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Abstract*

Ambient air pollution is a serious problem in cities in south-central Chile because of massive combustion of wood as fuel for residential heating. To reduce air pollution emissions, Chile's environmental authority has implemented a large-scale program consisting of replacing old, highly polluting residential wood stoves with new, less polluting ones. However, to extend burning time and save on wood fuel expenditures, users tend to dramatically constrain the air flow in these new wood stoves, which creates a highly polluting combustion process. To address this issue a behavioral intervention was designed to provide users with feedback on their wood stoves' air pollution emissions. The intervention consists of a metallic sign that aligns with the wood stoves damper lever and that informs users of the level of pollution emissions according to the chosen setting of the wood stove's damper. To assess the effectiveness of this information sign, a randomized controlled trial (RCT) is conducted in selected households in the city of Valdivia, Chile. Results from this intervention show that the information sign induced a behavioral change in wood stove users that translates into a 17.3 percent reduction in residential pollution emissions.

JEL classifications: C93, O13, Q53, Q56.
Keywords: Field experiment, Environment and development, Air pollution, Wood stoves

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1. Introduction

Ambient air pollution caused by burning wood fuel for heating and cooking is a serious concern in many urban areas of the developing world (Chávez, Stranlund and Gómez, 2011). This problem is particularly serious during the cold months in the south-central region of Chile, where ambient air pollution concentrations, largely from wood stoves, have reached extremely high levels, causing serious consequences for the health and wellbeing of the population. According to a 2018 ranking of the world's most polluted cities for fine particulate matter (PM2.5), eight of the top 10 most polluted cities in South America are in Chile's south-central region. Valdivia, the city where we conducted the field experiment discussed in this paper, is ranked fourth. In addition, seven more cities in this region appear among the top 20.[1]

To address this issue, Chile's environmental authority has pushed in recent years for a large-scale program to replace high-polluting residential wood stoves with new and less polluting models.[2] These heavily subsidized woodstoves, as well as all those that have been available in the market in the last decade, feature state-of-the-art combustion technologies. This results in minimal indoor pollution emissions and low outdoor pollution emissions, but only under "optimal" operating conditions and not necessarily under "real world" operating conditions. This is because wood stove outdoor pollution emissions vary largely according to the setting of the stove's damper, which regulates airflow inside the combustion chamber, and these new wood stoves allow users to freely choose the damper's setting. Moreover, to extend wood-burning time and reduce expenditure on wood fuel, users usually set the damper so as to fully choke airflow.

Wood stove outdoor pollution emissions present a highly non-linear relationship with respect to the damper setting, and those emissions when fully choked are many times larger than those in any other setting (even compared to emissions when only partially choking them). As a

[1] The cities in Chile's south-central region listed in this ranking are: Padre Las Casas (Rank #1), Osorno (#2), Coyhaique (#3), Valdivia (#4), Temuco (#5), Linares (#8), Rancagua (#9) and Puerto Montt (#10). Santiago, Chile's capital but not in the south-central region, is ranked #6. Source: www.airvisual.com/world-most-polluted-cities

[2] Chile's environmental authority has designed and implemented Air Pollution Control and Prevention Plans (PPDA, according to the Spanish acronym) in most of the cities in this region. There are currently 10 PPDAs at different stages of implementation. The PPDAs consider four lines of action focused on improving the energy efficiency of homes, the quality of heating systems, the quality of fuels for energy, and education programs. However, these policies have not yielded the expected results and, despite their implementation, ambient air pollution concentrations have continued to increase in all major cities of the region (Schueftan and González, 2015).

consequence, the choking of wood-stoves can result in outdoor pollution emissions as much as five times greater than under optimal wood fuel burning conditions (Jordan and Seen, 2005).[3]

