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Addressing Household Air Pollution

A Case Study in Rural Madagascar

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Abstract

Household air pollution is the second leading cause of disease in Madagascar, where more than 99 percent of households rely on solid biomass, such as charcoal, wood, and crop waste, as the main cooking fuel. Only a limited number of studies have looked at the emissions and health consequences of cook stoves in Africa. This paper summarizes an initiative to monitor household air pollution in two towns in Madagascar, with a stratified sample of 154 and 184 households. Concentrations of fine particulate matter and carbon monoxide in each kitchen were monitored three times using UCB Particle Monitors and GasBadge Pro Single Gas Monitors. The average concentrations of both pollutants significantly exceeded World Health Organization guidelines for indoor exposure. A fixed-effect panel regression analysis was conducted to investigate the effects of various factors, including fuel (charcoal, wood, and ethanol), stove (traditional and improved ethanol), kitchen size, ventilation, building materials, and ambient environment. Judging by its effect on fine particulate matter and carbon monoxide, ethanol is significantly cleaner than biomass fuels and, for both pollutants, a larger kitchen significantly improves the quality of household air. Compared with traditional charcoal stoves, improved charcoal stoves were found to have no significant impact on air quality, but the improved wood stove with a chimney was effective in reducing concentrations of carbon monoxide in the kitchen, as was ventilation.

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Addressing Household Air Pollution: A Case Study in Rural Madagascar

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1. Introduction

More than half the world's population still cooks with wood, dung, coal or agricultural residues on simple stoves or open fires. Dependence on solid-fuel for cooking leads to high exposures to household smoke, particularly where ventilation is limited, and is associated with significant health risks, particularly for women and children.[4] In analyzing the risks associated with Household Air Pollution (HAP), the Global Burden of Disease Study 2010[5] (GBD 2010) considered its contribution to the following health outcomes: lower respiratory infections; trachea, bronchus, and lung cancers; ischemic heart disease (IHD); cerebrovascular disease; chronic obstructive pulmonary disease (COPD); and cataracts.[6]

GBD 2010 determined that the three leading risk factors for the global burden of disease were high blood pressure (7.0% of global Disability-Adjusted Life Years - DALYs[7]), tobacco smoking including second-hand smoke (6.3%), and HAP from solid fuels (4.3%). In most of Sub-Saharan Africa (SSA) childhood underweight, HAP, and non-exclusive/discontinued breastfeeding were the leading risk factors in 2010.[8] In Asia and Sub-Saharan Africa, where a large share of ambient particulate matter originates from solid fuel use, exposure to ambient pollution and HAP are related, and cleaner fuels would bring benefits both for people who currently use solid fuels, as well as for their neighbors who do not.

While the transition to cleaner sources of domestic energy will ultimately reduce the disease burden associated with this risk factor, during the transition good ventilation, improved stoves, and public information leading to behavior change can significantly reduce exposure to household smoke. While reduction of HAP has been recognized as an important development objective, the design of HAP reduction strategies has been hindered by lack of information about actual air quality in households and health benefits of potential mitigation measures. Data on HAP have been scarce because monitoring in households has been difficult and costly. While many studies have measured gaseous and sometimes particulate emissions from standardized or laboratory tests, it is not clear whether these emissions are representative of cook-stoves in use.[9]

[4] WHO, 2009
[5] The Global Burden of Disease Study 2010 is a collaborative project of nearly 500 researchers in 50 countries led by the Institute for Health Metrics and Evaluation (IHME) at the University of Washington.
[6] Lim et al., 2012
[7] Disability-adjusted life years (DALYs) quantify both premature mortality and disability within a population.
[8] Ibid.
[9] Roden et al., 2009

In particular, there have been a limited number of studies of the emissions and health consequences of cook-stoves in use in Africa. In 2000, a study of health effects in the Kiambu District of Kenya demonstrated statistically significant reductions in the prevalence of Acute Respiratory Infections (ARI) and conjunctivitis among women and children under five who used improved stoves compared with those who did not.[10] The study found that the probability of children under five having ARI in households with traditional three-stone fires was 2.6 times greater than for households with improved stoves, and was 2.8 times greater for women aged between 15 and 60. Similarly, the chance of contracting conjunctivitis was 3.3 times higher for children, and 3 times higher for women, in households using three-stone fires rather than improved stoves. More recent evidence from Africa is provided by measurements undertaken in Ghana to test the *Gyapa* stove compared to a traditional stove, which showed a reduction in kitchen concentrations of fine particulates of 52%, as well as measurements in Ethiopia to test the *CleanCook* ethanol stove, which showed a reduction of 84% in average kitchen concentrations of $PM_{2.5}$.[11]

Using new air monitoring data, this paper presents a case study conducted in Madagascar and provides evidence on fine particles whose diameter is less than 2.5 microns ($PM_{2.5}$) and carbon monoxide (CO) concentrations in rural households of Madagascar. Attempts have been made to analyze sources of variation in HAP: fuel type, stove type and structural ventilation characteristics of houses, to inform decision-making regarding the effectiveness of alternate HAP mitigation measures. Given that fuelwood is the primary source of household energy in Madagascar and that consumption is expected to increase with population growth, it is anticipated that national production of wood will no longer be able to meet national demand in a sustainable manner. It is in this context that the Ministry of Environment has proposed the goal of replacing 30% of fuelwood for cooking with ethanol, and that this study considered ethanol as a potential HAP mitigation measure.

