Jeuland et al. 2015; Lewis et al. 2015).

1.5 Institutional challenges implementing improved cookstoves

A review of Sustainable Energy for All's 2017 report on ICS progress and numerous other papers suggest there are many environmental and institutional barriers hindering ICS uptake in energy-poor countries. Institutional barriers include but are not limited to weak government investment or enforcement of quality standards, lack of cooperation between governments, businesses, and NGOs, distributional challenges, consumer distrust of products, and underdeveloped markets (Atteridge and Weitz 2017; Sustainable Energy for All 2017). First, there has been little horizontal and vertical idea flow within and between countries. Up until recently,

artisanal and small-scale stove production has dominated the sector; thus, the spread of technological innovations and cooperation within and between countries has been constrained by small and localized markets. Additionally, there has been poor recognition by governments to make ICS a national priority and set standards or clear goals for ICS initiatives. In cases where there has been large-scale market penetration of ICS, many consumers are wary of adopting new technologies they are not familiar with, especially new stoves that may not fit their cooking preferences (Jeuland et al. 2015). Furthermore, the distributional challenges and limited financing options reduce the accessibility of improved cookstoves particularly in rural and more remote communities (S K Pattanayak et al. 2016). Lastly, small profit margins have dis-incentivized large-scale ICS production (Sustainable Energy for All 2017; Wolf et al. 2017).

1.6 Context matters when implementing improved cookstoves

In addition to these numerous institutional challenges, there are many contextual factors that inhibit uptake of ICS. Numerous studies point to the importance of tailoring ICS technologies to local cooking preferences and found that successful uptake was highly dependent on the performance of stoves in cooking local dishes and working with local cooking utensils (Lewis and Pattanayak 2012). Beyond this, consumers care about price, durability, maintenance costs, and perceived benefits of a new stove technology (Muneer and Mohamed 2003). Market-dominated approaches to ICS may be insufficient to ensure equitable access to individuals and communities with the least amount of resources and ability to invest in ICS; thus, some level of subsidization or loan servicing by local governments, NGOs, or banks is also necessary (Rehfuess et al. 2014; Sustainable Energy for All 2017). In addition to suitability and affordability, knowledge surrounding the benefits of ICS, or the dangers of traditional cooking practices for that matter, is not widely accepted. Even with this knowledge, sufficient financial capital, and access to ICS technologies, adoption of ICS still depends on the attitudes and priorities of consumers. It is

fuelwood collection in Mandena was almost exclusively performed by adult males on personally-owned or family-owned land.

1.8 Improved cookstoves in the SAVA

Beyond Mandena, there is limited infrastructure for electricity or LPG transport, and much of the region relies on solid biomass fuels (wood, crop waste, or charcoal) for its energy needs. Furthermore, little work has been done in this region to assess the market drivers of improved or clean cooking technologies, and little is known about the actors producing and selling ICS in the region. Local cookstove makers rely almost exclusively on local resources, and cookstove manufacturing is a significant source of income for many individuals. Improved cookstoves are sold locally and in regional markets, but access is limited in more remote communities. Additionally, most ICS producers operate out of their homes and sell stoves by pre-order, only, significantly constraining markets and ICS access. Many of the aforementioned barriers exist in the SAVA and must be considered when designing a successful ICS intervention or expanding the market for ICS in the region.

II. Thesis Statement and Hypotheses

In this thesis, I will seek to identify and quantify health, environmental, and livelihood impacts associated with traditional open fire cooking practices in Mandena, Madagascar by adding to and confirming findings in the existing literature. Furthermore, I will assess the ability of locally manufactured improved cookstoves to mitigate these impacts. To address these objectives, I examined the following questions:

Question 1: Are traditional biomass cooking practices significant sources of household air pollution in Mandena?

Question 2: Does air quality vary by kitchen size? By the moisture content of wood? By cooking

need (which varies by meal (breakfast, lunch, and dinner))?

Question 3: Has deforestation resulted in increased per capita investment in wood collection as wood sources become more distant from Mandena?

Question 4: Does heightened exposure to household air pollution increase likelihood of respiratory and cardiovascular-related illnesses in Mandena?

Question 5: Are improved cookstoves (both wood and charcoal) faster and more efficient than traditional stoves?

III. Methods

3.1 Data collection and partnerships

Data collection for this project has been completed by Dr. Charles Nunn's Bass Connections research team, and with support from the Duke Lemur Center: SAVA Conservation, DukeEngage, and the Sanford School of Public Policy. Air quality, fuel use, and health data were collected during the summers of 2015, 2016, and 2017 by the Bass Connections team in Mandena, Madagascar. Data on cookstove efficiencies, and survey data on cookstove producers throughout the SAVA were collected in collaboration with the Duke Lemur Center: SAVA Conservation, and support from DukeEngage.

3.2 Participant selection

Participants were selected from each household for the deforestation and exposure studies in Mandena. Since official census data is not available for the village, a map of the village (from a drone photograph) was overlaid with a coordinate system. Two numbers were randomly generated over many iterations, and if a house fell on the generated coordinates, it was added to our study. 42 households were contacted and asked to participate. Three households declined to

participate and six households were deemed ineligible due to young age or physical disability. At the end of the selection process, thirty three households participated in the survey process, and from these 33 households, 11 chose to participate in the GPS mapping of fuel collection activities and 23 chose to wear a personal exposure monitor and enroll in the accompanying health study. General health data was also collected each summer since 2015, where recruitment of participants did not occur and participation was an option for any adult living in the village.

Focus group participants were selected on a village walk by convenience and based on the availability of women to attend the discussions. Lastly, stove producers were identified through discussions with town leaders, connections with other stove producers, or recruited to two cookstove competitions via a region-wide radio announcement.

3.3 Identification of potential bias

There are many potential sources of bias within our selection of participants for the various studies. For our household selection, it is possible that larger households or households with more physical infrastructure (i.e. multiple bedrooms) had a higher likelihood of being selected from the coordinate generation process. Additionally, it is possible that households collecting fuelwood from the national park or along the park boundary were excluded, as several participants opted-out of this study. Additionally, it is likely that our general health data is biased since participants with poorer health were more likely to participate. For our focus groups, it is likely that the voices of women with less time or women working in the fields during the day were excluded from our discussions. Lastly, stove producers working in remote regions (or producers without radio or electricity access), or those not well connected to other producers were also excluded from the producer survey.

3.4 Air quality measurements

Several air pollutants were measured, including PM_{2.5} (fine particles whose diameter is less than or equal to 2.5 microns), carbon monoxide (CO), and carbon dioxide (CO₂). Household-level air quality was monitored in the summer of 2016 using UCB-PATS PM_{2.5} monitors and Lascar CO monitors. Both monitors took one measurement each minute. A set of these monitors were placed in the kitchen on a shelf or tabletop near the cooking area and another set were placed near the head cook's bedside. Devices were kept there for 24 hours to estimate daily in-kitchen and in-home air pollutant concentrations. For 2017, participants who opted-in to the air quality study were asked to wear a personal exposure backpack for 24 hours



Figure 3: Participant wearing a personal exposure backpack

that measured CO, CO₂, and PM_{2.5}. These sensors were situated in the front straps of the backpack, near to the wearer's collarbone. At nighttime, participants were asked to take off the backpack and set it near their bedside. Lascar CO pens were again used to measure CO and for PM_{2.5}, Shinyei infrared-LED sensors were used, which take a measurement every second and average those values into a single value per minute. Alphasense sensors were used to measure CO₂ every second (again, averaged into a single value per minute). CO and CO₂ were measured in parts per million (ppm) and PM_{2.5} was measured in mg/m³ and µg/m³ for the in-kitchen monitoring and the personal exposure monitoring, respectively.

3.5 Fuel collection walks and fuelwood measurements

Participants who opted to track their fuel collection walks were instructed to turn on a GPS

tracker (an i-gotU GT 120 travel logger) at the location where they collected fuelwood. Some participants, however, took a single point measurement and did not turn on active tracking. Once they returned to their households with the fuelwood, they were instructed to turn off the device and wait for a member of our research team to retrieve the device the next day. Fuelwood consumption was estimated by using an electronic scale to weigh bundles of wood set aside by participants used for breakfast, lunch, and dinner. Moisture content of fuelwood was measured with a General Tools TS06 digital moisture meter. Three measurements were taken at different locations on a randomly selected piece of fuelwood from a bundle, and these values were averaged for each species of wood used, per participant.

3.6 General Health

The general health clinic was set up in the town hall (located along the main road connecting Mandena to its neighboring village) every weekday for approximately one month each summer from around 9am–12pm and from 2pm–5pm. First, participants were asked if they were at least 18 years of age and if they lived in Mandena. If they failed to meet either condition, they were excluded from data collection. Eligible participants had their blood pressure taken a total of three times with at least 5 minutes in between each measurement to account for the white coat effect¹ (Nieuwenhuize, Geuze, and Oppewal 2013). Normal and elevated blood pressure were classified using the 2017 guidelines developed by the American College of Cardiology and American Heart Association (see Figure 4) (Whelton et al. 2017). Participants also had their height, weight, and body temperature measured, and were asked a brief set of questions about their age,

¹ The white coat effect is a phenomenon which may lead to elevated transient blood pressure observed in patients in clinical environments, or when the patient is in the presence of a doctor or other clinician (Nieuwenhuize, Geuze, and Oppewal 2013). Taking blood pressure measurements multiple times over a 20-minute period is thought to reduce the white coat effect, and thus yield more accurate results.

gender, occupation, and medical history. In 2016, two rounds of spirometry measurements were taken at the general health clinic. Spirometry results were interpreted via the guidelines developed by the American Academy of Family Physicians, with FVC values below 80% classified as below the lower limit of normal (LLN) (Johnson and Theurer 2014). Lastly, if participants had immediate health concerns or questions, they were directed to a local doctor on-site.

