Impacts of Improved Biomass Cookstoves on Child and Adult Health: Experimental Evidence from Rural Ethiopia

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Abstract

We present the three-year impacts of an improved biomass cookstove on child and adult health in rural Ethiopia. After near complete stove adoption during an initial one-year randomized controlled trial, 60 percent of treatment households continued to use the improved stoves three-years on and experience significant reductions in hazardous airborne particulate matter. We find treatment status is associated with a precisely estimated 0.3-0.4 standard deviation improvement in height-for-age of young children exposed to the stoves during their first years of life—a substantial effect with implications for greater health and well-being throughout the life course. This association notwithstanding, we find no changes in the respiratory symptoms or physical functioning of older children and adult cooks. Measures of fine particulate matter taken within study households are consistent with the observed health effects. The results advance understanding of the health impacts of hazardous air pollution while also refining design and implementation options for interventions geared toward improving well-being in similar environments.

Highlights

- A randomly distributed, improved biomass cookstove technology improved child growth by 0.3-0.4 standard deviations after 3 years
- The positive effect of the intervention holds only for children exposed to the improved stove during their first 3 years of life
- We find no impact on the health outcomes of older children or adults
- Measures of indoor fine particulate matter ($PM_{2.5}$) are consistent with the observed health impacts

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1. Introduction

The disease burden from indoor air pollution results in an estimated 4 million premature deaths per year and is one of the largest drivers of poor health across the world (Lim et al., 2012). While the diminished quality of air in outdoor environments is, appropriately, a growing concern, the burning of solid biomass materials for cooking and heating *within* homes is the primary source of the pollution burden (Smith et al., 2012). Forty percent of the world relies on solid fuels such as wood, coal, charcoal, and dung for household cooking with resulting emissions disproportionately harming women and young children in the form of lower-respiratory infections, pneumonia, low birth weights, growth deficits, and fatigue (Alexander et al., 2018; Dadras and Chapman, 2017; Fullerton et al., 2008; Pope et al., 2010; Walker et al., 2007; WHO, 2016).

In addressing these and other health concerns, organizations have sought to improve the quality of indoor air by reducing the use of biomass fuel. The World Health Organization identifies a number of cooking fuels and associated technologies, such as electricity, biogas and natural gas, that are expected to meet WHO household air pollution guideline values, such as a 24-hour average limit of fine particulate matter of $25\mu g/m^3$ (WHO, 2006b, 2015). However, these technologies and fuels are often cost prohibitive or unavailable in low and lower-middle income countries where the number of households reliant on biomass fuels is estimated to grow for the foreseeable future (IEA, 2017).

The WHO also recognizes the potential contributions improved biomass cookstoves can make to reducing household air pollution, but cautions that many stoves do not meet WHO guidelines (WHO, 2011; 2019). Improved cookstove technologies (ICTs), which increase efficiency and reduce emissions by more thoroughly burning biomass fuels, are commonly recommended as an intermediate way for households to transition away from open-fire cooking (Jeuland and Pattanayak, 2012) and improve health outcomes if demonstrably clean (WHO, 2016). For example, in Ethiopia, the setting of this study, the Federal Government has proposed distributing ICTs to 30 million households by 2030 and identified reducing demand for biomass by increasing fuel efficiency as a strategic priority in the energy sector (FDRE, 2011, 2015).

This paper contributes to a growing body of work that assesses health and environmental benefits of improved cookstoves in field settings (Bensch and Peters, 2015; Hanna et al., 2016; Mortimer et al., 2017; Smith et al., 2007; Quansah et al., 2017). We examine the health impacts of the *Mirt* stove, a particular type of ICT engineered to bake the Ethiopian staple bread, *injera*. Working with a representative set of approximately 500 households across 36 rural communities, we disseminated *Mirt* stoves to a random subset of households and study stove use, indoor air quality, and health outcomes of women and children three and a half years after the initial randomization. While tailored to a specific food, and thus not intended to entirely replace traditional cooking methods, the *Mirt* stove is well suited to the context and research question as firewood for cooking *injera* is the end-use of over half of all primary energy consumed in Ethiopia (Bizzari, 2010; Tesfay, 2014). Evidence from laboratory-based controlled cooking tests shows *Mirt* reduces carbon monoxide emissions by 92 percent and fine airborne particulate matter by 41 percent relative to traditional open-fire cooking (Teshome, 2007). While the exact gradient of the pollution-health relationship is not yet well established in the literature (WHO, 2016), the intensive energy use of *injera* cooking and laboratory-based values represent considerable reductions with potential health gains (Burnett et al., 2014).

We build on an initial one-year impact evaluation of *Mirt* dissemination that showed the stoves saved wood when cooking standardized *injera* batches and users highly valued the benefits provided by the stove (Gebreegziabher et al., 2018). We also found they were adopted and used by over 90 percent of treatment households in the 12 months after their distribution (Beyene et al., 2015). This rate is significantly higher than a number of high-profile prior trials involving improved stoves (e.g. Hanna et al., 2016; Mobarak et al., 2012; WHO, 2006a), and in line with more recent work studying low-cost stoves particularly well-suited to the local environment and cooking practices (e.g. Bensch and Peters, 2015; Rosa et al., 2014).[2]

[2] As Bensch and Peters (2015) note, the varied complexity of different stoves and their relative similarity with the existing cooking technology is a critical factor in stove adoption. Jetter et al. (2012) provide estimates of emissions and efficiency for 22 different cookstoves, for example. While we focus here on health outcomes from an improved biomass

In the present study, we focus on secondary health outcomes that may benefit from several years of reduced indoor air pollution. We estimate the impact of the *Mirt* stove on child growth, a marker of inflammation and early-life health sensitive during the first years of life that is a powerful predictor of wellbeing in adulthood (Hoddinott et al., 2013), as well as symptoms of respiratory disease and measures of physical function.[3] Comparing across those randomly offered the *Mirt* stove with those that were not, our findings suggest the *Mirt* treatment increased height-for-age for children exposed to the technology before the age of three by approximately 0.3 to 0.4 standard deviations, while the respiratory symptoms and physical functioning of adult cooks and older children did not improve. These observed patterns are consistent with a critical early period in life where health interventions see their largest positive impacts (e.g. Cusick and Georgieff, 2016; Walker et al., 2007) and the effects of accumulated exposure causing lasting damage in older individuals. The comparison across treatment and control households is supported by within household estimates that focus on those exposed during the sensitive early-life period to isolate the *Mirt* treatment effect from confounding factors.

The observed effect on child growth is both precisely estimated and meaningful in magnitude. A wide body of evidence links early-life health to adult health, educational attainment, cognitive function, and earnings (e.g. Adair et al., 2013; Almond et al., 2018; Fogel, 2004; Glewwe and Miguel, 2008; Grimard and Laszlo, 2014; Groppo and Kraehnert, 2016; Hoddinott et al., 2008; LaFave and Thomas, 2017; Strauss and Thomas 1998; Wisniewski, 2016). For example, analysis of the Ethiopian Rural

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stove, we refer the reader to Bensch and Peters (2015, 2018), Bensch et al. (2015), Beyene et al. (2015), Cundale et al. (2017), Langbein et al. (2017), Levine et al. (2018), and Lewis and Pattanayak (2012) for detailed cookstove adoption studies.

[3] While child growth is often used as a marker of nutrition, a significant and growing body of work notes physiological associations between household air pollution from biomass cookstoves and reduced height-for-age (e.g. Balietti and Datta, 2018; Edwards and Langpap, 2012; Ghosh et al., 2011; Kim et al., 2016; Kyu et al., 2009; Mishra and Retherford, 2007; Ponguo et al., 2006; Tielsch et al., 2009).