The remainder of the paper is organized as follows. Section 2 introduces the household air quality problem in Madagascar. Section 3 discusses determinants of HAP and our stratified sampling strategy. Summary data on the factors affecting HAP are described in Section 4.

[10] E.M. Wafula, M. Kinyanjui, L. Nyabola and E.D Tenambergen, Department of Paediatrics and Child Health, College of Health Sciences at the University of Nairobi, January 2000
[11] Pennise et al., 2009

Section 5 presents the HAP monitoring methods and descriptive statistics, and an econometric analysis of sources of variation in HAP is documented in Section 6. Section 7 briefly concludes.

2. Household Air Pollution in Madagascar

The 2010 Living Standards Measurement Survey (LSMS)[12] demonstrated that solid biomass remains the principal type of fuel used for cooking by more than 99% of households in Madagascar. Gathered fuel-wood is the primary source of cooking fuel for more than 77% of households, followed by charcoal (17.1%) and purchased fuel-wood (4.5%). In rural areas almost 87% of households continue to rely on gathered fuel-wood for cooking, compared with 45% in urban areas where more than 47% of households use charcoal as their principal cooking fuel, against 8.7% of rural households. Only 1.8% of urban households can afford clean fuels (LPG, electricity or kerosene) as their principal cooking fuel, and the percentage is even lower in rural areas (0.3%).

Among the health disorders associated with HAP, three figure among the top 25 causes of Years of Life Lost[13] (YLLs) due to premature mortality in Madagascar estimated by GBD 2010. Contributing an estimated 9.2% of YLLs, lower respiratory infections rank as the equal second cause of YLLs along with diarrheal diseases, after top-ranked malaria. IHD and COPD rank ninth and twenty-third respectively, contributing 3.0% and 0.8% of the YLLs. In 2007 the WHO estimated that more than 10,000 deaths from acute lower respiratory infections in children under five in Madagascar are attributable to solid fuel use, as well as an additional 1,400 deaths from chronic bronchitis predominantly in women over 30 years of age.[14] The top three causes of DALYs[15] in Madagascar in 2010 were malaria, diarrheal disease and lower respiratory infections.[16] While a range of risk factors may contribute to each of these disorders, HAP is the second leading risk factor in the burden of disease for Madagascar, accounting for some 6.7% of

[12] Enquête Périodique auprès des Ménage (EPM) 2010, Institut National de la Statistique, Direction des Statistiques des Ménages.
[13] Years of Life Lost (YLL) quantify premature mortality by weighting younger deaths more than older deaths (GBD 2010).
[14] Indoor Air Pollution: National Burden of Disease Estimates, WHO 2007
[15] Disability-Adjusted Life Years combine YLLs with Years Lived with Disability (YLDs) (GBD 2010).
[16] GBD 2010

the burden of disease, behind the top-ranked factor of childhood underweight (which accounts for about 8.8% of the burden of disease).[17]

Against this background of strong indications of a significant socio-economic problem, but contradictory and very limited availability of HAP data, the subsequent sections sketch out the survey and HAP monitoring conducted in Madagascar and the econometric findings on the effectiveness of various mitigation measures.

3. Household Air Pollution Factors and Sampling in Madagascar

Previous studies on HAP have identified several potential determinants: fuel type, stove type, cooking locations, structural characteristics of houses/kitchen and household ventilation practices, such as opening of windows and doors.[18] The level of emissions from fuel use depends on the efficiency of combustion and heat transfer, and hence on stove type. Given the level of emissions from fuel and stove use, the extent and duration of pollutant concentration in a space depends on the location of a kitchen (inside the house/within-dwelling; in a space attached to the house/"attached" kitchen; in a space enclosed by walls, a roof at a little distance from the house/"detached" kitchen and in the open air); the extent of ventilation: the porous nature of materials used to construct the roof and walls of the kitchen, size and placement of doors and windows.[19] All of these factors may be important in Malagasy households, which exhibit significant diversity in cooking fuels, stove types, cooking locations, and quality of ventilation.