BP Category	SBP		DBP
Normal	<120 mm Hg	and	<80 mm Hg
Elevated	120–129 mm Hg	and	<80 mm Hg
Hypertension			
Stage 1	130–139 mm Hg	or	80–89 mm Hg
Stage 2	≥140 mm Hg	or	≥90 mm Hg

Figure 4: Guidelines used to determine normal and elevated blood pressure values among adults (SBP represents systolic blood pressure and DBP represents diastolic blood pressure).

3.7 Focus Groups

A total of two 60-minute focus groups were conducted in the summers of 2016 and 2017. Focus group discussions were conducted with women who served as the head cook of their household. Focus groups were conducted in concert with the research team and two translators to facilitate conversation and communicate participant answers to the research team. Focus group questions focused exclusively on cooking and ventilation practices, fuelwood collection behaviors, and cookstove preferences. Findings from these discussions will be woven in with quantitative results and be used to further justify conclusions and recommendations.

3.8 Cookstove efficiency testing

Efficiencies of improved cookstoves were measured via the Water Boiling Test (WBT) protocol (version 4.2.3) – see (Global Alliance for Clean Cookstoves 2014). Locally sourced wood and charcoal was used for testing (species and moisture content of fuelwood was typical of fuelwood used in Mandena). At least three rounds of tests (consisting of two high power and one

low power phase) were conducted on 3 unique wood-burning stoves and 11 unique charcoal-burning stoves. To calculate thermal efficiency the following formula was used:

$$h_c = \frac{\left[4.186 * \sum_{j=1}^4 (P_{j_{ci}} - P_j) * (T_{j_{cf}} - T_{j_{ci}}) \right] + 2260 * (w_{cv})}{f_{cd} * LHV}$$

The following formulae were used to calculate specific fuel consumption (SC_c) and temperature-corrected specific fuel consumption (SC_c^T), respectively (Global Alliance for Clean Cookstoves 2014). Both metrics are measured in grams of wood burned per grams of water brought to boiling.

$$SC_c = \frac{f_{cd}}{\sum_{j=1}^4 \left[(P_{j_{cf}} - P_j) * \left(\frac{T_{j_{cf}} - T_{j_{ci}}}{T_b - T_{j_{ci}}} \right) \right]}$$

$$SC_c^T = SC_c * \frac{75}{T_{cf} - T_{ci}}$$

3.9 Deviations from WBT protocol

While this testing procedure adhered strictly to the WBT protocol, several important modifications were made to the protocol to better replicate local lighting, fuel-loading, and cooking practices. As such, it is not feasible to compare the results from these tests to results from other water boiling tests performed in the laboratory. First, the tests were not conducted in a controlled



Figure 5: Preparation for a WBT

environment, but were done in a makeshift kitchen using building materials typical of a kitchen in Mandena. Second, fuel parcels (sticks of firewood or bricks of charcoal) were not perfectly standardized in dimension and volume. This was done due to the infeasibility of cutting fuel parcels to the same dimensions and because parcels are rarely of consistent size and volume in practice. Lastly, pot lids were used during the tests, as is the regional cooking practice.

3.10 Cookstove producer interviews

Producers were identified through conversations with village and town leaders and market sellers. Additionally, a radio advertisement was broadcast throughout the SAVA region to invite producers to participate in two cookstove competitions held in Andapa and Antalaha during the month of July. While time and feasibility of travel may have been a barrier to some producers, we attempted to mitigate these constraints by fully reimbursing travel costs for all participants. ICS producers were also identified through our conversations community leaders and with other producers. Each producer was asked a series of semi-structured questions about their business, its size, their monthly sales, and their production process.

3.11 Data analysis

ArcGIS software was used to map fuel collection sites around Mandena and identify points of potential forest loss along the boundaries to neighboring Marojejy National Park. *R Studio* software was used to analyze air quality measurements of PM_{2.5}, CO, and CO₂ for the 24-hour personal exposure measurements from Mandena cooks from 2017 and the 24-hour in-home measurements from 2016. *R* software was used to analyze (1) survey data from cooks and firewood collectors from Mandena, and (2) interviews and focus group discussions with cookstove users and cookstove producers throughout the SAVA. Kruskal and Wilcox tests of significance were used to determine differences in fuel consumption for the wood and charcoal improved stoves.

V. Results

5.1 In-kitchen air pollutant concentrations (2016)

Of the 21 households included in our 2016 study, the average 24-hour concentration of $\text{PM}_{2.5}$ was 1.91 mg/m^3 . The WHO guideline for indoor concentrations of $\text{PM}_{2.5}$ over this period is 0.010 mg/m^3 (World Health Organization 2006). The average 24-hour CO concentration in Mandena was 19.1 ppm, whereas the WHO standard for indoor CO concentration is 6.1 ppm (Penney et al. 2010). Figure 6 indicates the distribution of household measurements and the WHO standards for $\text{PM}_{2.5}$ and CO are represented as a yellow and green dashed line, respectively. Every household in our sample exceeded the standard for PM, and roughly 76% of households exceeded the standard for CO.

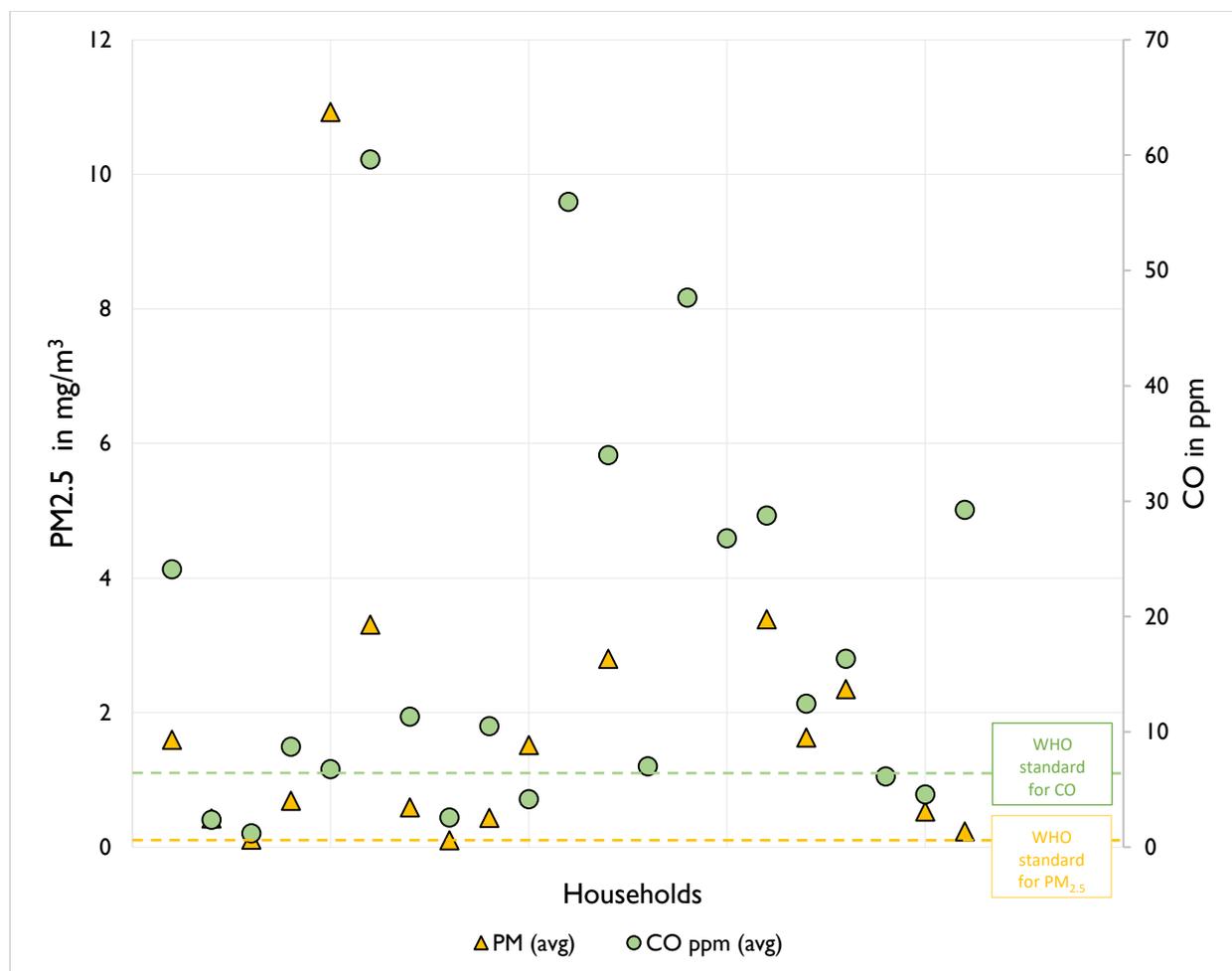


Figure 6: 24-hour in-kitchen concentrations of CO (in green) and PM (in yellow), with corresponding WHO standards

5.2 Individual exposure to air pollutants (2017)

The average PM_{2.5} concentration head cooks in Mandena were exposed to was 39.6 μg/m³ and 0.9 ppm of CO (see Figure 7). Approximately 78% of households in our sample exceed the WHO standard. Since inhalation of PM_{2.5} is toxic at any concentration, it is also useful to observe the cumulative exposure to PM_{2.5} throughout a 24-hour period. The average of cumulative PM_{2.5} exposure was 56,798 μg/m³ and Figure 8 represents a typical individual’s accumulation of PM_{2.5} exposure throughout the day. Plateauing indicates times when there were not significant sources of PM contributing to the individual’s exposure, while steep increases represent events where PM

levels were high. The three distinct “steps” visible in Figure 8 indicate preparation for lunch, dinner, and breakfast, in that order.