Household Survey in Dercon and Porter (2014) suggests the observed height gains in the treatment group would result in approximately 3 to 4 percent increases in annual earnings as an adult.[4]

To better understand the underlying mechanisms behind the effects, we simultaneously collected measures of fine airborne particulate matter with a diameter of 2.5 micrometers or less ($PM_{2.5}$) in a random subsample of study households. These concentrations of matter, averaging approximately 1250μg/m^3, or 50 times more than the World Health Organization's (WHO) threshold for healthy exposure (WHO, 2006b, 2015), decreased by 10 percent on average for all households in the *Mirt* treatment arm, relative to the control group.[5] Meanwhile, households with young children, which also cook more frequently, experienced reductions of 24 percent on average. When examining whether measured health outcomes relate directly to particulate matter, we demonstrate a precisely estimated gradient between reduced household air pollution and increased child growth, and do not find a statistically significant or otherwise meaningful relationship between the level of particulate matter and respiratory symptoms or adult physical functioning. This evidence further contributes to the important understanding of the pollution exposure-health response relationship at high levels of particulate matter.

The results of this study advance our understanding of the health impacts of hazardous air pollution while also refining design and implementation options for interventions geared toward mitigation in similarly situated environments. We contribute to a growing effort to study the adoption, emissions, and health benefits of improved cookstoves in multiyear field settings. Results from prior studies in this literature are often mixed, with Hanna et al. (2016) finding low levels of adoption with no related respiratory health benefits at the end of a four-year randomized controlled trial in India, and Mortimer et al. (2017) observing no statistically significant impacts of an improved stove intervention on the incidence of pneumonia among children in Malawi. In contrast, work by Bensch and Peters (2015)

[4] Dercon and Porter (2014) estimate a 1cm increase in adult height results in a 1% increase in earnings. Our observed 0.3 to 0.4 standard deviation impact is approximately a 2cm increase in height at age 3, or 3 to 4cm as an adult.

[5] Bluffstone et al. (2018) reports on the details of the air pollution aspect of this project. Similar levels of $PM_{2.5}$ have been observed in traditional open-fire cooking environments in India (Dutta et al., 2007) and Nepal (Chen et al., 2016).

finds positive health benefits on self-reported symptoms from improved stoves in a year-long RCT of 250 households in rural Senegal, consistent with observational studies in, for example, Cameroon (Pongyo et al., 2006), Guatemala (Edwards and Langpap, 2012), India (Balietti and Datta, 2018; Mishra and Retherford, 2007), and Indonesia (Kim et al., 2016).

While health benefits for adults and older children do not arise in our data, our results suggest mitigation of indoor air pollution to be one of many important ways to improve child health and well-being. Given the link between early-life health and later life educational attainment, cognition, health, and earnings, the demonstrated advancement for young children represents a substantial and meaningful impact.

2. Study Design

2.1 Ethiopian context and *Mirt* improved cookstove technology

Despite enjoying economic growth over the preceding decade, Ethiopia is known as a "hotspot" for forest depletion, and it is one of the top four countries in the world to simultaneously maintain a high level of nonrenewable fuelwood consumption per capita and disease burden from household air pollution (Bailis et al., 2015). Neonatal disorders and lower respiratory infections, both linked to household air pollution (Amegah et al., 2014; Smith et al., 2000; Perez-Padilla et al., 2010), are two of the top three leading causes of death in Ethiopia (GBD, 2018), and improved cooking technology is virtually nonexistent in rural areas.

This study focuses on the dissemination and use of *Mirt* stoves in rural Ethiopia. *Mirt* (translated as "best") stoves are a locally developed technology specifically designed to cook *injera,* the staple bread of Ethiopia. The stove was designed by the Ethiopian Ministry of Water and Energy, is produced from locally available raw materials, and sells at a market price of 100-250 Birr (approximately $10.00 USD at the start of the study). Repeated controlled cooking trials done is a laboratory setting suggest the *Mirt* reduces fuelwood use by 50.7 percent, carbon monoxide emissions by 92.3 percent, and particulate matter by 41 percent compared to traditional open-fire or three-stone technology (Teshome, 2007).

Given the estimated fuel savings and a typical *injera* baking frequency of two to three times per week, the break-even period of two months compares favorably with the stove's five-year life expectancy.

While GIZ, a German governmental development organization, has supported the stoves since 1998, very few households in rural settings have access to the *Mirt* technology or other improved cookstoves. No improved stoves were present in our study households at baseline, and data from the 2013 Ethiopian Rural Socioeconomic Survey indicate that 98.4 percent of households in rural areas cook exclusively over traditional open-fires (Central Statistics Agency of Ethiopia, 2013).

2.2 Initial randomized controlled trial and adoption estimates

In 2013 we conducted an initial one-year randomized evaluation of *Mirt* stove adoption, its fuel savings, and users' willingness to pay for the product (Gebreegziabher et al., 2018). The baseline of the study surveyed households from 36 communities (*Gots* or sub-*Kebeles*) randomly selected to represent the forest cover in Amhara, Oromiya, and Southern Nations, Nationalities, and Peoples' (SNNP) regional states. The three states cover approximately 70 percent of the land area and 80 percent of the population of Ethiopia.

Within each enumeration area, we randomly drew 14 households from a local census, and assigned them into treatment and control groups at the household level within each community. The ten households in the treatment group received a *Mirt* stove and were allocated an additional behavioral treatment based on price (free vs. subsidized), incentives based on use (none vs. a small payment for recorded use), or a social networking intervention (home training only vs. home training plus community training). The control and treatment households were balanced on covariates at baseline, as well as across arms within the treatment group, and there we no other health-related behavioral change communication programs being implemented in enumeration areas throughout the study (see Beyene et al., 2015 for detail on the sampling and baseline analysis).[6]

The initial adoption of the stoves was assessed from both self-reports by the primary cook within the household and by electronic stove-use monitors (SUMs) attached to each stove to record time and temperature readings. Interviewers returned to the households to record SUM measurements four times throughout the first year following the randomization. Adoption was high and remained high throughout the year—12 months after the intervention use rates were approximately 90 percent with no statistically significant differences across the treatment arms. The frequency of use remained high as well, with treatment households averaging 2.5 cooking events per week on the *Mirt* stoves, a rate consistent with the traditional frequency for baking and storing *injera* (Beyene et al., 2015).

Important for interpretation of the health results presented below, baseline results suggest households chose to continue using traditional three-stone open-fire stoves for all non-*injera* cooking. *Mirt* stoves are highly specialized for cooking *injera*, with the main burner approximately 50cm in diameter, leaving it necessary to have a second stove to cook other foods such as stews and coffee. The *Mirt* technology was adopted for its specific use, with overall pollution and health improvements constrained by the continued use of open fires by both treatment and control households.

2.3 Three-year follow up and health outcomes

This study reports on the three-year follow-up investigation conducted in late 2016, approximately 40 months after the establishment of the baseline and the initial distribution of the stoves. Given the initial high adoption rates, we added collections of household indoor air pollution and health outcomes in the follow-up survey to assess the secondary outcomes potentially associated with adoption of the improved biomass stoves. We focused on children and adult cooks—the two groups thought to be most at risk from exposure to indoor air pollution from biomass cooking.

[6] Balance implies baseline demographics are unrelated to treatment status. At the household level, a regression of treatment status on baseline characteristics returns a *p*-value of 0.19 for the joint overall significance of household factors. A similar test at the individual level including age, gender, and parental characteristics returns a *p*-value of 0.35.

Households in the follow-up survey were re-interviewed with minimal and balanced attrition across treatment and control arms. Of the original 504 households, 480 were re-interviewed, yielding a 95 percent re-contact rate.[7] Uptake of the original stoves remained quite high as 60 percent of the treatment households continued to use their original *Mirt* stoves with no observed differences across the price, incentive, or networking groups (*p*-value = 0.67).

In the current study, we specifically focus on three sets of secondary health outcomes linked to indoor air pollution and, potentially, *Mirt* stove use: child growth, symptom reports of respiratory-related conditions, and measures of physical function captured through activities of daily living.