In order to ensure cost-effective coverage of the key determinants of HAP concentrations, a stratified sampling technique was followed in this study to select households for indoor air monitoring in rural Madagascar. Stratification was based on region, fuel and stove type. Households were selected from the towns of Ambositra[20], located in the central highland,

[17] Ibid.

[18] Dasgupta et al, 2009, Dasgupta et al, 2006a, Dasgupta et al, 2006b, World Bank, 2002, Brauer and Saxena, 2002, Moschandreas et al, 2002, Freeman and Sanez de Tajeda, 2002

[19] Ambient air quality is also an important determinant of HAP. A quicker dispersion of pollutants is expected during strong windy conditions. Suspension time of fine particulates in air is reduced when it rains, and also in summer when ground temperature is generally higher.

[20] Ambositra is located at an altitude of 1,295m from sea-level; experiences a lower rainfall and cooler temperature but has a distinct wet (November-March) and dry (April-October) seasons. It has a population of 44,726 (August 2008 estimate). Most of the houses are made of brick and wood and the kitchens are typically located inside the house. Cooking with charcoal and traditional charcoal stoves is a common practice in Ambositra.

approximately 260 km south of the capital city of Antananarivo, and Vatomandry[21], located on the central east coast of Madagascar. The sampling focused only on two types of fuel use: (i) charcoal and (ii) wood, given that cooking with LPG and electricity is rare.

Since use of improved stoves is also atypical, after a baseline household survey and baseline monitoring of HAP, improved charcoal and improved wood stoves were distributed to a group of households to investigate the effectiveness of improved stoves as potential mitigation measures. While traditional charcoal stoves are made of metal without insulation, which leads to most of the heat escaping, the disseminated improved charcoal burning stove is similar to the Kenya Ceramic Jiko, and consists of an hour-glass shaped metal cladding with an interior ceramic liner that is perforated to permit the ash to fall into a collection box at the base. A single pot is placed on the top of the stove. The disseminated wood-burning stove, provided only in Vatomandry, is called Fatana Pipa and is produced by a company called Bionerr. The stove consists of a metal-covered ceramic bucket with a chimney and supports one pot. The ethanol burning stove disseminated to the households is a stainless steel stove called the CleanCook. The type given to the households in this study has one pot stand. The non-pressurized fuel tanks hold the ethanol in a special adsorptive fiber. The burner flame is adjusted or extinguished by means of a simple regulator.

In selecting households, the criteria used were (i) use charcoal or wood as main fuel during the survey, (ii) purchase at-least half of their fuel, (iii) have enclosed kitchen and (iv) have interest in using an improved stove.[22] Household kitchen concentrations of $PM_{2.5}$ and CO were measured in every study household three times during February-March 2009 (baseline), April 2010 (round 2), and July-August 2010 (round 3). A number of questions were asked about fuel use, stove type, cooking locations and structural characteristics of kitchen in all three rounds of the survey.

There was a significant loss of households between the baseline and round 2 due to an unanticipated delay of one year between the baseline and round 2. Scarcity of a safe, effective ethanol stove was the major reason behind the delay. Civil unrest and consequent economic

[21]Vatomandry is located at an altitude of 4m from sea-level and records more rainfall than Ambositra. It has a hot climate throughout the year, yet distinct wet (December-March) and dry (April-November) seasons. The housing stock is primarily wooden homes with detached kitchens in the back of the main house. Majority of the households use wood and traditional wood stoves for cooking in Vatomandry, but charcoal and traditional stoves are also used.

[22] In order to assess health impacts of the mitigation measures, two additional criteria considered were presence of a child under 4 year of age in the household and the mother of the child was the main cook.

disruption during this period forced people to migrate. The round 2 monitoring took place during the harvest period; some households moved temporarily to the countryside. A few households expressed reluctance to be part of the study group and dropped out. After the necessary data cleaning was done, a total of 338 households (154 from Ambositra and 184 from Vatomandry) were retained from each of the three rounds for data analysis.

4. Summary Data on Household Air Pollution Factors

Summary statistics of determinants of HAP as reported in the survey are presented in Table 1 and Table 2. Table 1 summarizes information on fuel and stove use, and observations of enumerators on characteristics of the kitchen and ambient environment are documented in Table 2.

Fuel type: At the baseline, 76% of the households reported charcoal and 38% of the households reported wood as their main cooking fuel. There was no use of ethanol to start with; however, 6.5% of the households reported use of "other" biomass fuels.[23] Ethanol was introduced as a cooking fuel before round 2 by design of the experiment; roughly 18% of the households reported use of ethanol in round 2 and 3.[24] As a result, the share of households reporting use of charcoal and wood went down from the baseline period to round 2 and 3, as the percentage reporting the use of fuels other than charcoal and wood increased, from 6.5% in the baseline to 14.8% and 17.5% in round 2 and round 3 respectively.