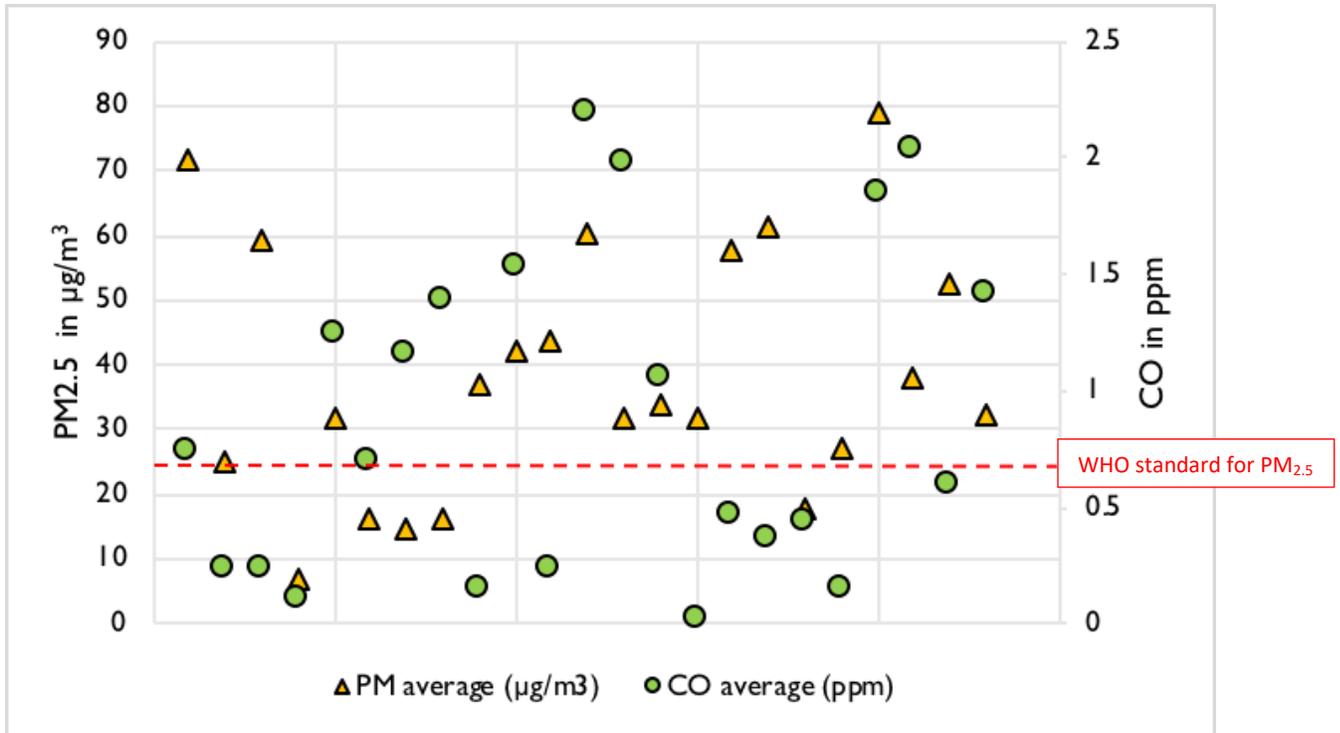


Figure 7: 24-hour average exposures for CO (in green) and PM (in yellow), with corresponding WHO standard for PM

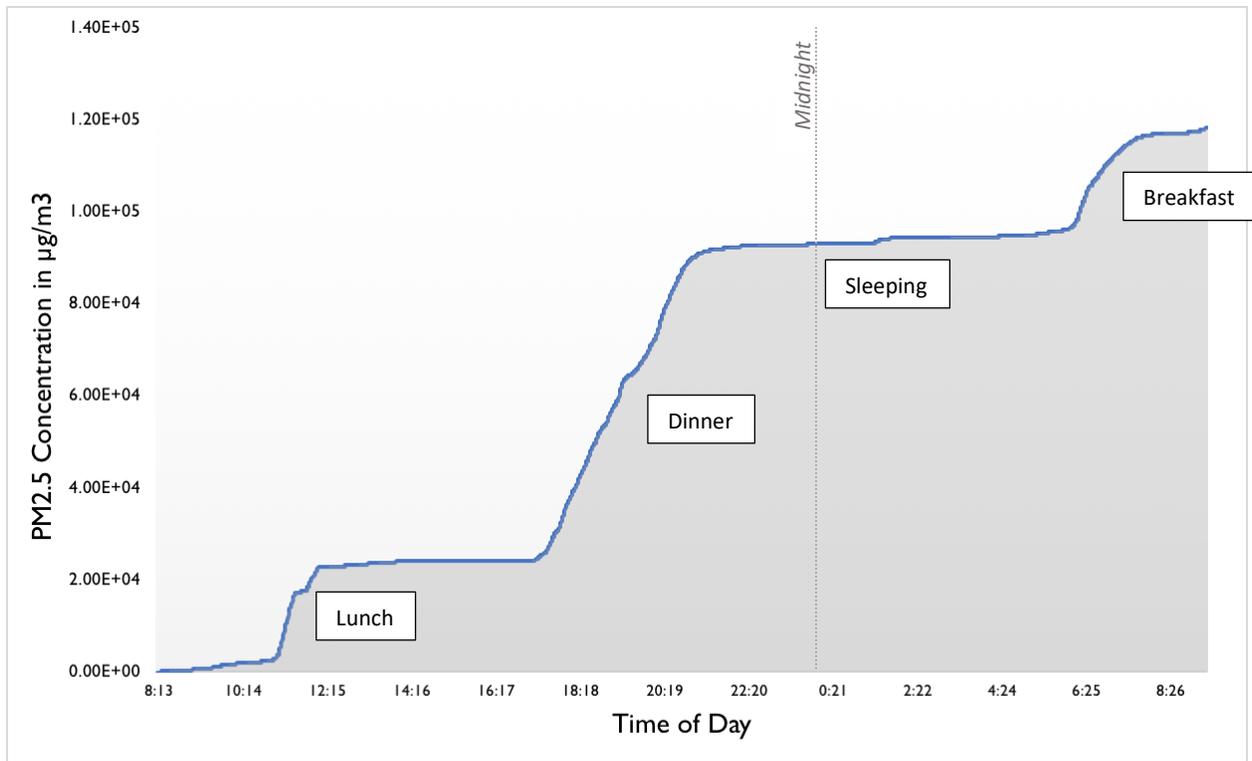


Figure 8: Cumulative PM exposure over 24 hours for a typical head cook

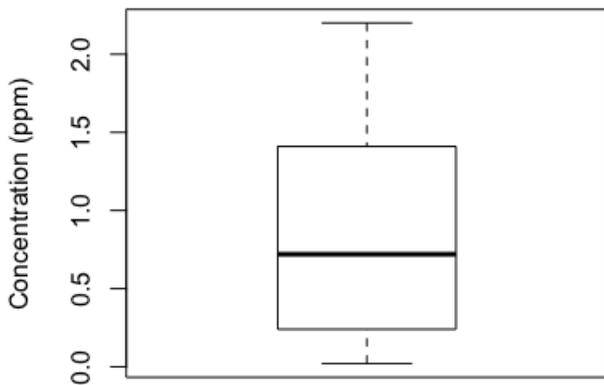


Figure 9a: Average exposure to CO

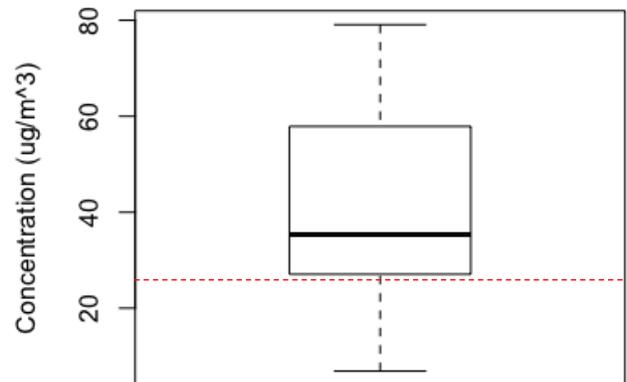


Figure 9b: Average exposure to PM and WHO exposure limit (in red)

5.3 Fuelwood consumption and collection

The average family in our sample consumed roughly 8.46 kg of fuelwood per day. Assuming this represents a household's typical consumption on any day of the year, this can be

extrapolated to about 3,088 kg of wood used for cooking per household per year. The amount of fuelwood used per meal varies, with breakfast requiring slightly less fuel than lunch or dinner (see Figures 10a and 10b). There is little correlation of family size to quantity of fuelwood collected or number of collection trips, which is consistent with data from 2016. Figure 11 shows the average moisture content of fuelwood was 18.96%, below the recommended maximum moisture content for seasoned fuelwood of 20% (The University of Tennessee Agricultural Extension Service 2010). There was little relationship between moisture content of the fuelwood and emissions, although fuelwood that was dried above the fire (~64% of households) before use produced half as much CO on average and 10 $\mu\text{g}/\text{m}^3$ less $\text{PM}_{2.5}$ per 24-hours, on average.