First, young children during the key early-life developmental period are thought to be the most at risk from household air pollution as they inhale and absorb higher levels of particles given the same exposure as adults (Bruce et al., 2013; Kurt et al., 2016; Sturm, 2012). To assess health among this population, a trained enumerator measured height (or recumbent length for children under two years of age) which was then standardized into a z-score relative to a representative, well-nourished child of the same age in months and gender using the Centers for Disease Control and Prevention growth tables (CDC, 2012). Height, conditional on age and gender, is both straightforward to measure and a well-established indicator of health status during very early childhood, reflecting both the genetic endowment and the influence of the disease environment during the in utero period and the first two to three years of life, commonly referred to as the "1st 1,000 days" (Cusick and Georgieff, 2016; Martorell and Habicht, 1986; Victora et al., 2010; Waterlow et al., 1977). As there is limited potential for catch-up growth to offset early-life deficits, child height is a powerful predictor of attained height as an adult and is thereby associated with reduced mortality and morbidity, as well as greater economic prosperity, educational attainment, and cognitive function (Adair et al., 2013; Fogel, 2004; Glewwe and Miguel, 2008; Hoddinott et al., 2008; LaFave and Thomas, 2017; Strauss and Thomas 1998).

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[7] Supplementary Appendix Table A1 reports tests of differential attrition across treatment and control groups at both the household and individual levels, and shows that attrition is orthogonal to treatment status as well as a baseline wealth index.

Understanding the biological mechanisms linking biomass smoke exposure and child growth is an active area of inquiry (e.g. Burnett et al., 2014; Gordon et al., 2014; Rylance et al., 2015) with a recent National Institutes of Health review noting the link between household air pollution and child growth a specific priority (Martin et al., 2013). Exposure to particulate matter from biomass smoke is a risk factor through in utero exposure as well as direct inhalation during early life (Jayachandran, 2009; Pope et al., 2010). Prenatal impacts occur both as a result of the effect of pollution on the mother and the transfer across the placenta of toxins present in wood smoke that reduce nutrient flows and disrupt the central nervous system of the fetus (Perera et al., 1998; Perera et al., 1999; Poursafa and Kelishadi, 2011). Additional medical evidence links exposure to wood smoke among children to increased inflammation and a weakened immune system (Rylance et al., 2015).

Second, we assess the presence of symptoms indicating respiratory disease for all children and each adult cook in the household. Participants were asked whether they've experienced a series of symptoms over the prior four weeks, including various types of coughs, difficulty breathing, wheezing, and eye problems. Prior studies show that such symptoms assessments are closely linked to clinical markers of respiratory infection and chronic obstructive pulmonary disease (e.g. Bensch and Peters, 2015; Hanna et al., 2016; Pattanayak and Pfaff, 2009) and sensitive to particulate matter exposure (e.g. Duflo et al., 2008).

Finally, each primary cook within the household also provided information on their physical functioning through their ability to perform regular tasks. For each activity of daily living (ADL), the cook reported whether they could do the activity easily, whether they could do it by themselves but with some difficulty, whether they needed assistance, or whether they could not perform the task at all. We included difficult activities such as walking 5km or carrying a heavy load, tasks known as intermediate ADLs, as well as basic ADLs such as standing from sitting and performing routine housework.

Measurement of indoor air pollution in the cooking areas during the follow-up wave was collected in a random subsample of 202 of the 480 study households. Particulate matter with an aerodynamic diameter of 2.5 micrometers or less ($PM_{2.5}$) was recorded using light-scattering sensors and gravimetric pumps and filters.[8]

The health module and indoor air pollution measurements were not collected in the baseline survey and added only for the follow-up wave after considering power calculations based on the baseline sample size. In the empirical analysis that follows, we pay particular attention to this fact and provide evidence that the research design does not bias the identification of our causal treatment estimates given the randomized nature of the study.

3. Empirical Approach

Our baseline analysis compares outcomes across treatment and control households with the control group representing the counterfactual if the treatment group had not been offered *Mirt* stoves. We complement this difference approach when examining child growth by exploiting the physiology of child development where height is only sensitive to interventions in the first three years of life (Cusick and Georgieff, 2016; Martorell and Habicht, 1986). This extension allows us to exploit variation between younger and older siblings to identify the effect by a difference-in-difference between children within a household. All regression approaches and outcomes were pre-specified prior to data collection and analysis.

3.1 Baseline treatment and control comparison

Our baseline models estimate the difference across individuals in treatment and control households. For a given individual *i* in household *h* and community *c*, we estimate the following model:

$$y_{ihc} = \beta_0 + \beta_1 I(Treatment)_h + \delta X_{ih} + \mu_c + \varepsilon_{ihv} \quad (1)$$

where *y* is a health outcome and β_1 is the coefficient of interest that captures the causal effect of one's household being assigned to the treatment group. As treatment was randomly assigned and orthogonal to the vector of additional control variables measured at baseline, *X*, the inclusion of controls aids only

[8] See Bluffstone et al. (2018) for additional details on the protocol, collection, and analysis of $PM_{2.5}$ readings.

in improving the precision of the estimates. Additional covariates include the following: gender; flexible polynomials in years of age for adults or age in months for children; household size and demographic composition; the age, education, and gender of the head-of-household; dwelling characteristics; and a composite wealth index. Models also include community fixed effects, μ_c, to capture observed and unobserved features of local areas that may impact health such as access to services and local markets.

We observe a median of 3 children under the age of 15 per study household and are therefore able to estimate household random effects extensions of equation (1) for child outcomes. This approach allows the unobserved error to contain a fixed component common to all household members yet uncorrelated with treatment status–a plausible specification given the randomized nature the treatment.

Equation (1) estimates intent-to-treat (ITT) effects identified by the random assignment of treatment status. This causal estimate includes both the sixty percent who continued using the *Mirt* stove and the forty percent who had stopped using it at some point during the prior three and a half years. As stoppage is potentially a confounding choice, we also present estimates of actual stove use using an instrumental variable strategy. These two-stage models replace *I(Treatment)* with a variable measuring the fraction of time since the baseline the household has used the stove (Hanna et al., 2016). This variable takes a value of 1 for households still using the stove. For those who have abandoned the *Mirt,* use is measured based on SUM temperature sensor readings and reports by the cook on when the household stopped using the stove. The mean of this stove use measure is 0.89, suggesting that the forty percent of households who had stopped using the stove at the time of the follow-up survey used the *Mirt* for approximately 29 of the 40 months on average. Randomly assigned treatment status then serves as an instrumental variable for stove use in a first stage. As some from the treatment group do not use the *Mirt* stove but households in the control group were not observed to start using *Mirt* on their own, our setting satisfies the necessary condition of one-sided noncompliance to interpret this estimate as the average treatment effect of actual *Mirt* use (Imbens and Rubin, 2015).

3.2 Child growth

Our analysis of child linear growth, also referred to as height-for-age, makes use of the additional feature that the timing of the intervention within a child's life is critical. A significant literature in nutrition and epidemiology defines the first 1,000 days of a child's life to be a crucial period when health interventions can significantly affect child height (e.g. Currie and Vogl, 2013; Hoddinott et al., 2008), after which reduced exposure to indoor air pollution is expected to have no effect on growth (Berkey et al., 1984). Given the significance of this cut-off, improvements in height-for-age should only occur for those children young enough to benefit from the *Mirt* treatment. Similar identification strategies based on the biology of height-for-age have been used to examine the child health impacts of primary care services (Frankenberg et al., 2005), pension income (Duflo, 2003), cash transfers (Farfan et al., 2012), and supplementary child feeding programs (Giles and Satriawan, 2015), among others.

With forty months between the baseline and follow-up waves, we're able to separate children into two groups based on their age and expected effect of exposure to the *Mirt* stove:

[Figure 1 here]

		Expected Effect	
Age at baseline (2013)	**Age at follow-up (2016)**	**Treatment**	**Control**
< 36 months (or not born)	< 76 months	(+)	0
≥ 36 months	≥ 76 months	0	0

Figure 1: Expected child height-for-age effects by treatment status and age

The fact that only very young children in treatment households should benefit from the intervention allows for within-household comparisons to estimate the treatment effect—conditional on age and gender, young children in treatment households should be closer in height to their older siblings than young children in control households are to their older siblings.