Stove type: Households mostly used traditional stoves as their main cooking stove before the experiment. During the baseline, 92% of the households reported use of traditional stoves: 58.9% of the households were using traditional charcoal stoves, 29% three-stone fire stoves and 4.1% other traditional stoves. While 8% of the households were using improved charcoal stoves, use of improved wood stoves was not reported. Improved charcoal stoves, improved wood stoves and ethanol stoves were distributed by design of the experiment, except to the control group. Of those who received stoves, most of the users of traditional charcoal stoves and three-stone fire stoves switched to ethanol stoves or improved wood and improved charcoal stoves by round 2 and round 3. In particular, 18% of households were using ethanol stoves, 23% and 9% of the households were using improved charcoal and improved wood stoves respectively during round

[23] "Other" fuels consist of dry leaves, crop residue, saw dust, animal dung etc.
[24] It should be noted that most of the households did not switch completely to ethanol from biomass fuel even after receiving ethanol stoves. Only 22% of the ethanol users in round 2 and 19% in round 3 used ethanol exclusively.

3. The share of households using traditional stoves as a whole dropped from 92% during the baseline to 50.7% by round 3, but the percentage of households using "other" traditional stoves recorded a steady increase from 4.1% to 14.8% and 17.5% over time.

Table 1: Summary statistics of household fuel consumption variables

Variables	Baseline	Round 2	Round 3
Fuel use			
%Households using wood	37.6	31.9	32.3
	(48.5)	(46.7)	(46.8)
%Households using charcoal	75.8	64.8	63.0
	(43.9)	(47.8)	(48.3)
%Households using "other" biomass fuels	6.5	14.8	17.5
	(24.7)	(35.6)	(38.0)
%Households using ethanol	0	18.9	18.3
	(-)	(39.2)	(38.8)
Stove use			
%Households using traditional three-stone fire stoves	29.0	10.1	10.7
	(45.4)	(30.1)	(30.9)
% Households using traditional metal charcoal stove	59.1	26.0	22.5
	(49.2)	(43.9)	(41.8)
%Households using other traditional stoves	3.9	14.8	17.5
	(19.3)	(35.5)	(38.0)
%Households using improved biomass stove	0	9.2	8.6
	(-)	(28.9)	(28.0)
% Households using improved charcoal stove	8.0	21.0	22.5
	(27.2)	(40.8)	(41.8)
%Households using ethanol stoves	0	18.9	18.3
	(-)	(39.2)	(38.8)
Fuel consumption			
Average wood consumption among users (kg/week)	75.8	57.5	58.8
	(144.9)	(54.5)	(49.6)
Average charcoal consumption among users (kg/week)	21.7	20.2	21.8
	(14.7)	(13.5)	(16.1)
Average ethanol consumption among users (liters/week)	0	4.0	4.7
	(-)	(2.0)	(2.0)

* Note: Figures in parentheses are standard deviations. Information on the consumption of other inferior fuels was not collected. The sum of the percentage figures within the sample can exceed 100 because households used multiple fuels and multiple stove types. The averages of the quantity of fuel consumption were calculated for users only, that is, users of zero-consumption were excluded.
Source: World Bank household survey (2009-2010)

Fuel Consumption: As far as the quantity of fuel consumption is concerned, information was self-reported by respondents. There was virtually no change in the average quantity of charcoal consumption from the baseline (21.7 kg/week) to round 3 (21.8 kg/week) despite the distribution of improved charcoal stoves to a subset of households, which is counter-intuitive. On the other hand, the average quantity of wood consumption, registered a 22.5% decline from the baseline to round 3. Average consumption of ethanol was around 4-5 liters/week.

Table 2: Kitchen Characteristics and Ambient Environment: Descriptive Statistics

Explanatory variables	Baseline	Round 2	Round 3
Kitchen is open (1=Yes, 0=No)	0.219	0.246	0.201
	(0.414)	(0.431)	(0.401)
Kitchen is airy (1=Yes, 0=No)	0.175	0.145	0.121
	(0.380)	(0.353)	(0.327)
Kitchen roof is permeable (1=Yes, 0=No)	0.166	0.009	0.012
	(0.372)	(0.094)	(0.108)
Kitchen wall is permeable (1=Yes, 0=No)	0.065	0.003	0.0
	(0.247)	(0.054)	(0.0)
Size of kitchen (Sq. ft.)	18.1	21.3	20.8
	(11.9)	(14.0)	(13.7)
Size of kitchen vent (Sq. ft.)	1.9	1.9	1.8
	(1.2)	(1.3)	(1.4)
Wind is strong (1=Yes, 0=No)	0.059	0.009	0.027
	(0.236)	(0.094)	(0.161)
The day is dry (1=Yes, 0=No)	0.464	0.589	0.346
	(0.499)	(0.493)	(0.476)
The day is rain-free (1=Yes, 0=No)	0.485	0.589	0.601
	(0.501)	(0.493)	(0.491)
Temperature is warm (1=Yes, 0=No)	0.707	0.825	0.189
	(0.456)	(0.380)	(0.392)