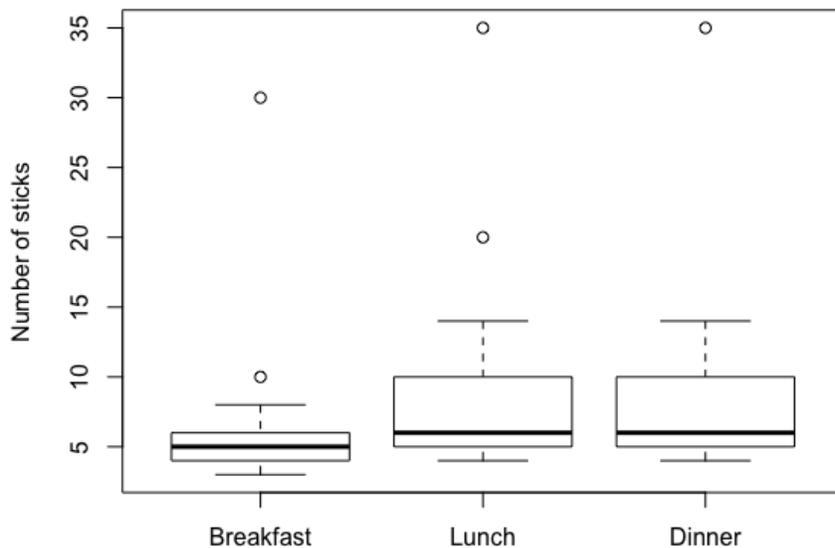


Figure 10a: Number of sticks used per meal

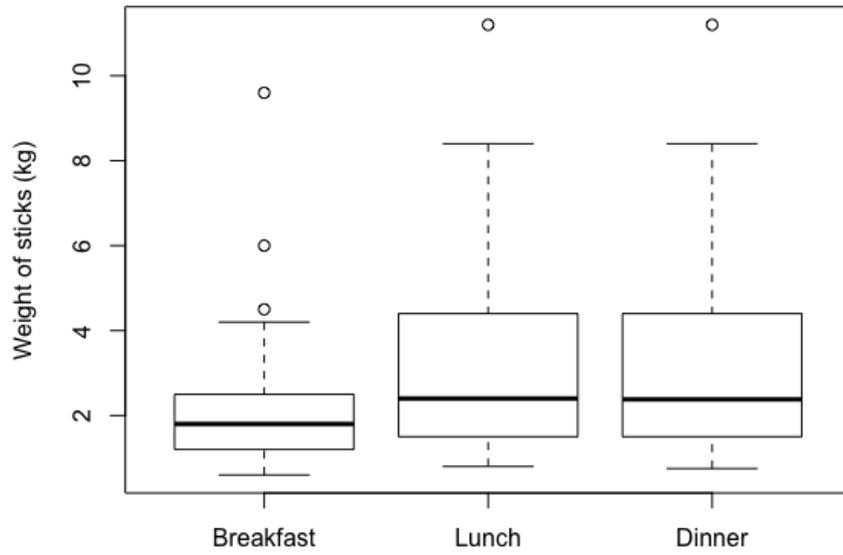


Figure 10b: Weight of fuelwood used per meal

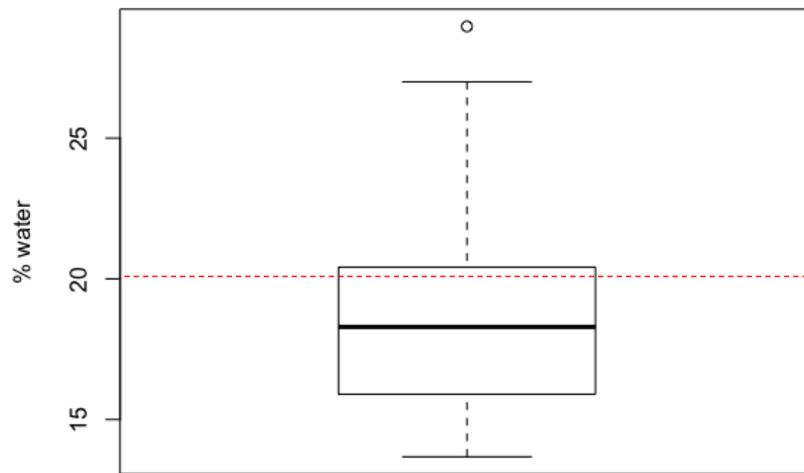


Figure 11: Moisture content of fuelwood (with optimal wood moisture content in red)

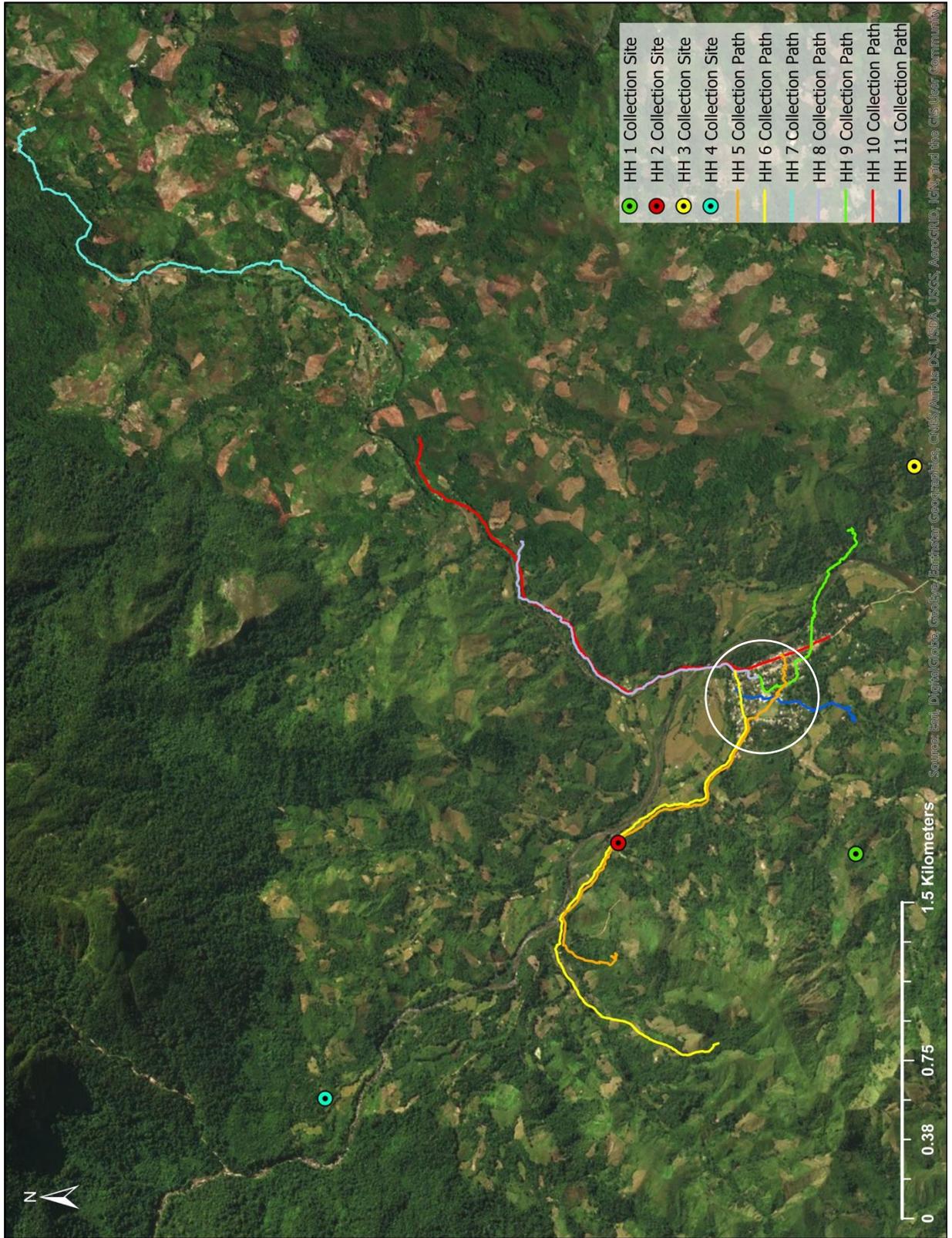


Figure 12: Fuelwood collection paths and points based on GPS recordings (village boundary represented by white circle)

In most households, adult males perform the task of fuelwood collection. These individuals collect fuelwood about 3 times per week on average, and all individuals surveyed cut timber on personally owned or family-owned land. About a third of all wood collectors reported having to travel further for wood compared to last year, although these numbers may be unusually low as many participants reported having more trees available for harvest after Cyclone Enawo ravaged the region in March of 2017. Additionally, respondents reported regularly collecting firewood from multiple locations. On average, each collector visited two separate sites to collect fuelwood, and these locations were near their vanilla, fruit, or rice fields. From our GPS data presented in Figure 12, we found that participants travelled nearly in every direction to collect fuelwood, and the average distance from the center of town to their collection site was 3.31 kilometers (n=11). The shortest trip was 0.93 km while the longest trip was about 8 km NW of the village. All but one of the 21 respondents reported that these were the same collection locations they visited last year. There was a weak, insignificant, negative correlation of -0.19 ($t = -0.85$) between number of collection sites and collection frequency. This suggests that greater access to fuelwood supply may reduce the number of trips a collector must take each week.

5.4 Respiratory and cardiovascular health

Our data reveal a slight, insignificant correlation of 0.36 ($t = 1.68$) between blood pressure and CO exposure (see Figure 13). Village-wide data from 2017 indicate that 42% of participants had hypertension (with another 16% pre-hypertensive), and spirometry measurements estimate that 1 in 5 participants had impaired lung function (lung capacity below the LLN). A household survey from 2016 also revealed that 79% of respondents reported at least one member of their family having a cough or runny nose within two weeks before the survey was administered. Multi-

year village health data also reveal that women are more likely to be hypertensive than men for all age groups.