Moreover, because most dwellings in cities of south-central Chile suffer from high rates of infiltration (through windows, doors, walls, roofs and ceilings that are not properly sealed) ambient air pollution from wood fuel burning leaks to the interior of dwellings. This generates a problem of local air pollution where the most affected individuals are members of households using wood stoves and their close neighbors. As a consequence, when aggregated at the neighborhood and city level in these cities in south-central Chile, individual household behavior creates large systemic effects on overall concentrations of ambient air pollution.[4] As per the individuals that operate their woodstoves, it is certainly more convenient to choke them, as doing so extends wood fuel burning time of the wood-fuel. Thus, in addition to the convenience of not constantly having to load their woodstoves, choking wood stoves allows users to save on wood fuel expenditures. Therefore, users' decision on whether or not to choke their own wood stoves can be characterized as a voluntary contribution to a local public good in which wood stove users face individual (or household-level) incentives to choke their woodstove at the expense of (marginally) contributing to higher local ambient air pollution concentrations. Furthermore, whereas the benefits of using their wood stoves in such a way that saves on wood fuel are immediately perceptible (via a comfortable warm dwelling and savings in fuel costs), the costs of air pollution are shared among the neighboring population (regardless of who emits air pollutants). While those costs do not necessarily produce immediate consequences, they are likely to be cumulative over time.[5]

In this paper we examine whether users can be *nudged* into low outdoor air pollution emissions by providing information feedback on their wood stove emissions. As wood stove pollution emissions vary according to damper setting, which in turn, adjusts the airflow in the

[3] The choking of these wood stoves creates smoldering and low-temperature combustion, thus creating a highly polluting combustion process with no vivid flame that efficiently burns wood-fuel. Moreover, when choking these wood stoves the smoke from the burning of wood-fuels exits the chimney at a low temperature and so that reaching a low elevation upon exiting. Thus, as opposed to being taken away by stronger winds at higher elevations, this causes the smoke from burning wood-fuel to remain at ground-level, which further exacerbates the problem of high air pollution concentrations.

[4] This problem is even more serious in low-income neighborhoods where there is a higher density of dwellings (with low quality construction materials and more infiltrations), which creates higher concentrations of air pollution with more emitters and less distance between them.

[5] Miller and Ruiz-Tagle (2018) provide causal estimates of the effect of exposure to air pollution on infant mortality for Santiago, Chile. The authors find that the cumulative effects (over a six-month period of exposure) of air pollution on infant mortality could be twice as large as the acute (same-week) effects.

combustion chamber—the information sign informs users of current air pollution emissions of their own respective wood stoves according to the damper setting selected. Our hypothesis is that users will respond to this visual aid by decreasing the frequency of the choking of their wood stoves. Therefore, in this paper we evaluate whether providing an information sign that delivers *real-time* feedback on wood stove pollution emissions can effectively reduce outdoor air pollution emissions. We assess this by conducting a randomized controlled trial (RCT) involving a framed field experiment in which we provided a random group of households (*treatment group*) with an information sign. Users subject to this intervention were free to set their wood-stove's damper in any way they want—choking it to save on wood fuel expenditure, opening the airflow in the combustion chamber to decrease outdoor pollution emissions, or any setting in between. However, by means of the information sign users in this group knew that any setting of the damper they choose is associated with a certain level of their wood-stoves' actual outdoor pollution emissions. On the other hand, users in the *control group* were not provided with this information sign. Moreover, the actual setting of wood stoves dampers was monitored and recorded for both treatment and control groups.

Our results show that conveying feedback on wood stove emissions induces a significant behavioral change in wood-stove users by reducing the frequency with which they choose the fully choked damper setting. Moreover, this induced behavioral change has also important effects on reducing wood-stoves' outdoor air pollution emissions. Our results show that providing users with this information significantly reduces wood stove outdoor emissions of fine particulate matter ($PM_{2.5}$).

The rest of the paper is organized as follows. The next section reviews the related literature, and Section 3 describes in greater detail the problem of air pollution in these cities as well as policies targeted to address this problem. Section 4 explains the experimental design, and Section 5 presents the main results of the behavioral intervention. Finally, Section 6 presents concluding remarks.