Note: Figures in the parentheses are standard deviations
Source: World Bank household survey (2009-2010)

Kitchen characteristics: In order to understand the role of ventilation, questions were asked about location of the kitchen (separate/attached/within-dwelling), nature of the kitchen (enclosed/semi-open), ambience of the kitchen (bright and airy/dark and enclosed), and building materials (bricks/mud/wood/reed/thatch etc.). Enumerators of the survey also measured kitchen, window and door dimensions during their visits. As expected, structural characteristics of kitchens displayed less variation over a year and a half when three rounds of survey were carried out. Survey enumerators observed that only 22% of the kitchens were open and 15% were airy. On an average, the size of a kitchen was around 20 sq. ft. with a small opening. Walls of the kitchens were hardly permeable and approximately 1% of the kitchens had permeable roof during the experiments.

Ambient Environment/ Weather: As mentioned above, the baseline survey was conducted during February-March (hot, rainy season) 2009, round 2 in April (transition between hot and cooler season) 2010 and round 3 in July-August (cooler, dry season) 2010. Ambient environment, as expected showed variability to some extent. Climate was mostly warm during the baseline and round 2. On average, 50% of the days during the baseline survey and 60% of the days during other two rounds were free from rain. Humidity was considerably lower in winter (round 3).

5. Monitoring Household Air Pollution: Methods and Descriptive Statistics

Household kitchen concentrations of $PM_{2.5}$ and CO were measured over periods lasting 24 hours in each study household. The air samplers and real-time monitors were placed on a wall in the kitchen area, 1.0 meter from the stove and 1.5 meters above the floor.

Monitoring of $PM_{2.5}$

$PM_{2.5}$ was measured in every study household using the UCB Particle Monitor, which uses a light-scattering detector.[25] For consistency, in each household the UCB monitor used in baseline sampling was used for subsequent rounds. Additional $PM_{2.5}$ measurements were taken with a TSI DustTrak 8520 Aerosol Analyzer (TSI Inc., USA) in 25% of houses to validate the results from the UCB Particle Monitor. The DustTrak also uses a light-scattering detector. These two instruments recorded real-time kitchen concentrations throughout the sampling period.

Gravimetric $PM_{2.5}$ samples were also collected in the households where the DustTraks were employed, in order to calibrate the light-scattering measurements. The gravimetric sampling used aluminum cyclones equipped with 37 mm diameter Teflon filters. Casella Apex (Casella Measurement, UK) constant flow pumps were operated at a flow rate of 1.5 liters/minute, achieving a median particulate matter cut point of 2.5µm. The pumps were calibrated using a DryCal DC-Lite primary flow meter (Bios International, USA) to within ±5% of the target flow rate. Analysis of the gravimetric samples was conducted in a temperature- and humidity-controlled lab at the University of California Berkeley using a Mettler-Toledo balance. The balance was calibrated annually by a certified Mettler-Toledo representative.

[25] Litton et al., 2004; Edwards et al., 2006; Chowdhury et al., 2007

Monitoring of CO

The GasBadge Pro Single Gas Monitor (Industrial Scientific) was used to record minute-by-minute kitchen concentrations of Carbon Monoxide (CO) in the 0-1,500 ppm range in 1ppm increments. All GasBadge monitors were calibrated prior to each round in Berkeley, California, using 50ppm span gas. Drager Carbon Monoxide Diffusion Tubes 50/a-D (50-600 ppm*h) were collocated with the GasBadge monitors in a sub-set of kitchens in each round in order to establish a relationship between the CO readings from the GasBadge Pro and the Drager tubes.

Table 3 presents the descriptive statistics of the 24-hour average concentrations of $PM_{2.5}$ and CO from the detailed readings of the UCB Particle Monitor and GasBadge Pro. Average concentrations of $PM_{2.5}$ recorded in the households studied were 0.776 mg/m^3 (baseline), 0.320 mg/m^3(round 2), 0.444 mg/m^3(round 3) and average concentrations of CO were 28 ppm (baseline), 21.6 ppm (round 2) and 21 ppm (round 3).