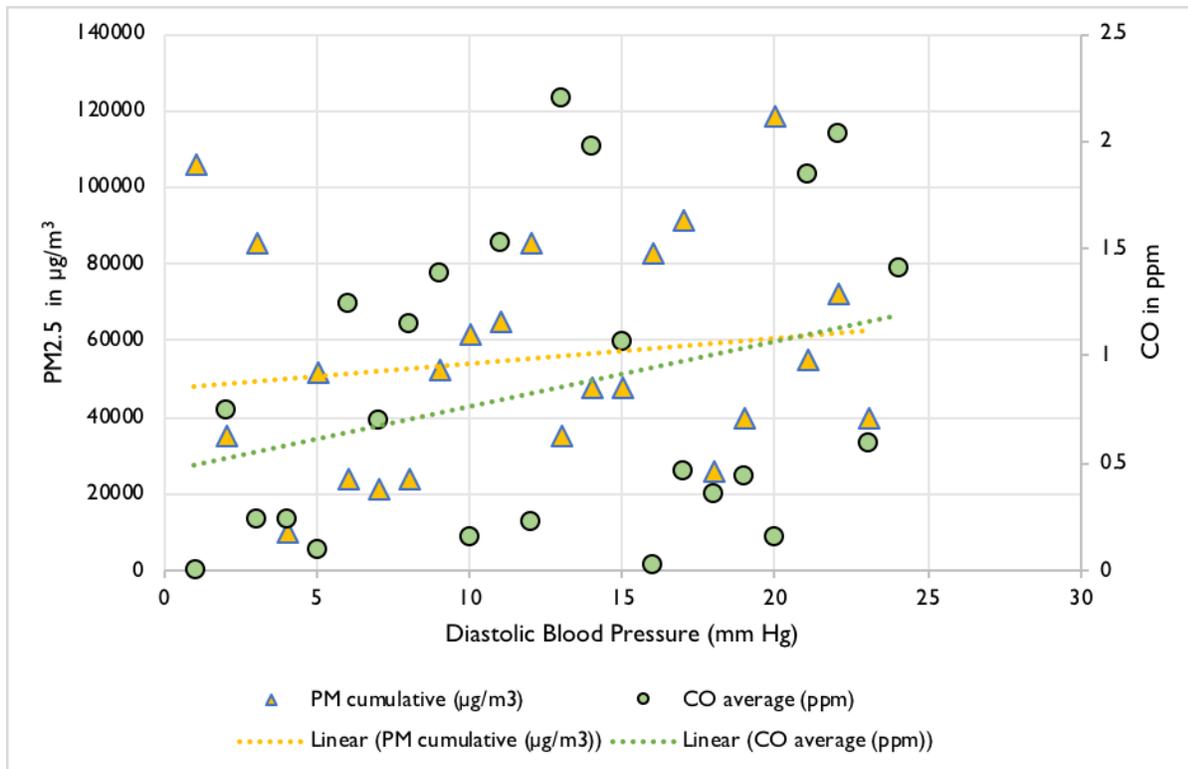


Figure 13: Relationship between exposure and diastolic blood pressure

5.5 Cookstove efficiency data

Results for fuel consumption during the cold and hot start phases of the test for the wood-burning stoves are summarized in Figure 14. The mean fuel consumption for both the Red-Multi stove and ADES Wood stove were statistically significantly lower than the Tripod stove. Figure 15 indicates the average time to boil during the cold and hot start phases of the tests. Average boiling times are summarized in Figure 15. On average, the ADES takes about 1.5 times longer to boil water for cold starts, but boils water about a minute faster than the tripod during the hot starts. On average, the Red-Multi stove takes about 1.4 and 1.3 times longer than the Tripod for cold and hot start tests, respectively. It is important to note that there are no hot start tests for the Tripod,

because there is no stove to pre-heat. Thermal efficiencies of wood stoves are summarized in Figure 18a. Prices of these three stoves are summarized below:

- **Tripod Stove:** 3,000 Ariary (\$0.94)
- **Red Multi Stove:** 10,000 Ariary (\$3.12)
- **ADES Wood Stove (unsubsidized):** ~60,000 Ariary (\$18.72)

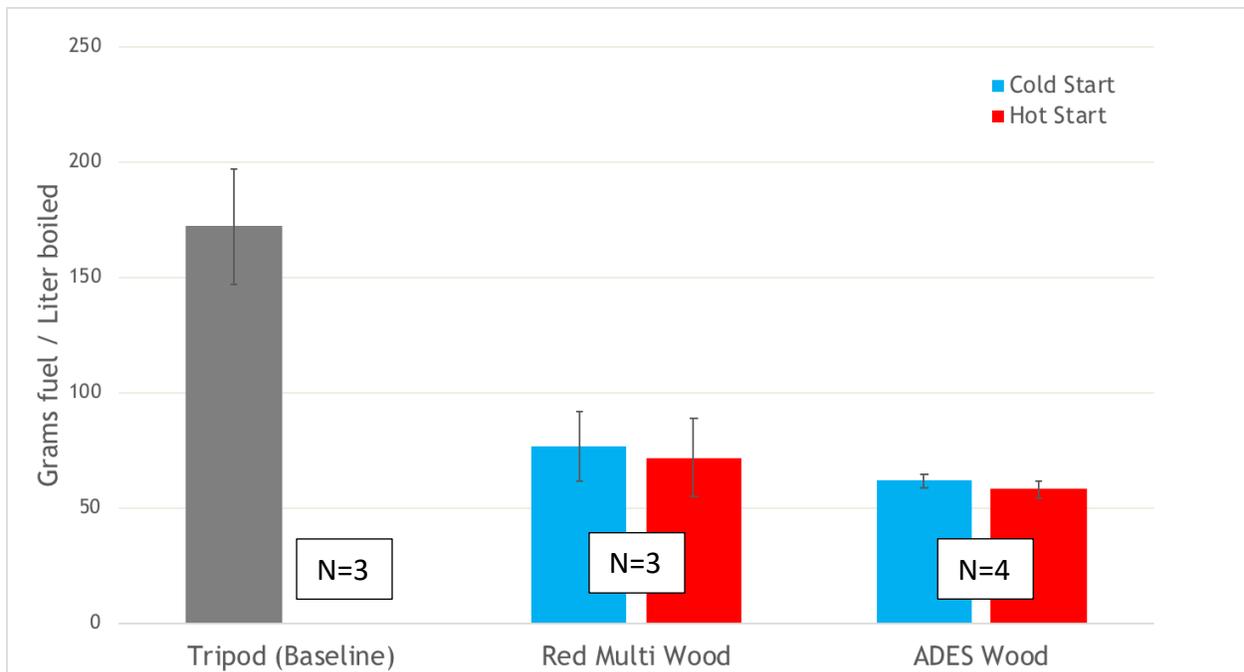


Figure 9: Specific fuel consumption for improved wood stoves

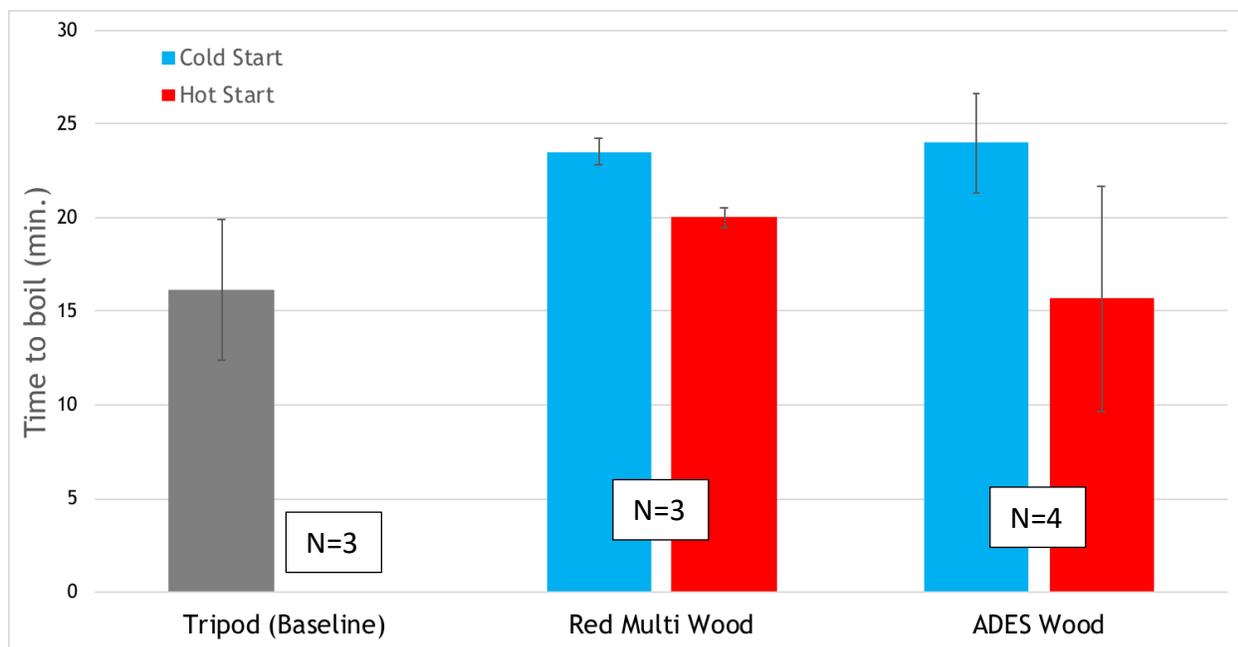


Figure 10: Boiling times for improved wood stoves

All charcoal stoves performed somewhat similarly in terms of fuel use, consuming an average 36.3 grams of charcoal for each liter of water boiled for cold start phases. The distributions for cold and hot start fuel consumption are listed in Figure 16. While fuel consumption varied only slightly, boiling times for charcoal stoves varied significantly, with the fastest stove averaging 12 minutes and the slowest averaging 24 minutes for hot start. Distributions of boiling times for both cold and hot start tests are summarized in Figure 17. Thermal efficiencies of charcoal stoves are summarized in Figure 18b. Prices for these five stoves are included below:

- **Square Clay Stove:** 10,000 Ariary (\$3.12)
- **Basic Metal Stove:** 4,000 (\$1.25)
- **Red-Multi Stove:** 10,000 Ariary (\$3.12)
- **ADES Charcoal Stove (unsubsidized):** 60,000 Ariary (\$18.72)
- **Blue Stove:** 10,000 Ariary (\$3.12)