This intuition maps to a regression model with the following modification of (1):

$$z_{ihv} = \gamma_1 I(Treat\&BaseAge < 36\ mo.)_{ih} + \gamma_2 I(Treat\&BaseAge \geq 36\ mo.)_{ih} + \delta X_{ih} + \mu_h + \varepsilon_{ihv} \quad (2)$$

where a child's height-for-age z-score is the dependent variable. Additional baseline controls, in *X*, include the same factors as in model (1), as well as controls for mother and father's height to capture the genetic determinants of height. The parameter of interest, γ_1, measures the relative change in height for children in the treatment group who were under 36 months old or not yet born at the time of the baseline.[9]

Compared to the treatment vs. control difference in equation (1), the model in equation (2) incorporates two key additional features. First, the inclusion of household fixed effects, μ_h, is now possible, as treatment effectively varies at the individual level. This allows for the fixed effects to capture any shared characteristics common to all children in a household and restricts identification to within-household comparisons. This strategy accounts for a large set of potentially confounding variables that have plagued past associations of stove use and health. Second, it identifies an expected placebo effect for those treatment children three years and older in the baseline wave: Compared to children in the control group of the same age, these children should see no change in height and γ_2 should be zero.

4. Summary Statistics and Descriptive Evidence

Table 1 reports descriptive means and standard errors of key variables of interest. Panels A and B report measures at the individual level for children under the age of 15 as well as adult cooks. Columns 2 and 3 distinguish between the control and treatment households, and Column 4 reports *p*-values for tests of equality across the two groups.

Mean height-for-age in the sample is -1.2 standard deviations, suggesting that the average child is 1.2 standard deviations shorter than a healthy child of the same age (in months) and sex. Comparing across treatment and controls suggests that the treatment group is 0.06 standard deviations taller, but the difference is not statistically significant, as seen in column 4.

[Table 1 here]

[9] The validity of this approach requires that fertility did not respond to the intervention in a way that might bias the sample of new, young children in the 2016 follow-up. Supplementary Appendix Table A2 reports results from regressing the number of new children in a household against treatment status, showing the two have no relationship.

Table 1: Descriptive Statistics
Means and Control vs. Treatment Differences

A. Child Outcomes (n = 1152)	**All (1)**	**Control (2)**	**Treatment (3)**	**C vs. T (p-val) (4)**
Age	8.378	8.359	8.386	0.920
	(0.121)	(0.231)	(0.142)	
Female	0.492	0.452	0.507	0.078
	(0.014)	(0.026)	(0.017)	
Child Growth				
Height-for-age (z-score)	-1.220	-1.263	-1.203	0.532
	(0.043)	(0.082)	(0.050)	
Symptom Reports				
Any reports	0.463	0.516	0.443	0.021
	(0.014)	(0.027)	(0.017)	
Any cough reports	0.242	0.271	0.231	0.137
	(0.012)	(0.024)	(0.014)	
N. symptoms reported (max: 20)	2.041	2.262	1.954	0.142
	(0.094)	(0.183)	(0.110)	

B. Adult Cook Outcomes (n = 475)	**All (1)**	**Control (2)**	**Treatment (3)**	**C vs. T (p-val) (4)**
Age	37.609	37.557	37.571	0.963
	(0.975)	(0.601)	(0.511)	
Female	0.922	0.915	0.917	0.763
	(0.021)	(0.013)	(0.011)	
Activities of Daily Living (ADL) Reports				
N. ADLs with any difficulty (max: 12)	3.896	3.947	3.933	0.867
	(0.262)	(0.161)	(0.137)	
Symptom Reports				
Any symptom reports	0.787	0.773	0.777	0.720
	(0.032)	(0.020)	(0.017)	
Any cough reports	0.329	0.377	0.364	0.278
	(0.037)	(0.024)	(0.020)	
N. symptoms reported (max: 20)	4.726	4.677	4.690	0.911
	(0.375)	(0.227)	(0.194)	

C. Household Level (n=475)	**All (1)**	**Control (2)**	**Treatment (3)**	**C vs. T (p-val) (4)**
Household size	5.975	5.870	6.018	0.462
	(0.091)	(0.157)	(0.111)	
N. Children (ages 0-14)	2.521	2.399	2.570	0.284
	(0.072)	(0.132)	(0.087)	
N. Prime age (ages 15-59)	3.181	3.159	3.190	0.833
	(0.066)	(0.124)	(0.078)	
Age of household head	46.419	46.993	46.187	0.524
	(0.571)	(1.108)	(0.666)	
Female headed household	0.083	0.051	0.096	0.101
	(0.013)	(0.019)	(0.016)	
Stove use (share of months since baseline using improved stove)	0.632	0.000	0.888	0.000
	(0.020)	(0.000)	(0.011)	
Indoor Air Quality				
log 24-hr Mean $PM_{2.5}$	6.341	6.414	6.263	0.428
	(0.095)	(0.134)	(0.135)	
log 24-hr Maximum $PM_{2.5}$	10.463	10.469	10.455	0.909
	(0.060)	(0.083)	(0.089)	

Notes: Table reports means and standard errors of key variables for the entire sample as well as separately for control and treatment groups. Column 4 reports p-values of a means test across the control and treatment groups. Panels A and B report measures at the individual child and cook level. Panel C reports measures at the household level.

Figure 2 below illustrates the treatment and control height-for-age measure for children up to age 10, constructed by nonparametric regressions of height-for-age on age in months at the 2016 follow-up survey. We illustrate the sensitive period of growth with vertical lines as those children exposed during their first three years of life were up to 76 months old in the follow-up survey.

[Figure 2 here]

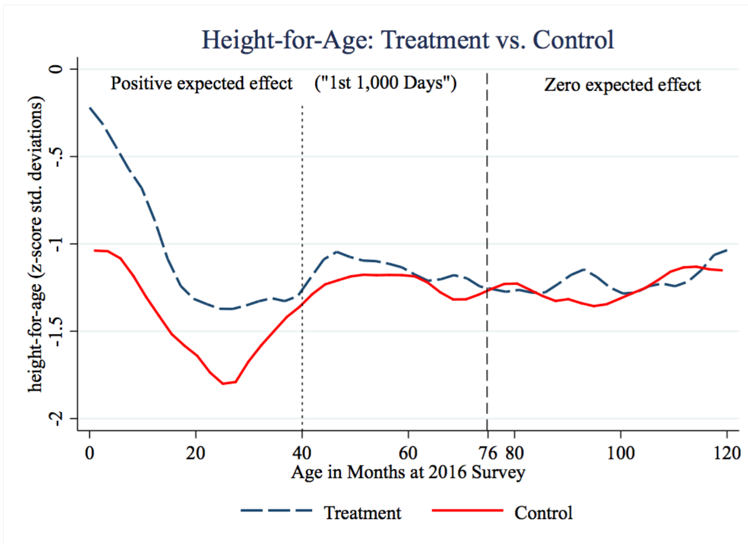

Figure 2: Treatment and Control Height-for-Age Comparison

The overall mean level and general trend with respect to age are consistent with commonly used nationally representative datasets including the 2011 Ethiopian Demographic and Health Survey (DHS) and Living Standards Measurement Surveys (LSMS), and seen across a variety of developing settings in population-representative data (e.g. Strauss and Thomas, 2007).

Figure 2 shows that there is a marked difference in the height of children at early ages when comparing across treatment and control households. As the intervention had been in place for 40 months, children in the treatment group 40 months old and younger have had complete potential exposure to the *Mirt* stove, while those between 40 and 76 months have an amount of exposure decreasing in their age. Regression models below further examine these differential effects.

Figure 3 below represents the corresponding treatment and control comparison for child and adult symptom reports. Children report an average of 2.3 symptoms in the control group compared to

2.0 in the treatment group, although the difference is not statistically significant (p-value = 0.14). The gaps are generally quite small between the groups but tend toward the expected direction with treatment individuals 8 percentage points less likely to report any symptoms at all (p-value = 0.02). Regression results below assess the gap between treatment and control including additional covariates.