2. Literature Review

2.1 Literature on Air Pollution from Burning Wood Fuel in Chile

Chile's environmental authority (Ministry of Environment) has designed a battery of policies to address the problem of ambient air pollution under the Air Pollution Control and Prevention

Plans (PPDA). Chile's Ministry of Environment has produced official reports that assess ex ante the expected effect of different policies on mitigating the problem of ambient air pollution (MMA, 2014a). These reports predict scenarios for the different programs that are being implemented under the PPDA as well as the expected effects that those programs could have in the next 15 years. Using official data from laboratory tests of the performance and emissions produced by different types of wood stoves, these reports assess the expected effects of the wood-stove replacement programs. Users' behavior regarding actual operation of these wood-stoves, however, has not yet been assessed, and that behavior can have a large effect on pollution emissions.

On the other hand, recent academic papers assess the potential effect of alternative policies to reduce air pollution. For instance, Chávez et al. (2009) examine the effect of price incentives such as demand and supply subsidies as well as strengthening command-and-control policies of standards on wood fuel consumption.[6] Additionally, UFRO-CONAMA (2009), Chávez, Gómez and Salgado (2011); and Gómez et al. (2017) have focused on evaluating the wood-stove replacement program, particularly for the city of the Temuco—which was the first city to have a PPDA and to extensively apply these pollution reduction policies.[7] Furthermore, more recently Gómez et al. (2014); Gómez et al. (2013); and Jaime, Chávez and Gómez (2017) have focused on assessing the design of subsidies and the effect of prices and income in order to increase adoption of cleaner wood fuels and improved wood stove devices. However, all these papers acknowledge that the real effect on emissions reduction is uncertain due to the impact of users' behavior when operating their wood stoves.

Moreover, a recent paper by Schueftan et al. (2016) compared the environmental, economic and social effect of different policies focused on improving heating systems, quality of fuels and energy efficiency of dwellings. Schueftan et al. (2016) argue that the most effective strategy is to focus on reducing energy demand by improving the energy efficiency of

[6] Chávez et al. (2009) examined the use of certified wood fuel with appropriate moisture content. The authors conclude that command-and-control policies are more cost effective and therefore be the preferred environmental policy for tackling air pollution caused by burning wood fuel in cities in the south-central region of Chile. Therefore, the use of certified-dry wood fuel with an appropriate moisture content should be enforced, as only 1 percent of dwellings use certified-dry wood fuel due to its higher price. However, the effects of command-and-control policies on reducing air pollution are expected to be small.

[7] These studies presented different technology options to induce the adoption of cleaner and more efficient wood burning technologies. Jaime, Chávez and Gómez (2017) considered a pilot program and studied the factors that affected the decision to participate in these programs. They found that the availability of a subsidy and the possibility of having a credit were both very important, especially in low-income households.

buildings.[8] Nonetheless, energy efficiency retrofits are a more complex and expensive strategy that still has many barriers in order to be implemented as a large-scale program, and implementing such programs take a long time. In the meantime, other complementary interventions should be considered in the short term.

2.2 Literature on Information Feedback Interventions

The strategy of providing feedback on wood stoves' pollution emissions can be more closely linked to recent studies that assess information feedback strategies to induce savings in residential energy and resource consumption in the developed world. This literature focuses largely on evaluating the effectiveness of smart meters and in-home displays in achieving reductions of residential energy consumption. A review of this literature shows that providing information and feedback on energy consumption promotes more efficient patterns of energy use and thus promotes conservation efforts (Price, 2014).[9] In this section we draw some lessons from this literature that are also relevant for the context of this work. In particular, information feedback is more effective when the action that aims to affect occurs with high frequency and feedback is given soon after this action (Fischer, 2008). The literature thus underscores that *real-time* feedback is a desirable feature of information feedback strategies as it strengthens the link between the current action and its associated consequences (Tiefenbeck et al., 2016).[10]