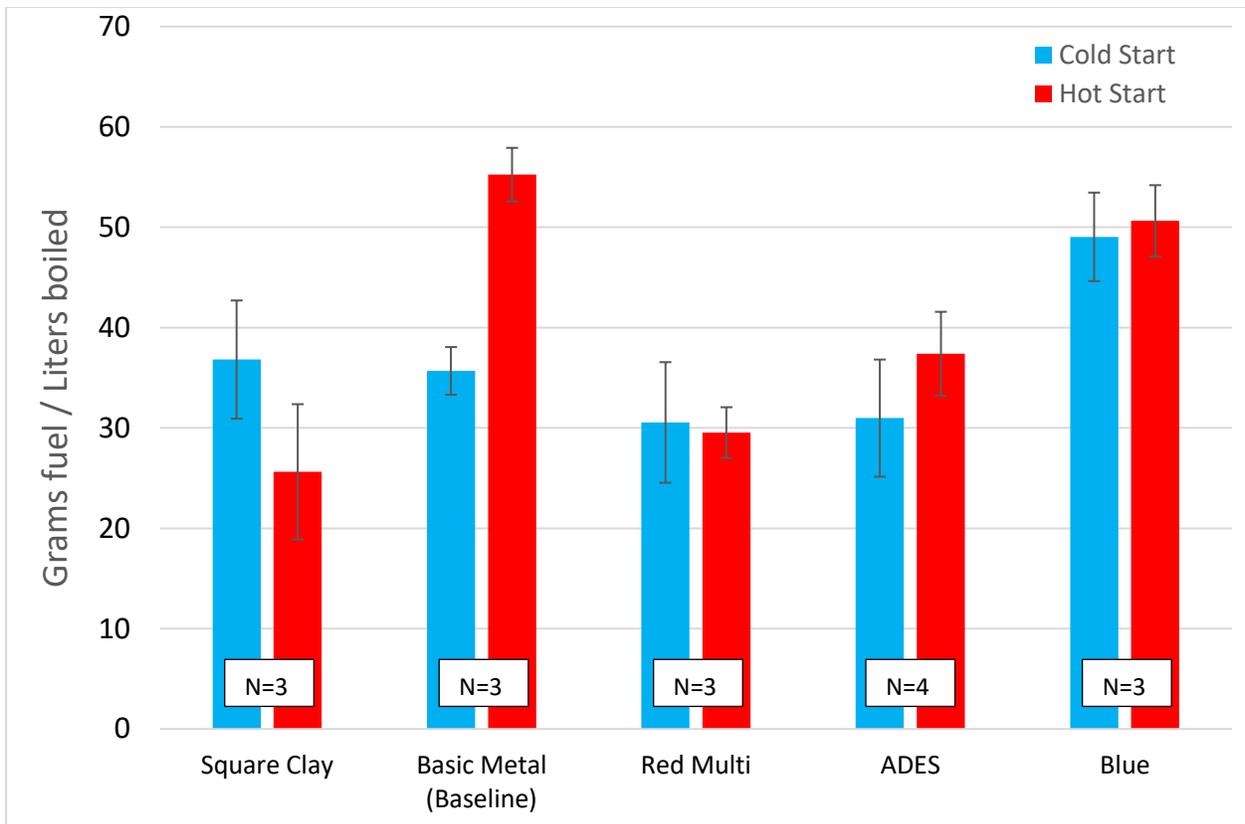


Figure 11: Specific fuel consumption for improved charcoal stoves

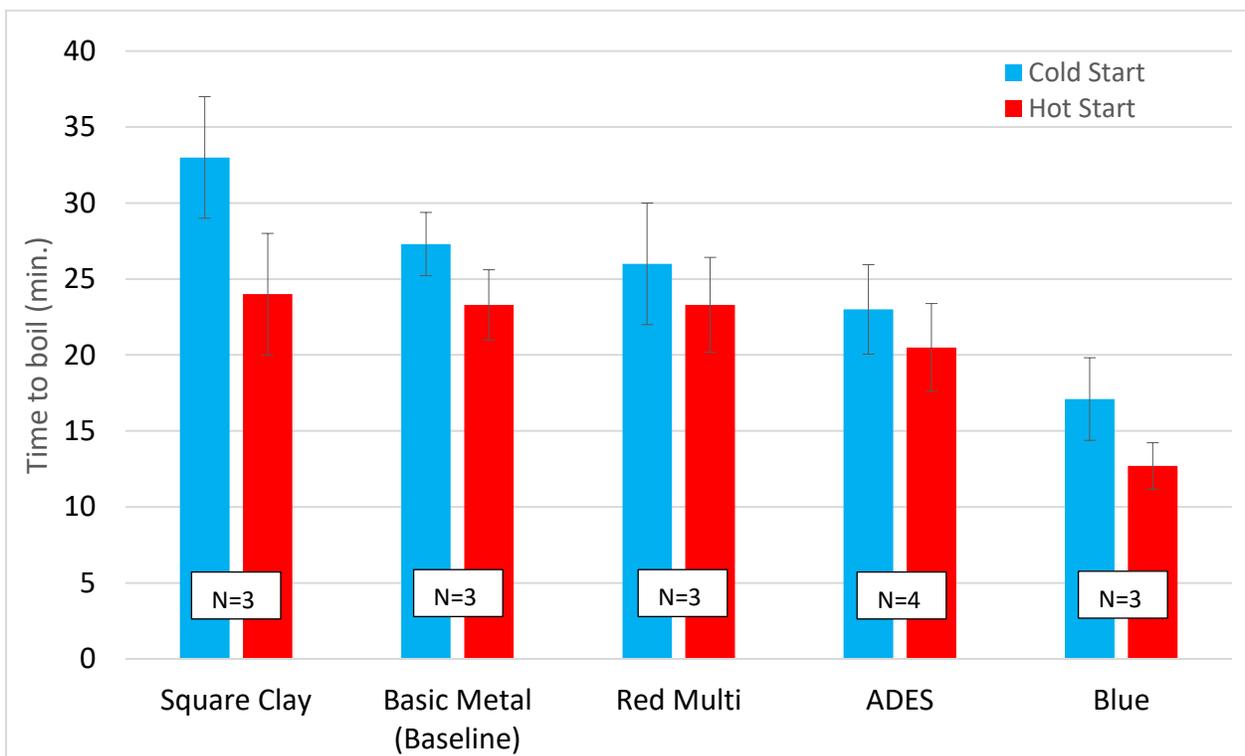


Figure 12: Boiling times for improved charcoal stoves

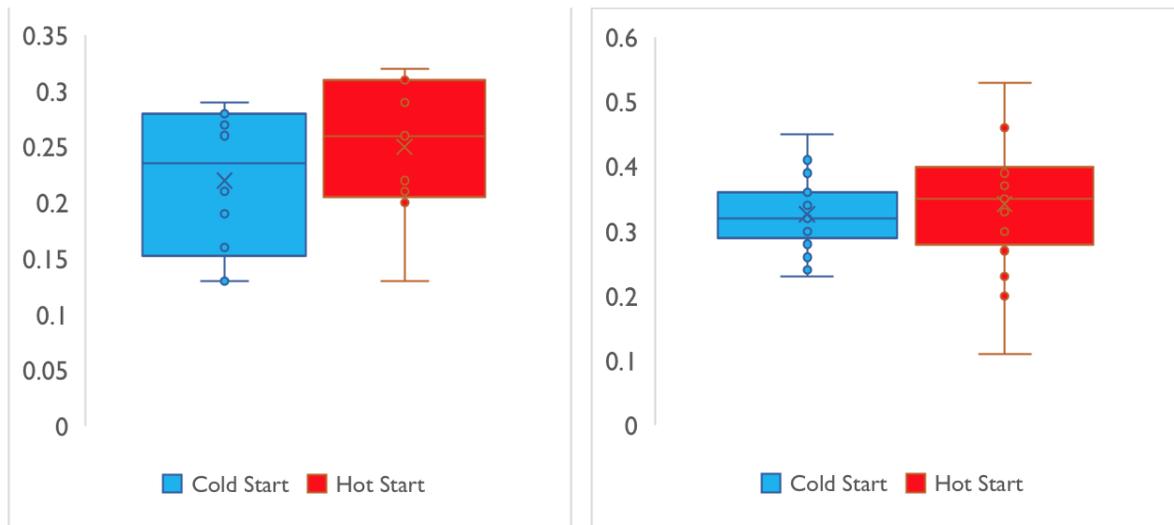


Figure 18a: Thermal efficiencies for wood stoves Figure 18b: Thermal efficiencies for charcoal stoves

5.6 Cookstove producer interview data

There are few improved biomass cookstoves manufactured and sold in the SAVA region, and most of the existing businesses are small-scale and employ no additional workers. A survey of 18 of these local manufacturers reveals that 7 individuals sell door-to-door or on an as-ordered basis, and 6 sell in larger, town markets. In addition to being extremely localized, the improved cookstove market is virtually exclusive to charcoal-burning stoves, with only 2 out of 18 individuals actively selling wood-burning models. Of the 11 individuals who did not produce on an as-ordered basis, the average monthly output was around 103 stoves per month (with a standard deviation of ~93).

Among the producers surveyed, stove manufacturing materials are relatively uniform. These materials include clay, concrete, sheet metal, sand, and/or dung. Despite this uniformity, there is a considerable array of diversity in stove design and innovation. While there are a few similar models, stoves were made in all shapes and sizes (with many sellers offering multiple sizes

of the same model to accommodate different cooking capacities). Design innovations were made, including improved drafting for the combustion chamber, removable ash trays, fuel storage drawers, pot skirts, and features to facilitate portability and durability. Figure 19 displays a few of these unique models. The average market price of these stoves was about 13,000 Ariary (or \$4.30 USD) and average cost of production was 2,500 Ariary (or \$0.83 USD).



Figure 19: Improved Cookstoves in the SAVA

VI. Discussion

6.1 Household air pollution and health outcomes

The in-kitchen air quality measurements from 2016 revealed an average 24-hour concentration of PM_{2.5} of 1.91 mg/m³. The WHO guideline for PM_{2.5} over this period is 0.010 mg/m³, at which point cardiopulmonary and lung cancer mortality have shown to increase with more than 95% confidence (World Health Organization 2006). Dasgupta et al. (2015) find an average 24-hour PM_{2.5} concentration of 0.776 mg/m³ in Malagasy kitchens in Central Madagascar. Dasgupta also found an average CO concentration as high as 28 ppm, whereas our study found a mean CO concentration of 19.1 ppm (Dasgupta, Martin, and Samad 2015). The WHO standard for indoor CO is 6.1 ppm, and an average of over 3 times higher poses serious health hazards for family members spending extended time in kitchens (Penney et al. 2010). CO is a better proxy for air quality because combustion is the only source of the air pollutant, whereas particulate matter

can come from a variety of sources (such as stirred up dust or ash).