[Figure 3 here]

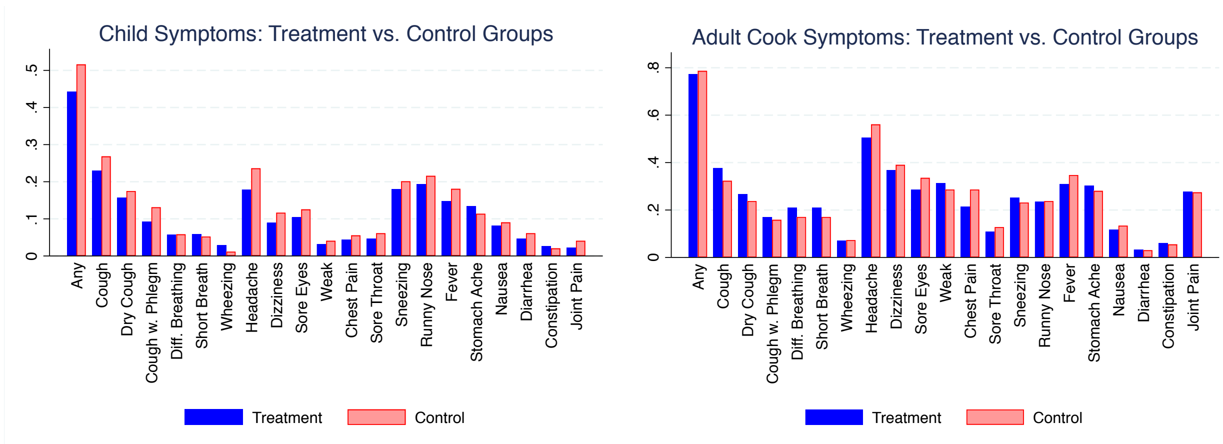

Figure 3: Means of child and adult symptom reports across treatment and control households.

Figure 4 summarizes adult cooks' reported difficulties with activities of daily living. For each question, the four-step scale is collapsed to a binary indicator equal to one if the respondent reports severe or moderate difficulty with the activity. As in Figure 3, the differences across the groups are minimal and statistically insignificant. Lack of significant differences across the groups persists using alternative severity thresholds. We move next to the corresponding regression results.

[Figure 4 here]

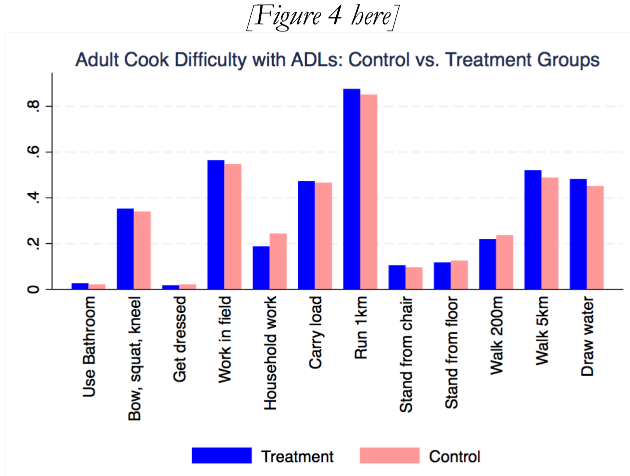

Figure 4: Mean of adult cook ADLs across treatment and control

5. Empirical Results

5.1 Child growth

Table 2 presents estimates of the impacts of treatment status and stove use on child growth from equation (2). Columns 1 through 3 focus on intent to treat effects of treatment assignment. All models include additional individual and household level controls and standard errors adjusted for clustering at the household level given the multiple children per household structure of the data.

[Table 2 here]

Table 2: Effects of Improved Stoves on Child Height-for-Age

	Dep. Var.: Height-for-age (z-score std. deviations)					
	Intent to Treat Effects (ITT)			**Stove Use Effects**		
Model Specification	**OLS**	**RE**	**FE**	**IV**	**IV-RE**	**IV-FE**
	(1)	**(2)**	**(3)**	**(4)**	**(5)**	**(6)**
Treatment X Baseline Age < 36 mo.	0.277*	0.367**	0.383**			
	(0.153)	(0.148)	(0.168)			
Treatment X Baseline Age ≥ 36 mo.	-0.013	0.024				
	(0.140)	(0.135)				
Stove Use X Baseline Age < 36 mo.				0.320*	0.425**	0.447**
				(0.172)	(0.170)	(0.195)
Stove Use X Baseline Age ≥ 36 mo.				-0.016	0.026	
				(0.155)	(0.153)	
Additional controls	yes	yes	yes	yes	yes	yes
Household random effects		yes			yes	
Household fixed effects			yes			yes
Observations	1,152	1,152	1,152	1,152	1,152	1,152

Notes: Table reports intent to treat estimates of stove offers in columns 1-3 and instrumental variable effects of stove use in columns 4-6. Columns 2 and 5 include household level random effects and columns 3 and 6 include household fixed effects. Dependent variable is child height-for-age (z-scores), standardized according to the CDC growth tables. Sample is all children ages 15 and under. All models include a cubic polynomial in age in months, sex, mother's height and age, and father's age. Household level controls are omitted from regressions with household fixed effects, and include household size and demographic composition, age, education and sex of the household head, dwelling characteristics, community fixed effects, and a composite wealth index. Standard errors clustered at the household level in parentheses. ** p<0.05, * p<0.1.

Column 1 presents treatment estimates for both those children exposed while in the sensitive period and older children. The estimates suggest being in a household that was offered a *Mirt* stove while in the sensitive period of growth is associated with a 0.277 standard deviation increase in predicted height-for-age relative to the control children of the same age. This is a sizeable effect and similar in scale to the estimated benefits of improved cookstoves on birth outcomes such as gestational age and birth weight (e.g. Alexander et al., 2018), suggesting part of the mechanism may work through in-utero exposure.

The underlying physiology predicts there should be no impact on older children in the treatment group. The point estimate of -0.013 standard deviations (p-value = 0.92) points to this conclusion, as treatment children older than 36 months at the baseline saw no benefit in terms of their height-for-age at follow-up compared to children in the control group. This is in-line with established literatures in nutrition and epidemiology, and supports the experimental design of our study as it implies there were no pre-existing differences in height-for-age across treatment and control children.

Column 2 of Table 2 exploits the multiple children per household structure of the data and includes household random effects. Estimates in Column 2 suggest a precisely estimated 0.367 standard deviation treatment effect for young children (p-value = 0.013) and a null effect for older children.

Column 3 is the most demanding of the specifications as it includes household fixed effects and is identified only from comparisons of siblings within the same household. Given the within-household design, it is not possible to identify the effects for both younger and older children presented in columns 1 and 2, as older treatment children become the comparison group for younger treatment children. All observed and unobserved characteristics common at the household level are absorbed into the fixed effect, and biases threatening the causal interpretation of the estimates would have to vary within treatment and control households in such a way as to be correlated both with treatment status and only positively impact the youngest children.

The 0.383 estimate in Column 3 suggests that, conditional on the ages of the children, young children in treatment households are 0.383 standard deviations taller compared to older children within their same households than young children in control households are compared to their older control siblings. The result is again precisely estimated (p-value = 0.023). This is a large and meaningful finding, corresponding to approximately a 2cm gain for a 3-year-old child.

Columns 4 through 6 report treatment effects of stove use measured as the share of months the household used the stove. These results are instrumental variable estimates where stove use-by-age interactions are instrumented with treatment status interacted with the corresponding ages. The results suggest the use of the stove over the full period relates to gains in height-for-age between 0.32 and 0.45 standard deviations for children in the sensitive period of growth, with no benefits for older children. Both results are important—these are sizable gains for young children, and the expected placebo effect of older children again suggests this is a valid empirical approach.

5.2 Respiratory symptoms and adult physical functioning

Table 3 summarizes the ITT and use impacts on acute respiratory symptoms and measures of physical functioning for older children and adults. Unlike height-for-age, these domains are potentially malleable across the age distribution, thus estimates are determined by differences across households. Models include individual, household, and community-level controls as in equation (1) and standard errors are adjusted for clustering.[10] Supplementary Appendix Tables A3, A4, and A5 report results for the 20 individual symptoms and 12 activities of daily living used to construct the summary measures in Table 3.