Table 3: Concentration of $PM_{2.5}$ and CO recorded in kitchen (24-hour average)

	Mean	s.d.	Maximum	Minimum
Baseline				
$PM_{2.5}$ (mg/m^3)	0.776	1.847	23.803	0.028
CO (ppm)	28.0	30.8	227.0	0.1
Round 1				
$PM_{2.5}$ (mg/m^3)	0.320	0.398	2.542	0.014
CO (ppm)	21.6	28.9	167.7	0.0
Round 2				
$PM_{2.5}$ (mg/m^3)	0.444	0.527	4.441	0.037
CO (ppm)	21.0	29.3	222.7	0.0

Source: World Bank household survey (2009-2010)

Inter-regional variations in pollutant concentrations were observed: average concentrations of $PM_{2.5}$ concentrations were generally higher and concentrations of CO were lower in Vatomandry compared to Ambositra. Average concentration of CO declined from the baseline period to round 2 in both locations and did not change much from round 2 to 3. $PM_{2.5}$ concentrations, on the other hand, did not change over time in Ambositra; but dropped significantly in Vatomandry from the baseline to round 2 and thereafter went up to some extent in round 3.

6. Regression Analysis: Determinants of $PM_{2.5}$ and CO Concentrations in Kitchens

The regression analysis investigates the roles of several basic determinants of HAP: fuels (charcoal, wood, ethanol), stoves (traditional, improved, ethanol), kitchen characteristics (size, ambience), building materials (permeable roof, permeable wall), and ambient environment. We estimate the following equation

$$IAP_{it} = \alpha + \beta S_{it} + \gamma K_{it} + \delta W_{it} + \chi L_i + \lambda_i + \varepsilon_{it}$$

where, HAP_{it} = Concentration (24-hour average) of $PM_{2.5}$ or CO in the kitchen in household *i*

S = Fuels and stoves used by household *i* (cooking with wood in traditional or improved stoves, cooking with charcoal in traditional or improved stoves, cooking with ethanol in ethanol stove),

K = set of kitchen characteristics of household *i* (kitchen size, size of vent: door and window openings, building materials of the roof and the walls, open/enclosed, airy/dark)

W = set of ambient weather variables for household *i* (wind condition, humidity, status of rain and temperature when air was monitored)

L = Location of household *i* (Ambositra/Vatomandry)

λ= set of unobserved characteristics of household *i* that might affect HAP

ε_{it} = random error term of the regression

t = the round of the survey

and α, β, γ, δ, and χ are the parameters to be estimated.

In order to avoid any potential ambiguity in the regression results, we dropped households using "other" fuels before running regressions. For regression, our panel consists of 3 observations (baseline, round 2 and round 3) for each household, and we estimate a household-level fixed-effects model with an unbalanced panel of 868 observations for $PM_{2.5}$ and 841 observations for CO.[26]

[26] Fixed-effects estimates are appropriate in this case as they control for time invariant household-specific unobserved factors that might affect the dependent variable (concentration of pollutants). Examples of such

Table 4: Regression results for log $PM_{2.5}$ concentration (mg/m^3) in kitchens

Explanatory variables	**(1)**	**(2)**	**(3)**
Fuel and Stove use			
Household uses wood and traditional stoves	0.305**	0.288**	0.273*
	(2.33)	(2.23)	(2.11)
Household uses wood and improved wood stoves	–0.023	–0.350	–0.075
	(–0.09)	(–0.15)	(–0.33)
Household uses charcoal and improved stoves	0.190	0.143	0.136
	(1.43)	(1.13)	(1.08)
Household uses ethanol	–0.856**	–0.701**	–0.722**
	(–4.96)	(–4.25)	(–4.40)
Kitchen characteristics			
Open Kitchen	-	–0.030	–0.020
		(–0.30)	(–0.21)
Airy Kitchen	-	–0.124	–0.131
		(–1.09)	(–1.15)
Kitchen with permeable roof	-	–0.058	–0.048
		(–0.36)	(–0.30)
Kitchen with permeable wall	-	0.270	0.297
		(1.03)	(1.10)
Size of kitchen (Sq. ft.)	-	–0.020**	–0.020**
		(–4.96)	(–4.91)
Size of kitchen vent (Sq. ft.)	-	–0.055	–0.060
		(–1.24)	(–1.37)
Weather characteristics			
Strong Wind	-	-	–0.299
			(–1.46)
Dry day	-	-	–0.089
			(–0.76)
Rain-free Day	-	-	–0.113
			(–1.04)
Warm Temperature	-	-	–0.072
			(–0.80)
R^2 for the regression model	0.219	0.265	0.280
Number of HHs (groups)	335	335	335
Number of observations	868	868	860

Note: Figures outside the parentheses are regression coefficients and in the parentheses are t-statistics based on robust standard errors. *=statistically significant at 10% level, **= statistically significant at 5% level or better. Regressions additionally control for survey rounds and locations, which are not reported.
Source: World Bank household survey (2009-2010)