While in-kitchen measures are important for understanding and quantifying indoor air quality in households, they do not give us an accurate picture of what individuals are exposed to on a daily basis. While head cooks spend a significant time in the kitchen, there is still little understanding of the behavioral changes people make to avoid or reduce their exposure to HAP. The exposure data from 2017 reveal that actual exposure is much less than what is being recorded in kitchens (assuming 2016 concentrations also represent HAP in 2017). Personal exposure data reveal significantly lower exposure to CO, suggesting that women are spending less time directly in front of the cooking fire. Unlike PM, CO disperses rather quickly, especially in more ventilated environments. PM exposure was also significantly less than indoor measurements, also suggesting that head cooks are limiting time spent in front of the cooking fires or in the kitchen environment. However, 78% of participants still had exposure levels above the WHO safe standard of $25 \mu\text{g}/\text{m}^3$.

All participants in our sample (except for one household cooking with charcoal) cooked with a Tripod cookstove. Even individuals who cooked in outdoor structures (with only a roof and no walls) experienced high levels of exposure to PM. While interventions to improve ventilation in Malagasy kitchens may help reduce HAP and exposure to these pollutants, the health effects of these interventions are likely to be minimal and may worsen ambient air pollution. Assuming that our estimated daily average PM exposure ($39.6 \mu\text{g}/\text{m}^3$) represents a typical day throughout the year, the annual $\text{PM}_{2.5}$ exposure for head cooks in Mandena is roughly $14,454 \mu\text{g}/\text{m}^3$. Hadley et al. (2018) demonstrates on the exposure-response curve in Figure 20 that risk of mortality from ischemic heart disease and stroke does not begin to decline until $100 \mu\text{g}/\text{m}^3$ annually (Hadley, Baumgartner, and Vedanthan 2018).

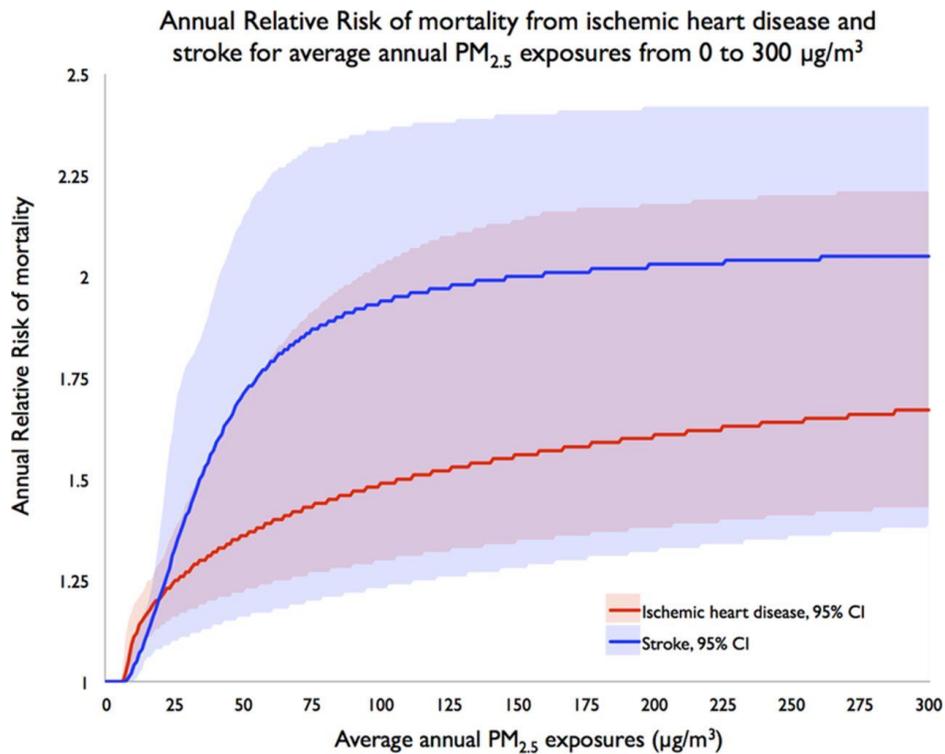


Figure 20: Annual Relative Risk of mortality from ischemic heart disease and stroke for average annual PM_{2.5} exposures from 0 to 300 µg/m³

These data raise the question of what can be done to reduce HAP and exposure to these pollutants. Dasgupta et al. (2015) find that improved wood stoves were successful at reducing CO concentrations, while results for PM were inconclusive. The size of a kitchen (in square feet) was also found to significantly impact CO concentrations. This suggests a multi-pronged approach to reducing HAP in regions where modern fuel penetration is nonexistent or unlikely in the near future may be impactful. Households should purchase improved stove technologies, build larger kitchens, and construct chimneys or other ventilation structures to reduce HAP from solid fuel combustion. Although the following recommendation is not based on our study, encouraging households to cook outside may also reduce exposure. Focus group discussions in Mandena revealed that many head cooks preferred to cook indoors, however, to avoid wind and rain, secure their cooking utensils from theft, and prevent food from being poisoned.

Improved cookstoves have the ability to improve indoor air quality and deliver meaningful health outcomes. Although the exposure-response curve demonstrated in Figure 20 sets an aggressive standard for HAP reduction, the WHO’s guidelines take a “less is better” approach. While improved cookstoves might not be the solution to eliminating cardiopulmonary and respiratory illness in the developing world, HAP reductions from improved stoves can lead to significant and tangible health outcomes. For example, some argue that improved cookstoves reduce acute lower respiratory infections (ALRI) in children under 5 and chronic obstructive pulmonary disease (COPD) in adults over the age of 20 (see Figure 21, drawn from Mehta & Shahpar, 2004). While improved cookstoves do not deliver the same magnitude of health benefits as clean-fuel cookstoves, they are often considerably cheaper to manufacture, and thus more cost-effective options for interventions seeking to improve energy access and reduce instances of ALRI and COPD (Mehta and Shahpar 2004).

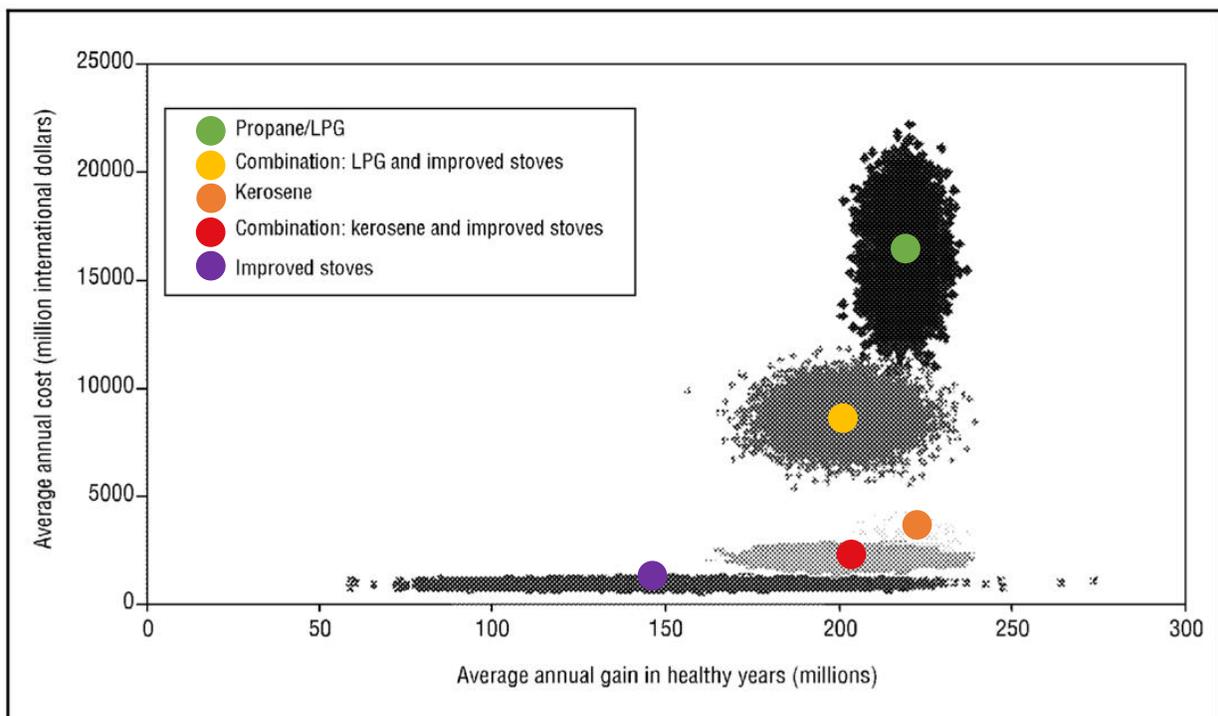


Figure 21: Cost–benefit representation of ICS interventions, colorized to add clarity

Others have examined the effects of an improved cookstove on blood pressure in rural Bolivia (Alexander et al. (2015)). They compare the blood pressures of 28 head cooks before the intervention and one year after to find a statistically significant reduction in systolic blood pressure from 114.5 ± 13.0 mm Hg to 109.0 ± 10.4 mm Hg. The study also corroborates our findings by identifying a relationship between exposure to $PM_{2.5}$ and blood pressure. The intervention resulted in an 83% reduction in kitchen $PM_{2.5}$ concentrations. It is important to note that post-intervention PM concentrations were still well above WHO guidelines, with an average 24-hour concentration of $135 \mu\text{g}/\text{m}^3$ (compared to the WHO standard of $10 \mu\text{g}/\text{m}^3$). Their findings suggest that improved cookstoves in Mandena may have the potential to meaningfully reduce indoor PM concentrations, currently averaging $1,910 \mu\text{g}/\text{m}^3$ per day.