[Table 3 here]

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[10] We cluster at the village level for adults and, to account for multiple children per household, at the household level for child outcomes. The lack of statistically significant effects shown in Table 3 are consistent with those that adjust for multiple hypothesis testing.

Table 3: Effects of Improved Stoves on Symptoms and Physical Functioning

	Children			Adult Cooks				
	N. Symptoms (1)	Any Symptoms (2)	Any Cough (3)	N. Symptoms (4)	Any Symptoms (5)	Any Cough (6)	Unable to Do any ADLs (7)	N. ADLs with Difficulty (8)
Intent to Treat								
Treatment	-0.116	-0.048	-0.018	0.042	-0.014	0.051	0.023	0.192
	(0.251)	(0.037)	(0.035)	(0.414)	(0.038)	(0.050)	(0.043)	(0.287)
Use Effects								
Stove Use	-0.132	-0.054	-0.020	0.048	-0.016	0.057	0.026	0.217
	(0.278)	(0.041)	(0.039)	(0.430)	(0.039)	(0.052)	(0.044)	(0.299)
Additional Controls	y	y	y	y	y	y	y	y
Control group mean	2.262	0.516	0.271	5.243	0.846	0.353	0.507	3.868
Observations	1,147	1,147	1,147	475	475	475	475	475

Notes: Table reports estimates of the impact of stove offers and stove use. ITT and stove use estimates come from separate regressions. The dependent variable is the number of symptoms reported in columns 1, 4, and 8 and linear probability models with binary outcome indicators for remaining columns. Sample is all children ages 15 and under in columns 1-3 and adult cooks 16 and older in columns 4-8. Additional controls include cubic polynomial in age in months, sex, mother's age and height, father's age, household size and demographic composition, household head age, education, and sex, dwelling characteristics, community fixed effects, and a wealth index. Standard errors clustered at the household level for child outcomes and community level for adult outcomes in parentheses.

Columns 1 through 3 report impacts on acute symptoms for older children. The results suggest there are no precisely estimated links between the *Mirt* intervention and one's symptom burden over the prior 4-week period. There is no evidence of ITT or use effects for the total number of symptoms in Column 1, an indicator for any symptoms in Column 2, or for cough specific symptoms in Column 3.

While many of the point estimates are negative and suggest reduced symptom loads for children in treatment households, the results should be interpreted as suggestive at best. For the 20 specific symptoms in Supplementary Appendix Table A3, we estimate one reduction at the five percent significance level on headaches and one effect at the ten percent level—results which are balanced out by estimated increases in wheezing and shortness of breath. Such a pattern is consistent with pure chance given the expected error rates and the number of outcomes. Adjusting statistical significance thresholds for multiple comparisons only further pushes the results toward concluding a lack of effect.[11] The null findings also hold when examining subgroups of the population based on specific 5-year age groups (ages 5 and under, 6–10, and 11–15), regions, and baseline wealth quantiles.

The remainder of Table 3 presents results for adult cooks. Columns 4 through 6 show that there are no meaningful links between a cook's reported symptoms and either assigned treatment status or stove use. Columns 7 and 8 report effects for summary measures of the activities of daily living outcomes assessing the likelihood of experiencing any specific difficulties and the number of reported difficulties. The estimated effects are small in magnitude and not statistically different from zero.[12] The null physical functioning results hold using ordered probit models to examine the gradient of difficulties

[11] This conclusion follows from multiple hypothesis adjustment using either the Bonferroni correction, the Benjamini-Hochberg procedure (e.g. Fink et al., 2014) or methods described in Duflo et al. (2007) and Young (2019).

[12] While lack of statistical power for adult outcomes, rather than lack of a true effect, is also a possible explanation for null findings, adult symptom and activities of daily living indicators had ex-ante minimum detectable effects (MDE) of 0.13 and 0.17, respectively. The corresponding coefficient estimates in columns 5, 6, and 7 of Table 3 are small in magnitude, both absolutely and relative to the MDEs, suggesting the lack of actual ITT and use effects.

for each outcome and when considering binary outcomes for severe levels of limitations rather than severe or moderate difficulty used in Table 3. As with children, the null findings hold after dividing the adult cooks by age, by region, and by wealth quantile.

Taken as a whole, the results suggest a nuanced pattern of significant gains in early-life growth for young children, yet no noticeable impacts for either adult cooks or older children. Understanding the physiological mechanisms facilitating growth effects alongside null results on other health domains for older individuals remains a key component in this research program. We next present evidence examining the link between pollution measurements and health outcomes.

6. Mechanisms–Pollution Concentrations and Health Outcomes

As a step toward explaining the high rates of *Mirt* use, positive child growth effects, and the absence of other health effects, we examine the relationship between indoor air quality measures and key health outcomes. Indoor exposure to pollutants from the combustion of solid fuels was measured with pump and filter kits and light scattering meters for a random subset of 202 households: 99 treatments and 103 controls. More details on the data collection process and treatment effects of the intervention on air pollution levels are provided in Bluffstone et al. (2018).

The recorded levels of particulate matter in the treatment and control households are consistent with measurements in similar environments (Chen et al., 2016; Dutta et al., 2007) and well above WHO standards. Mean (median) concentrations in treatment and control households are 1162 (464) and 1297 (525) $\mu g/m^3$ for average 24-hour exposure. Twenty-four-hour maximum concentration levels are an order of magnitude higher. For comparison, the WHO's current recommended 24-hour safety standard is 25 $\mu g/m^3$ (WHO, 2015).

Here, we make use of household air pollution measures to descriptively assess the possibility of pollution-health gradients. For each of our key outcomes, we estimate regressions of an individual's health marker against the natural log of their household's particulate concentration. As the shape of these exposure-response functions has only recently begun to be investigated (Burnett et al., 2014), particularly at the observed, high levels of $PM_{2.5}$, our results should be interpreted as suggestive evidence of a link rather than the exact magnitude of the health-pollution slope.

6.1 Indoor air pollution and child growth

Panel A of Table 4 reports results with a child's height-for-age z-score as the dependent variable and the log of the maximum particulate matter concentrations as the key variable on the right-hand side. Following the known sensitive period of growth, in columns 1 through 3 we focus on children currently under 36 months of age who would be contemporaneously impacted by the measured pollution level.[13]

There is a clear, statistically significant link between reductions in log maximum $PM_{2.5}$ and improvements in child height-for-age. Column 3, which includes individual and household level controls, suggests that a 24 percent decrease in maximum $PM_{2.5}$, the observed decrease across treatment and control households with young children, relates to a 0.1 standard deviation increase in height for age ($0.24*(e^{-0.569}-1)$). This effect is sizable yet smaller than the 0.3 standard deviation estimate in Table 2.

[Table 4 here]

[13] Supplementary Appendix Table A6 repeats the analysis in Table 4 using the mean $PM_{2.5}$ concentration rather than the maximum.