3. Background on Air Pollution in South-Central Chile

More than half of Chile's population is affected by high levels of ambient air pollution due to the widespread use of biomass burning for heating (though sometimes for cooking as well), and the energy produced by burning wood fuel is about 4 to 6 times cheaper than that of other alternative fuels such as gas or electricity (Schueftan and González, 2013). This is particularly serious in cities in the south-central region where 80 to 95 percent of the population uses wood fuel for

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[8] This strategy had the highest potential to reduce air pollution, reduce heating expenditure and improve indoor comfort conditions. Moreover, energy efficiency strategies do not depend on users' behavior, unlike stove replacement programs, whose outcome can be highly affected by this issue.

[9] Indeed, a number of studies have shown that households reduce electricity consumption by an average of approximately 7 percent, with observed reductions in energy use ranging from 3 to 13 percent (Faruqui, Sergici, and Sharif, 2010).

[10] For real-time feedback trials, the reduction in electricity consumption is 11 percent on average. It is only when information is given in real time (real-time feedback) or includes higher involvement interventions (e.g., home energy audits) that energy conservation is triggered over the span of monitored experimental periods (Delmas, Fischlein, and Asensio, 2013).

heating and cooking (MMA, 2014a, and CDT, 2010).[11] In this section we present data for the city of Valdivia, which reflects a situation that is very similar to that of comparable cities in Chile's south-central region.[12]

Air pollution from wood fuel combustion is largely comprised of fine particulate matter ($PM_{2.5}$), among the most harmful particulate pollutants for human health (WHO, 2005).[13] Figure 1 below shows the average concentrations of ambient $PM_{2.5}$ for the city of Valdivia from 2008 to 2017. The figure shows that during the cold winter months ambient $PM_{2.5}$ pollution concentrations far exceed both national and international guidelines and standards (see note in Figure 1).

Due to their design, however, these new wood stoves can potentially emit high levels of air pollutants, in a magnitude similar to that of the old stoves they are replacing. This occurs when users choke their wood stoves, dramatically limiting the airflow in the combustion chamber and thus preventing clean and efficient combustion (Jordan and Seen, 2005). To address this sort of problems, manufacturers in New Zealand, for example, are required to sell woodstoves with a "never-choked" damper setting. This regulation is a simple, fast and low-cost policy that complements other environmental policies to reduce air pollution emissions from burning of wood-fuel. This never-chocked damper setting regulation is currently being implemented in Chile, but only for new wood stoves that have entered the market since late 2017.[14]