Table 4 and Table 5 report the regression results for $PM_{2.5}$ and CO respectively. In each case, column (1) presents results for a model that includes alternative fuel and stove use variables only. Column (2) retains the fuel and stove use variables and adds controls for kitchen characteristics. Column (3) presents results for all relevant variables: fuel and stove use along with kitchen characteristics and controls for ambient environment. It should also be noted that

unobserved factors in this case may be ventilation behavior of the households: length of time the households keep doors and windows of kitchen open.

we used log-transformed HAP variables as dependent variables in the regressions by taking natural logarithm of $PM_{2.5}$ and CO concentrations.[27]

All the results presented in Table 4 highlight the importance of clean fuel for reduction of $PM_{2.5}$ concentrations, as expected. Column (1) indicates that use of clean fuel (ethanol) reduces, and use of traditional stoves for burning wood increases, the concentration of $PM_{2.5}$ significantly compared to the use of charcoal in traditional stoves.[28]

We find no significant impact of improved charcoal stoves or improved wood stoves on $PM_{2.5}$. Although this might be contrary to expectations, in the case of the improved charcoal stove, controlled cooking tests conducted in an earlier phase of the study found that this stove had essentially the same thermal efficiency as the traditional charcoal stove. While the emissions of the two charcoal stoves were not measured, the similarity of the thermal efficiencies implies that the $PM_{2.5}$ emissions from the two stoves are likely similar. In the case of the improved wood stove, one of the main issues reported by households was the fact that it took time to cut wood to the correct size so that it fitted into the stove. This observation may suggest difficulties with ignition and fuel addition, which have been found to cause emission of significant quantities of particulate matter from improved wood stoves with chimneys.[29]

The estimates after the introduction of kitchen configuration variables, presented in column (2), indicate that while most of the kitchen characteristics have the right sign, only the size of the kitchen has statistically significant impact on kitchen $PM_{2.5}$. In particular, an increase in the size of a kitchen by one sq. ft. is expected to lower concentration of $PM_{2.5}$ in the kitchen by 2%. Column 2 also shows that after controlling for the kitchen characteristics, the use of a traditional stove in burning wood increases $PM_{2.5}$ by 33.4%, and the use of ethanol reduces the concentration of $PM_{2.5}$ in the kitchen by 50.4%, compared to the traditional charcoal stove.[30] Finally, the introduction of ambient environment related variables in column (3) indicates that

[27] A log transformation of a dependent variable is advocated for estimation when the distribution of the variable is positively skewed. In our case, distributions of both $PM_{2.5}$ and CO are positively skewed, with numerical values of skewness of $PM_{2.5}$ and CO being 10.8 and 2.4 respectively.

[28] Use of charcoal in traditional stoves is the excluded category, hence the comparison is with respect to the use of charcoal in traditional stoves.

[29] Roden et al., 2009

[30] The regression coefficient of a log-transformed variable can be interpreted as the percentage of change only if its numerical value is less than 0.1. Otherwise, the percentage change is given by the expression: $exp(\beta) - 1$, where β is the regression coefficient and *exp* is the exponential function.

the weather characteristics did not play a significant role in determining the concentration of $PM_{2.5}$ in the kitchen air.

Table 5: Regression results for log CO concentration (ppm) in kitchens

Explanatory variables	(1)	(2)	(3)
Fuel and Stove use			
Household uses wood in traditional stoves	0.116	0.056	0.034
	(0.63)	(0.31)	(0.19)
Household uses wood in improved stoves	–1.132**	–1.146**	–1.176**
	(–3.65)	(–4.03)	(–4.11)
Household uses charcoal in improved stoves	0.102	0.128	0.129
	(0.70)	(0.91)	(0.91)
Household uses ethanol	–2.443**	–2.288**	–2.306**
	(–9.74)	(–9.47)	(–9.72)
Kitchen characteristics			
Open Kitchen	-	–0.053	–0.050
		(–0.63)	(–0.58)
Airy Kitchen	-	–0.021	–0.026
		(–0.15)	(–0.18)
Kitchen with permeable roof	-	0.222	0.241
		(1.43)	(1.55)
Kitchen with permeable wall	-	0.443	0.439
		(1.26)	(1.24)
Size of kitchen (Sq. ft.)	-	–0.027**	–0.027**
		(–5.07)	(–5.06)
Size of kitchen vent (Sq. ft.)	-	–0.058	–0.065
		(–0.78)	(–0.86)
Weather characteristics			
Strong Wind	-	-	–0.339*
			(–1.70)
Dry day	-	-	–0.044
			(–0.28)
Rain-free day	-	-	–0.054
			(–0.32)
Warm Temperature	-	-	0.003
			(0.03)
R^2 for the regression model	0.359	0.400	0.403
Number of HHs (groups)	334	334	334
Number of observations	848	841	841