Table 4: Relationship between Health Outcomes and Indoor PM2.5

A. Child Height-for-Age

	Age less than 36 months Height-for-Age (z-score)			Age less than 76 Months Height-for-Age (z-score)		
	(1)	(2)	(3)	(4)	(5)	(6)
ln(Maximum PM2.5 level)	-0.638**	-0.471**	-0.569**	-0.304**	-0.239**	-0.295***
	(0.252)	(0.177)	(0.239)	(0.123)	(0.110)	(0.108)
Individual Level Controls		y	y		y	y
Household Level Controls			y			y
Observations	53	53	53	159	159	159

B. Respiratory Symptoms and Physical Functioning

	Children		Adult Cooks			
	N. Symptoms	Any Symptoms	N. Symptoms	Any Symptoms	Any ADL limitations	N. ADL limitations
	(1)	(2)	(3)	(4)	(5)	(6)
ln(Maximum PM2.5 level)	-0.302	-0.007	-0.010	-0.004	-0.015	0.093
	(0.246)	(0.033)	(0.357)	(0.026)	(0.041)	(0.239)
Individual Level Controls	y	y	y	y	y	y
Household Level Controls	y	y	y	y	y	y
Observations	513	513	202	202	202	202

Notes: Table reports results from regressions of health outcomes on log maximum indoor PM2.5 concentrations. Panel A examines child height for age for children under 36 months old in columns 1-3 and under 76 months old in columns 4-6. Panel B. examines respiratory symptoms for children 15 years and under in columns 1 and 2 and adult cook outcomes in columns 4 through 6. Individual level controls include a cubic polynomial in age, sex, mother's height and age, and father's age. Household level controls include household size and demographic composition, age, education and sex of the household head, dwelling characteristics, and a composite wealth index. Standard errors robust to clustering at the household level used for child outcomes and community level used for adult outcomes. *** p<0.01, ** p<0.05

Columns 4 through 6 of Panel A repeat the analysis including all children under 76 months old who had the potential to benefit from the intervention during their sensitive period of growth. This approach requires that pollution readings captured at the follow-up wave reflect exposure across the prior forty-month period. The negative and statistically significant relationship between maximum $PM_{2.5}$ and height-for-age persists, although the magnitude falls by approximately fifty percent. The 36 to 76-month group independently has a -0.201 estimate (*p*-value = 0.11), suggesting that the link between measured pollution and height-for-age is strongest for children in the sensitive growth period.

6.2 Respiratory symptoms, adult ADLs, and pollution

While there is suggestive evidence of a pollution–height-for-age link at the observed levels of particulate concentration, we find no such link for respiratory symptoms or activities of daily living. Panel B of Table 4 presents estimates for summary measures of child symptoms in columns 1 and 2, and adult cook outcomes in columns 3 through 6. All regressions include additional individual and household level controls.

Of the six estimates, none are statistically significant. The effects do not appear to be driven by small sample size concerns, as many of the effects are small in magnitude.

Taken together with Panel A, the null findings in Panel B suggest a plausible pollution-health mechanism that would lead to growth effects for young children, even without observed health benefits for adult cooks and older children. This pattern is plausibly consistent with physiological scarring attributed to cumulative exposure to high levels of particulate matter in the past for adults and older children (Naeher et al., 2007).

7. Discussion

We examine the health impacts of transitioning to the *Mirt* improved biomass cookstove in a randomized trial conducted in rural Ethiopia. Though the *Mirt* stove is not a stove that may be expected to achieve WHO guideline levels for indoor air quality, in line with other studies (e.g. Bensch and Peters, 2015), we find potentially important health effects for part of our sample population. These findings suggest that some improved biomass cookstoves that reduce fuelwood consumption may also offer health benefits. Three and a half years after the initial distribution of the stoves, households randomly assigned to receive the units continued to use the technology at a high rate, and young children in these households experienced significant gains in height-for-age on the order of 0.3 to 0.4 standard deviations. We interpret these findings as suggesting the *Mirt* stove may be one additional tool to improve child well-being alongside established evidence on the importance of broad nutrition and child health programs.

However, adult cooks and older children experienced no gains in measured respiratory symptoms or markers of physical function. While little is known about the specific health benefits of pollution reductions at the high levels of $PM_{2.5}$ observed in the study, we find evidence suggesting the change in $PM_{2.5}$ due to the *Mirt* stove is enough to cause improvements in height-for-age, though not enough to see noticeable differences in older individuals. Compared to results seen in laboratory tests, the continued use of open-fire traditional cooking alongside the improved stove appears to attenuate the health benefits of the *Mirt* stove in actual households.

From a policy perspective, the child growth gains may appear modest given the null impact on adults and older children. Still, over the course of a child's life they represent significant benefits due to the later-life impacts of early-life health improvements. Children who are taller early in life are more likely to complete primary and secondary education, develop greater cognitive capacity, earn more as adults, and live longer, healthier lives. The results presented here suggest exposure to high levels of particulate matter from biomass smoke is a contributing factor to a significant health burden for young children, and that its mitigation may result in significant improvements in well-being around the world.

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Supplementary Appendix Tables

Appendix Table A1: No Evidence of Selective Attrition

	Dependent Variable: I(Not in 2nd Wave)					
	Household Level			Individual Level		
	(1)	(2)	(3)	(4)	(6)	(7)
Treatment	0.015	0.016	0.011	-0.017	-0.018	-0.025
	(0.019)	(0.019)	(0.019)	(0.027)	(0.028)	(0.027)
Baseline wealth index		-0.006	0.002		-0.004	-0.001
		(0.010)	(0.018)		(0.011)	(0.027)
Additional baseline controls			yes			yes
Constant	0.035**	0.034**	0.046	0.060**	0.107**	0.073
	(0.015)	(0.015)	(0.079)	(0.025)	(0.054)	(0.125)
Observations	504	504	504	1,257	1,257	1,257

Notes: Robust standard errors in parentheses. Additional controls include region, nationality, and religion indicators, household size and demographic composition, and size of landholdings. Individual level analysis also includes controls for age and sex. ** p<0.05

Appendix Table A2: No Evidence of Differential Fertility Across Treatment and Control

	Dep. Var.: N. New Children		
	All	Girls	Boys
	(1)	(2)	(3)
Treatment	-0.009	-0.025	0.016
	(0.059)	(0.050)	(0.039)
Constant	0.424***	0.245***	0.180***
	(0.050)	(0.043)	(0.033)
Observations	480	480	480

Robust standard errors in parentheses. *** p<0.01, ** p<0.05, * p<0.1

Appendix Table A3: Effects of Improved Stoves on Child Health Symptoms

	I(Experienced […] in last 4 weeks)										
	N. of Symptoms	**Any Symptoms**	**Cough**	**Dry Cough**	**Cough w. Phlegm**	**Difficulty Breathing**	**Shortness of Breath**	**Wheezing**	**Headache**	**Dizziness**	**Sore Eyes**
	(1)	**(2)**	**(3)**	**(4)**	**(5)**	**(6)**	**(7)**	**(8)**	**(9)**	**(10)**	**(11)**
Intent to Treat											
Treatment	-0.078	-0.046	-0.013	0.014	-0.034*	0.021	0.029*	0.024***	-0.060**	-0.018	-0.003
	(0.184)	(0.029)	(0.027)	(0.024)	(0.020)	(0.016)	(0.015)	(0.009)	(0.026)	(0.019)	(0.020)
Use Effect											
Stove Use	-0.088	-0.053*	-0.015	0.016	-0.039*	0.024	0.033**	0.028***	-0.068**	-0.021	-0.004
	(0.204)	(0.032)	(0.030)	(0.027)	(0.023)	(0.017)	(0.017)	(0.010)	(0.029)	(0.021)	(0.022)
Additional Controls	y	y	y	y	y	y	y	y	y	y	y
Control group mean	2.262	0.516	0.268	0.175	0.131	0.058	0.053	0.012	0.236	0.117	0.125
Observations	1,147	1,147	1,147	1,147	1,147	1,147	1,147	1,147	1,147	1,147	1,147

	I(Experienced […] in last 4 weeks)										
	Weak	**Chest pain**	**Sore Throat**	**Sneezing**	**Runny Nose**	**Fever**	**Stomach Ache**	**Nausea**	**Diarrhea**	**Constipation**	**Joint Pain**
	(12)	**(13)**	**(14)**	**(15)**	**(16)**	**(17)**	**(18)**	**(19)**	**(20)**	**(21)**	**(22)**
Intent to Treat											
Treatment	0.006	-0.002	-0.003	-0.003	0.004	-0.029	0.020	-0.008	-0.020	0.013	-0.021
	(0.013)	(0.014)	(0.016)	(0.024)	(0.023)	(0.023)	(0.019)	(0.016)	(0.016)	(0.010)	(0.013)
Use Effect											
Stove Use	0.006	-0.002	-0.003	-0.004	0.004	-0.033	0.023	-0.009	-0.023	0.015	-0.023*
	(0.014)	(0.015)	(0.017)	(0.026)	(0.026)	(0.026)	(0.021)	(0.018)	(0.017)	(0.012)	(0.014)
Additional Controls	y	y	y	y	y	y	y	y	y	y	y
Control group mean	0.041	0.055	0.061	0.201	0.216	0.181	0.114	0.090	0.061	0.020	0.041
Observations	1,147	1,147	1,147	1,147	1,147	1,147	1,147	1,147	1,147	1,147	1,147