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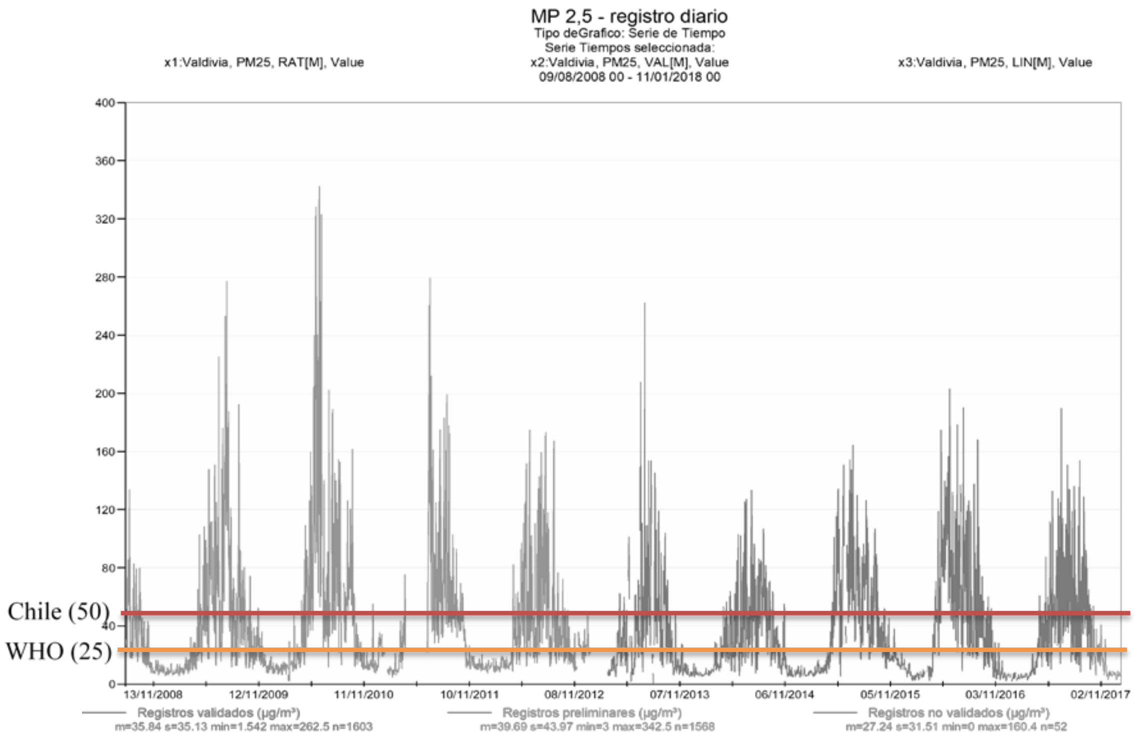
[11] The high consumption of wood fuel is consequence of a number of factors: low quality and high moisture content of the wood fuel used, low efficiency of burners and heaters, and poor thermal insulation of dwellings, which makes them require more fuel for heating (MMA, 2014a).

[12] Valdivia has a temperate humid climate with an average temperature of 12° C and abundant rainfall (Castillo, 2001). The cold season extends from April and November (late autumn, winter and early spring in the Southern Hemisphere), in which July is the coldest month with an average temperature of 8° C. These climatic conditions produce high demand for heating, which is mostly supplied by consumption of wood fuel, the cheapest and most accessible fuel in this region.

[13] There is growing evidence on the health effects associated with high concentrations of fine particular matter. For example, using data for Santiago, Chile, Miller and Ruiz-Tagle (2018a) provide causal estimates of the effect of exposure to air pollution on infant mortality; using similar data Ruiz-Tagle (2018) provides causal effects of exposure to air pollution on urgent care visits; and Ruiz-Tagle and Miller (2018b) find adverse effects of exposure to air pollution on the probability of a pregnancy ending in a miscarriage. Furthermore, Fuenzalida, Miranda Ferrada and Cobs Muñoz (2013) studied health problems from air pollution for different income levels in the main cities of Chile's south-central region, and Gómez-Lobo et al. (2006) examined the cost of each μg/m3 of emissions of particulate matter in excess of national and international guidelines.

[14] The "Standard for Emissions of Particulate Matter for Wood-fuel Devices" was enacted in Chile in 2014. It aims to gradually limit the constraining of the airflow in new wood stoves (MMA 2014b). This standard applies to new devices that operate with wood fuel and with power less than or equal to 25 kilowatts (kw). Furthermore, the standard established that heaters of less than 8 kw must limit emissions to 2.5 grams of particulate material per hour

Figure 1. Concentration of Fine Particulate Matter in the City of Valdivia: Daily Averages of $PM_{2.5}$, 2008-2017



Note: WHO guidelines recommend maximum concentrations of $PM_{2.5}$ not to exceed 25 ug/m^3 (WHO, 2005), while EPA sets standards for concentrations of $PM_{2.5}$ not to exceed 35 ug/m^3 (USEPA, 2016). The Chilean standard for $PM_{2.5}$ is 50 ug / m^3 (MMA, 2011). All values correspond to 24-hour averages.
Source: http://sinca.mma.gob.cl/ (Ministry of the Environment).