6.2 Fuel consumption and collection behaviors

Compared to other Sub-Saharan African countries, Madagascar is unique in that men more often collect fuelwood than women (World Bank Group, 2014). This trend was demonstrated in Mandena, where all but two households out of 37 had men collecting. This makes improved cookstove initiatives potentially more feasible, as the burden of traditional cooking is more evenly distributed between men and women. While men are more often in charge of household financial decisions, an ICS intervention would offer fuel savings benefits for men (via fewer collection trips) and HAP reductions for women (meaning better health outcomes). It is important to note that while men were largely responsible for fuelwood collection, in our focus groups, women expressed concern about the loss of biomass resources around Mandena, and future access to fuelwood. Brooks et al. (2016) found significant reductions in fuel consumption, fuel collection times, and cooking times in Northern India (Brooks et al. 2016).

Our GPS data reveal that individuals walk far to collect fuelwood, with two individuals collecting right on the edge of the national park boundary. Fuelwood collection often occurred near family-owned agricultural fields, and collectors reported cutting and carrying fuelwood back to the village at the end of the working day. This is important for understanding the level of burden and time spent collecting fuelwood. Individuals were rarely making separate trips only to collect fuelwood. An improved cookstove that consumed three times less fuelwood would not only mean fewer fuel collection trips, but a reduction in biomass removal from land—and a greater ability for the land to regrow to support future resource extraction. Furthermore, if individuals are able to more efficiently extract fuelwood from their own land, there is a lower likelihood that collectors will have to venture into the national park for wood or walk greater distances and disturb more pristine forest habitats. One study in Indonesia supports the idea that greater wealth and access to alternative energy sources may mitigate local deforestation (Pattanayak, Sills, and Kramer 2004). Our data suggest that the greater number of collection sites a family had access to, the fewer collection trips they made each week. This may suggest that poorer families (those with fewer or smaller plots of land) have greater difficulty finding fuelwood and have to make trips more frequently to procure it.

The lack of correlation between family size and fuelwood consumption suggests that more mouths to feed does not necessarily mean more fuelwood. We observed that most families used the same size pot, so it is possible that smaller families encountered greater heat loss due to inappropriate pot size for the amount of food they were cooking. This is further supported by the lack of relationship between family size and number of fuelwood collection trips. Further research is necessary to explore the relationship between family size and fuel consumption, since the data suggest there are other factors not being considered that contribute to this phenomenon. It is

important to note that our data set may be too small to draw larger conclusions, but no trend between family size and fuel consumption was observed in our 2016 sample either. This finding contradicts other studies, which have identified positive correlations between family size and fuelwood consumption (St. Clair 2016).

73% of households (n=37) were using well-seasoned wood (wood with a moisture content below 20%) and 64% of respondents reported drying their fuelwood outside and above the fire before use. The other 36% reported only drying their fuelwood outside before use. Just as there was no relationship between emissions and moisture content, there was also no relationship between seasoning procedure and moisture content. However, we identified a relationship between seasoning procedure and emissions, with wood that was dried over the fire in addition to outside producing less CO and PM emissions. Why we see a relationship between emissions and seasoning procedure but not moisture content is unclear, and further exploration of this issue is necessary to understand this phenomenon.

54% of households (n=37) were aware of certain species of wood that produced less smoke or dried faster, and often preferred to use those types of wood when available. This information may be useful for an NGO like the Duke Lemur Center working on community tree farms dedicated for sustainable resource extraction. Further research may also be useful for corroborating this survey data and determining species of wood that may contribute to HAP reductions. Additionally, 12 families reported using a kerosene lamp every night, but we did not witness elevated PM or CO levels past dinner time in a majority of our participants wearing exposure monitors. One possible explanation for this is that participants changed their behavior when they were being monitored. Further research is necessary to understand how kerosene lamps contribute to HAP and how a transition to pico solar products (like solar lanterns) may mitigate this.

6.3 Improved cookstove efficiencies

Both the ADES Wood and Red-Multi stove offer a sizable fuel savings potential compared to the Tripod stove. Furthermore, these stoves do not appear to require major sacrifices in boiling/cooking time. These stoves are also safer to operate, as the fire is contained within the combustion chamber, minimizing the risk of burns and injury from the open fire of the Tripod. While fuel consumption, cooking time, and safety are just a few factors that determine successful uptake of an improved stove, they are three of the most important, as emphasized by participants in our focus group discussions. During our team's time in Mandena, we met four individuals who owned an ADES improved wood stove and were able to informally ask them about the stove and how they liked using it. Only one individual actively used the stove, with the others reporting dissatisfaction with the fuel size requirements or surface area of the stovetop.

Water Boiling Test results were relatively consistent with those of other studies, despite the differences in protocol. Thermal efficiencies of most stoves were within the 15-30% range, although firepower of our stoves were several kW less than other studies of improved wood-burning stoves. Figure 22 below highlights the findings from other studies that have performed water boiling tests on locally-manufactured improved wood stoves (Jagger et al. 2017). It is important to note that while our study did not perform emissions testing of improved stoves, other studies have validated the relationship between fuel savings and lower emissions. Visser (2005) validates the reliability of water boiling tests to predict in-field fuel and emissions reductions (Visser 2005). Regardless, further research is still necessary to confirm that improved stoves do deliver on these reductions in the contexts where they are employed. In addition to the Water Boiling Tests, the GACC has also developed Kitchen Performance Tests which assess the efficiencies and emissions of improved or clean stoves during household use.

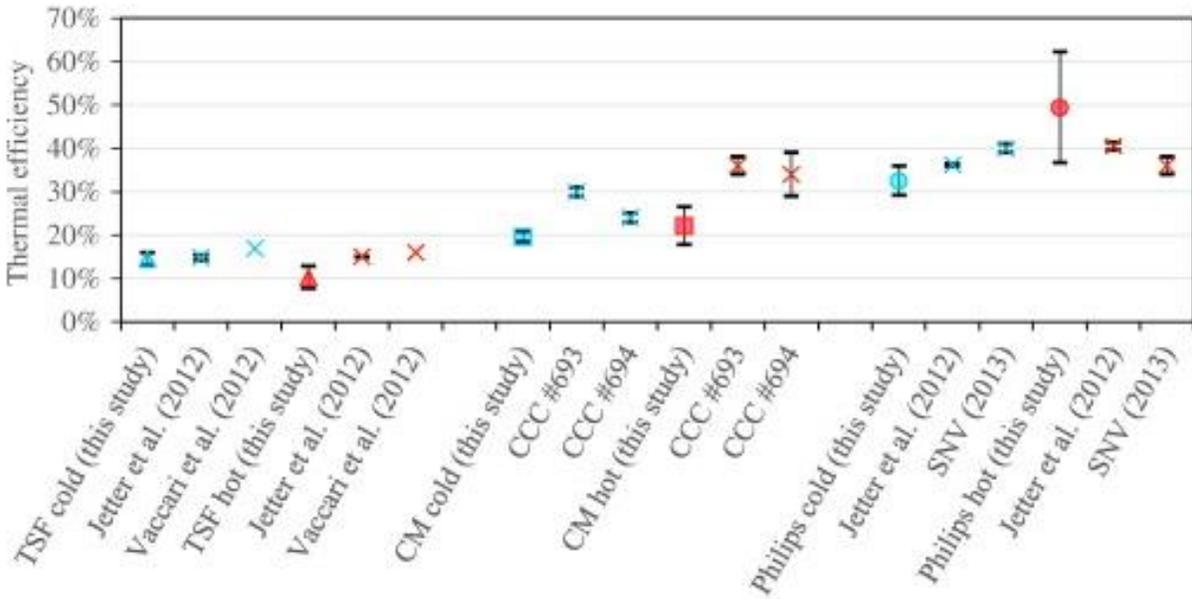


Figure 22: Thermal efficiencies of ICS across studies (Jagger et al. 2017)

6.4 Improved cookstove landscape

With the average Malagasy earning under \$1/day and under current market pricing, adoption of ADES stoves would be low and not deliver to the last mile household (WorldData 2016). Financing and subsidies would help make the ADES and other stoves like it more accessible but do not guarantee long-term program sustainability. Locally-manufactured stoves like the Red Multi stove offer the potential for fuel savings and emissions reductions at a fraction of the cost, and further exploration of these stoves is necessary. These stoves are not more widely implemented because the market is dominated solely by small-scale producers scattered around the region. ICS penetration is also weak, with only three individuals owning an improved wood stove in our sample of 37 households in Mandena. Focus group participants highlighted their desire for more fuel efficient stoves or clean fuels such as LPG and revealed a willingness to pay of about 10,000 Ariary for an improved stove. As highlighted by Atteridge and Weitz (2017),

market demand for improved cookstoves will continue to increase, and artisanal manufacturers will likely be replaced by commercial production. NGOs and local governments are best situated to facilitate ICS market expansion through scalability, but should be careful to ensure successful adoption and not neglect the last mile household (Atteridge and Weitz 2017).

VII. Conclusions

This study provides a brief overview of the many interrelated impacts of traditional cooking practices in rural Madagascar. Current cooking practices place stiff demands on the local environment, which has a diminishing ability to meet those demands over time. Traditional cooking also poses serious health risks for women and children spending time in kitchens and requires substantial time investments for both head cooks and wood collectors. Improved wood stoves may add time to cooking, but have the potential to considerably reduce consumption of wood fuels, and plausibly contribute to HAP reductions. While improved charcoal stoves do not deliver significant fuel savings, they may reduce cooking time. For the Duke Lemur Center and other NGOs operating in the region, there is an opportunity to promote education/awareness campaigns of the dangers of indoor air pollution and the benefits of using improved or clean cooking methods. There is also the opportunity to promote sustainable charcoal production, initiate tree re-planting, set improved cookstove design standards, and invest in cleaner burning fuels like liquid petroleum gas (LPG) while simultaneously promoting improved biomass stoves. It is crucial for these organizations to work not only with each other, but also with health officials, community members, and international researchers to reduce the adverse impacts of traditional cooking and energy poverty.

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