Notes: Table reports estimate of impact of stove offers and stove use. ITT and use estimates come from separate regressions. The dependent variable is the number of symptoms reported in Column 1 and linear probability models for presence of specific symptoms in columns 2 through 22. Sample is all children ages 15 and under. Additional controls include cubic polynomial in age in months, sex, mother's age and height, father's age, household size and demographic composition, household head age, education, and sex, dwelling characteristics, site fixed effects, and a wealth index. Robust standard errors in parentheses. *** p<0.01, ** p<0.05, * p<0.1

Appendix Table A4: Effects of Improved Stoves on Adult Cook Health Symptoms

						I(Experienced […] in last 4 weeks)					
	N. of Symptoms	Any Symptoms	Cough	Dry Cough	Cough w. Phlegm	Difficulty Breathing	Shortness of Breath	Wheezing	Headache	Dizziness	Sore Eyes
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)
<u>Intent to Treat</u>											
Treatment	0.062	-0.011	0.034	0.025	0.072*	0.053	-0.000	-0.046	0.015	-0.052	0.044
	(0.434)	(0.037)	(0.045)	(0.037)	(0.037)	(0.039)	(0.027)	(0.050)	(0.045)	(0.051)	(0.046)
<u>Use Effect</u>											
Stove Use	0.070	-0.012	0.038	0.028	0.081**	0.060	-0.001	-0.052	0.017	-0.059	0.050
	(0.457)	(0.039)	(0.048)	(0.039)	(0.038)	(0.041)	(0.029)	(0.053)	(0.047)	(0.053)	(0.049)
Additional Controls	y	y	y	y	y	y	y	y	y	y	y
Control group mean	5.259	0.844	0.348	0.252	0.156	0.185	0.193	0.0815	0.615	0.430	0.370
Observations	475	475	475	475	475	475	475	475	475	475	475

					I(Experienced […] in last 4 weeks)						
	Weak	Chest pain	Sore Throat	Sneezing	Runny Nose	Fever	Stomach Ache	Nausea	Diarrhea	Constipation	Joint Pain
	(12)	(13)	(14)	(15)	(16)	(17)	(18)	(19)	(20)	(21)	(22)
<u>Intent to Treat</u>											
Treatment	-0.063	-0.051	-0.002	-0.014	-0.054	0.049	-0.031	0.001	0.002	0.031	-0.063
	(0.046)	(0.034)	(0.046)	(0.044)	(0.050)	(0.049)	(0.036)	(0.018)	(0.026)	(0.045)	(0.046)
<u>Use Effect</u>											
Stove Use	-0.071	-0.057	-0.002	-0.016	-0.061	0.055	-0.035	0.001	0.003	0.035	-0.071
	(0.048)	(0.035)	(0.049)	(0.046)	(0.052)	(0.051)	(0.038)	(0.019)	(0.027)	(0.047)	(0.048)
Additional Controls	y	y	y	y	y	y	y	y	y	y	y
Control group mean	0.333	0.326	0.148	0.259	0.259	0.385	0.326	0.156	0.0370	0.0667	0.319
Observations	475	475	475	475	475	475	475	475	475	475	475

Notes: Table reports estimate of impact of stove offers and stove use. ITT and use estimates come from separate regressions. The dependent variable is the number of symptoms reported in Column 1 and linear probability models for presence of specific symptoms in columns 2 through 22. Sample is primary cook in the household. Additional controls include age indicators, sex, household size and demographic composition, household head age, education, and sex, dwelling characteristics, site fixed effects, and a wealth index. Robust standard errors in parentheses. *** $p<0.01$, ** $p<0.05$, * $p<0.1$

Appendix Table A5: Effects of Stove Offers and Use on Adult Cook Activities of Daily Living (ADLs)

	I(Unable to Do any ADL)	N. of ADLs with Difficulty	I(Experience any difficulty with […]) Use Bathroom	Bow, Squat, or Kneel	Dress without Help	Work in the Field for One Day	Routine Housework
	(1)	(2)	(3)	(4)	(5)	(6)	(7)
Intent to Treat							
Treatment	0.019	0.167	0.006	0.025	-0.003	0.025	-0.043
	(0.046)	(0.249)	(0.010)	(0.045)	(0.011)	(0.043)	(0.039)
Use Effect							
Stove Use	0.021	0.189	0.006	0.028	-0.004	0.028	-0.048
	(0.048)	(0.263)	(0.011)	(0.048)	(0.011)	(0.046)	(0.042)
Additional Controls	y	y	y	y	y	y	y
Observations	475	475	475	475	475	475	475

	I(Experience any difficulty with […]) Carry a Heavy Load 20m	Run for 1k	Stand from Sitting on Chair	Stand from Sitting on Floor	Walk for 5k	Walk 200m	Draw Water from a Well
	(8)	(9)	(10)	(11)	(12)	(13)	(14)
Intent to Treat							
Treatment	0.031	0.025	0.013	0.002	0.052	-0.008	0.044
	(0.046)	(0.034)	(0.027)	(0.031)	(0.049)	(0.038)	(0.050)
Use Effect							
Stove Use	0.035	0.028	0.015	0.002	0.058	-0.009	0.050
	(0.049)	(0.036)	(0.028)	(0.033)	(0.051)	(0.041)	(0.053)
Additional Controls	y	y	y	y	y	y	y
Observations	475	475	475	475	475	475	475

Notes: Table reports intent to treat and local average treatment effects of improved stoves on adult cook's Activities of Daily Living. Models in columns 2 through 14 are linear probability models with the outcome equal to one if the respondent reports any degree of difficulty (difficult, can do on own/difficult, can do with help/unable to do at all). Sample is all cooks ages 18 and above. Additional controls include age indicators, sex, household size and demographic composition, household head age, education, and sex, dwelling characteristics, site fixed effects, and a wealth index. Robust standard errors in parentheses. ** p<0.05, * p<0.1

Appendix Table A6: Relationship between Indoor Mean PM2.5 and Health Outcomes

A. Child Height-for-Age	Birth to 36 Months Height-for-Age (z-score)			Birth to 76 Months Height-for-Age (z-score)		
	(1)	(2)	(3)	(4)	(5)	(6)
ln(Mean PM2.5 level)	-0.355*	-0.274*	-0.242	-0.141	-0.102	-0.112
	(0.182)	(0.155)	(0.168)	(0.086)	(0.082)	(0.090)
Individual Level Controls		y	y		y	y
Household Level Controls			y			y
Observations	53	53	53	159	159	159

B. Respiratory Symptoms and Physical Functioning	Children		Adult Cooks			
	N. Symptoms	Any Symptoms	N. Symptoms	Any Symptoms	Any ADL limitations	N. ADL limitations
	(1)	(2)	(3)	(4)	(5)	(6)
ln(Mean PM2.5 level)	-0.044	-0.004	-0.121	-0.006	-0.006	0.043
	(0.119)	(0.017)	(0.250)	(0.019)	(0.027)	(0.144)
Individual Level Controls	y	y	y	y	y	y
Household Level Controls	y	y	y	y	y	y
Observations	513	513	202	202	202	202

Notes: Table reports results from regressions of health outcomes on log mean indoor PM2.5 concentrations. Panel A examines child height for age for children birth to 36 months in columns 1-3 and birth to 76 months in columns 4-6. Panel B. examines respiratory symptoms for children birth to 15 years in columns 1 and 2 and adult cook outcomes in columns 4 through 6. Individual level controls include a cubic polynomial in age, sex, mother's height and age, and father's age. Household level controls include household size and demographic composition, age, education and sex of the household head, dwelling characteristics, site fixed effects, and a composite wealth index. Standard errors robust to clustering at the household level used for child outcomes and community level used for adult outcomes. *** $p<0.01$, ** $p<0.05$, * $p<0.1$