4. Behavioral Intervention for Reducing Wood Stoves' Air Pollution Emissions

In this paper we examine the effectiveness of a low-cost intervention designed to reduce wood-stoves' outdoor air pollution emissions in cities of south-central Chile. In particular, we evaluate the effect of an information sign that provides *real-time* feedback on current outdoor pollution emissions according to the wood stove's damper setting.

(g/h); those from 8 to 14 (kw) up to 3.5 gr/h, and those of higher power, up to 4.5 gr/h. Heating and cooking devices are certified under laboratory conditions, with the damper setting on fully open (maximum airflow). Therefore, emissions measured under these conditions vary considerably when compared to emissions under real-world operating conditions.

4.1 Wood Stoves Combustion Technology and Outdoor Pollution Emissions

Figure 2 below shows one of the most popular wood stoves currently available in the Chilean market, which is also part of the wood stoves replacement program.[15] The figure illustrates the wood stove's embedded "double combustion" technology for low outdoor air pollution emissions and efficient wood-burning for heating.[16] It is important to underscore that only wood stoves with this technology are allowed in the Chilean market, and that this "double combustion" technology is fairly standard across different brands and models.[17] As shown in Figure 2 below, overall air inflow is controlled by the wood stove's damper, which is a lever located on top of the wood stove. The damper allows adjusting the airflow in the combustion chamber so as to adjust the overall combustion process (that is, the heating generated by wood fuel combustion). Setting the damper in the "open" position allows for high air inflow and clean wood fuel combustion. However, this comes at a cost of high consumption, as wood fuel burns quickly at this setting. Choking the wood stove, on the other hand, creates smoldering (that is, a combustion process with no vivid flame) and a highly-polluting combustion process. Choking thus slows combustion, which allows users to save on wood-fuel expenses but dramatically increases pollution emissions.

[15] This wood stove is a Bosca model Eco 360, and it is one of the models we targeted in this behavioral intervention.
[16] These wood stoves have an air-tight door and a sealed combustion chamber that allows for combustion of wood fuel with virtually no emissions of indoor air pollutants, so that almost all air pollutants exit through the chimney.
[17] All Bosca woodstoves are embedded with the exact same burning technology. Competing brands, such as Amesti, also have the same technology. Indeed, Amesti was founded by former Bosca engineer who left to start his own company, taking with him the wood burning combustion technology that he had originally designed.

Figure 2. Wood Stoves' Combustion Technology and Outdoor Pollution Emissions

Most common wood stove in Chile's south-central cities (such as Valdivia)	Wood stove's "double combustion" technology for low air pollution emissions and efficient heating

Note: The "double combustion" process of these wood stoves refers to an efficient airflow in the combustion chamber. This airflow creates a strong flame so that, after the wood fuel is burned at the bottom of the chamber (in the "first combustion"), the airflow allows for a "re-burning" of air pollutants at the top of the chamber (in a so called "second combustion"). The image on the right shows a cut-out of the interior design of these wood stoves. Air inflow starts from an intake on top of the wood stove. Then air inflow heats up as it travels around the wood-stove so that it enters the combustion chamber at a high temperature (which further facilitates an efficient combustion process). Furthermore, air enters the combustions chamber via two openings, one from underneath the wood fuel (to facilitate the "first combustion") and a second opening right above where the wood fuel is burning (to boost a strong flame which "re-burns" air pollutants in the "second combustion").

4.2 Behavioral Intervention: Information Sign

The information sign that we assess in this paper was especially designed for the purpose of this intervention, and it effectively provides real-time feedback to wood-stove users. The information sign aligns to the wood stove's damper lever, thus providing real-time information on the effects on emissions at each damper setting.