Note: Figures outside the parentheses are regression coefficients and in the parentheses are t-statistics based on robust standard errors. *=statistically significant at 10% level, **= statistically significant at 5% level or better. Regressions additionally control for survey rounds and locations.
Source: World Bank household survey (2009-2010)

Results presented in Table 5 highlight the significant role of improved wood stoves as well as ethanol in reduction of CO in the kitchen air. Column 2 indicates that the effects of kitchen characteristics on concentration of CO are similar to those on $PM_{2.5}$ concentration, with only the size of the kitchen showing a significant inverse effect. Estimates presented in column 3 further indicate that dispersion of CO is rapid when wind is strong. In particular, our estimates indicate that use of improved wood stoves reduces concentration of CO by 69.1% and use of ethanol reduces it by 90.0%. An increase in the size of a kitchen by one sq. ft. lowers concentration of CO in the kitchen by 2.7%. Finally, a reduction of CO by 28.8% has been recorded when wind was strong.

The finding that improved wood stoves reduce concentrations of CO but not $PM_{2.5}$ is not necessarily surprising. Other work has found that the ratio of CO to PM varies over the burn cycle of a fire[31], and that while PM and CO emission factors may be reasonably correlated in laboratory tests, this is less valid for in-use stoves where fuel type and combustion conditions vary widely from user to user.[32]

It should be noted that the elasticity estimates presented in this section are conservative as most households where air monitoring took place were using ethanol, wood and charcoal in the same kitchen as opposed to using one fuel exclusively. In round 2, 74% of the improved wood stove users were using wood, 82% of the improved charcoal stove users were using charcoal and 22% of the ethanol users were using ethanol exclusively. In round 3, these shares were 66%, 78% and 19%, respectively. Furthermore, households using ethanol and improved biomass stoves were also located in close proximity to households using traditional stoves and biomass fuels in neighborhoods where the spread of smoke among households and the potential for cross-contamination cannot be ruled out.

7. Summary and Conclusion

The Global Burden of Disease Study 2010 found that HAP is the second leading risk factor in the burden of disease for Madagascar, accounting for some 6.7% of the national burden of disease. Charcoal and wood are the main cooking fuels of Malagasy households and use of improved cooking stoves is atypical. Monitoring of household air is almost non-existent in Madagascar. This paper summarizes an initiative to monitor HAP in the kitchens of two towns of Madagascar: Ambositra and Vatomandry; and summarizes the findings on the effectiveness of various HAP mitigation measures.

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[31] Northcross et al, 2010
[32] Roden et al., 2009

A stratified sample of 154 and 184 households was selected from Ambositra and Vatomandry respectively for HAP monitoring. Concentrations of $PM_{2.5}$ and CO were monitored in the kitchen three times in every household during February-March 2009, April 2010 and August 2010 using UCB Particle Monitors and GasBadge Pro Single Gas Monitors. In each occasion monitoring periods lasted 24 hours. Wherever household air was monitored, findings suggest that air pollution is dangerously high in the kitchens. An average concentration of $PM_{2.5}$ of 0.776 mg/m^3 has been recorded, whereas the WHO Air Quality Guidelines for typical indoor exposures recommend the 24-hour average of 0.010 mg/ m3 $PM_{2.5}$ as the lowest levels at which total cardiopulmonary and lung cancer mortality have been shown to increase with more than 95% confidence (WHO, 2005). Similarly, while the WHO recommends 6.1 ppm of CO for typical indoor exposures (assuming that the exposure occurs when the people are awake and alert but not exercising), a concentration of 28 ppm CO is common in Madagascar, implying a serious health hazard (WHO, 2010).

We conducted fixed-effects panel regression analysis to investigate the roles of several basic determinants, such as fuels (charcoal, wood, ethanol), stoves (traditional, improved, ethanol), kitchen size, kitchen ambience (open, airy), building materials (permeable roof, permeable wall) of the kitchen, and ambient environment. Our econometric findings strongly suggest that variations in cooking fuel, stove types and kitchen size produced large differences in HAP. As expected, in terms of both $PM_{2.5}$ and CO, ethanol is significantly cleaner than biomass fuels, and for both parameters a larger kitchen makes a significant difference to the quality of household air. While we found no significant impact of improved charcoal stoves on air quality compared to traditional charcoal stoves, the improved wood stove (incorporating a chimney) was effective in reducing concentrations of CO in the kitchen. Circulation of wind also provides significant benefits to reduce the concentration of CO.

These results highlight household level adjustments that can significantly mitigate HAP exposure; first, switching to clean fuels (for example ethanol) is desirable. Second, if cooking with clean fuels is not possible, use of an improved wood stove with a chimney can make a significant difference for household concentrations of CO. Finally, a spacious kitchen and providing ventilation in cooking areas will yield a better household health environment. In short, clean fuels, improved stoves and good ventilation are effective means of reducing HAP.

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