The information sign consists of a metallic plaque that attaches to the top of the wood-stove and that precisely aligns with the setting of the damper's lever (see Figures 3 and 4). The sign shows that when the damper setting is all the way to the left (i.e., choking the wood stove), current pollution emissions are "Very High" (in "Muy Alto" in Spanish). By moving the damper setting slightly to the right, allowing for more airflow in the combustion chamber, the sign shows that current pollution emissions decrease to "High" ("Alto"), "Mid-level" ("Medio"), and "Low"

(“Bajo”).The information sign also denotes an “E” (“Encendido” in Spanish) for the ignition setting on the far right.[18]

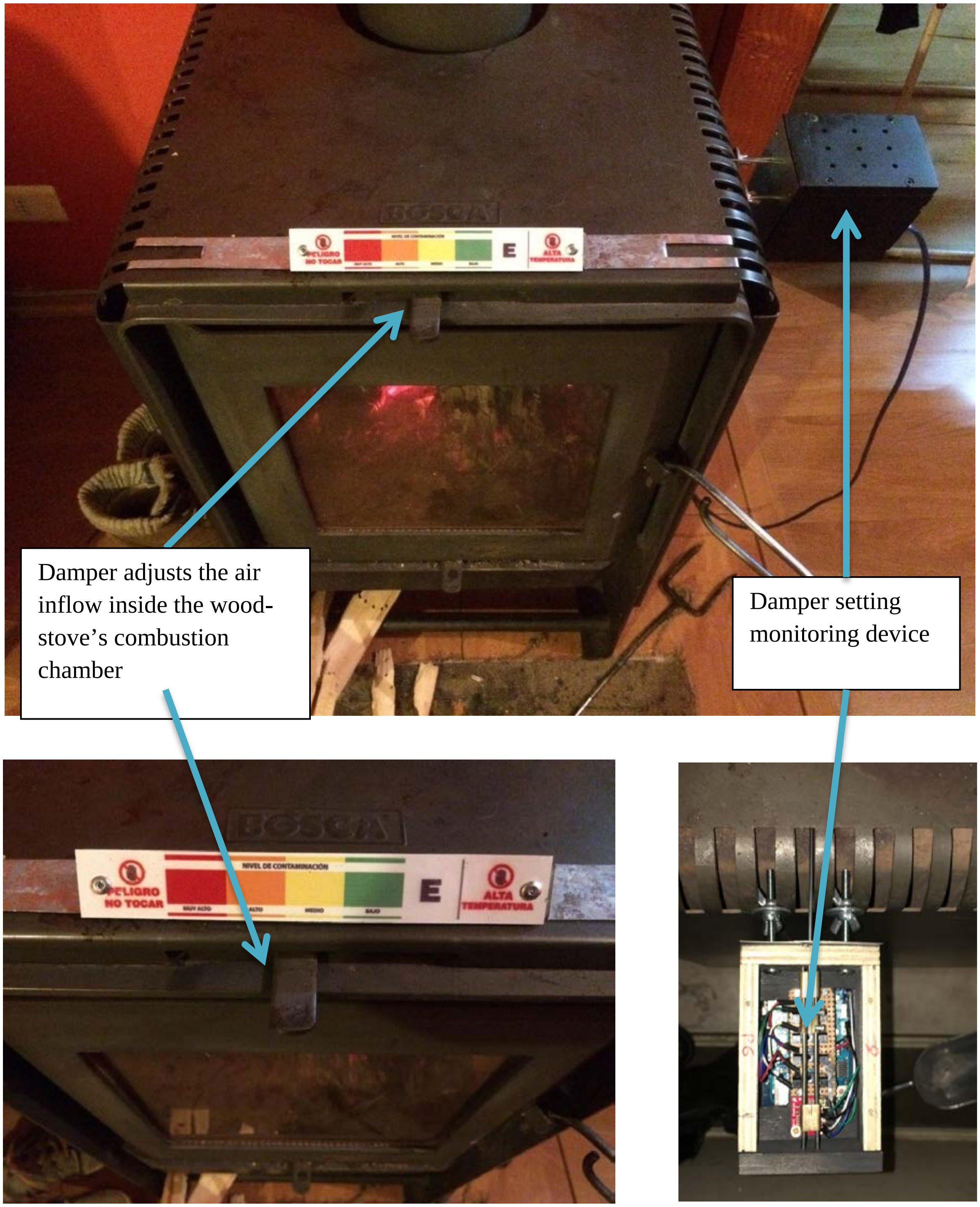
Figure 3. Information Sign

Note: The information sign shows that wood-stove’s pollution emissions for each setting of the damper are (from left to right): “Very High” (“Muy Alto”, in Spanish), “High” (“Alto”), “Mid-level” (“Medio”), and “Low” (“Bajo”). Also, “E” denotes the ignition setting (“Encendido”, in Spanish) on the far right.

In addition, in order to effectively record the actual position of the damper setting, a custom-made monitoring device was developed for the purposes of this research project (see Figure 4). This damper setting monitoring device, installed in each wood stove of households participating in the research project, records the position of the damper setting every 10 minutes and saves this information on a Flash memory card. The device records the damper setting at one of five different positions: “Choked” (all the way to the left), “Mostly Choked,” “Mid-Level,” “Mostly Open” and “Open” (all the way to the right). As the information sign is aligned so as to match the positions of the damper lever, these five positions of the damper match exactly those five positions of the information sign. That is, the “Choked” position of the damper matches the “Very High” pollution mark of the information sign (in red), the “Mostly Choked” position matches the “High” pollution mark of the information sign (in orange), and so on. Notice that the “Open” position of the damper matches the “E” mark in the information sign (again, “E” denotes ignition only). This means that the information sign reminds users that the damper setting “Open” should only be used for starting the woodstove, but not at any other time.

[18] Notice that wood stove manufacturers recommend not operating the wood stoves in the fully open “E” setting other than during ignition only. The information sign and the associated information flyer stress this recommendation from the manufacturer. This was also explicitly stated by the enumerators when they visited participating households to install the information sign.

Figure 4. Information Sign Attached to the Top of the Wood Stove



Note: The information sign aligns with the damper's lever and informs wood-stove users on emissions produced by each damper setting. To register the actual damper setting at each point in time this device was attached to the wood stove of each participating household for the entire duration of the experiment.

4.3 Field Experiment

We recruited 80 households to participate in a field experiment. All participating households had a wood stove that they used as the only source of heating in their dwelling. A household was eligible to participate as long as the damper setting monitoring device could be installed in the household's wood stove. The damper setting monitoring device was designed so to fit the most popular brand and model of wood stoves in Valdivia (Bosca Limit 360 or Bosca Limit 380), but there were a few additional cases in which the monitoring device was also installed in wood stoves of a different brand and model.

The experiment was conducted in two phases of 40 households each, and each phase lasted for one month. The two phases of the experiment were implemented in the city of Valdivia, Chile during the months of August and September of 2017. For each phase, a subset of participating households was randomly assigned to a treatment group (comprised of 26 households in each phase) and a control group (comprised of 14 households in each phase), so that adding up both phases there were 52 households randomly assigned to the treatment group and 28 household randomly assigned to the control group.[19] Household members were not aware of whether they were assigned to a treatment or a control group and did not know to which group other participating households were assigned. Furthermore, we believe that there was no communication between participating households. All participating households signed an informed consent form before starting the experiment which informed them of the different phases of the experiment.[20] As an incentive for participation, each participating household received one cubic meter (1 m^3) of certified-dry wood fuel. This also allowed us to make sure that the quality of wood-fuel being used throughout the experiment does not affect users' behavior regarding the setting of the wood-stove's damper.

For all participating households (both in the treatment as well as in the control group) the wood stove's damper setting was recorded for a full month, using the damper setting monitoring device as illustrated in Figures 4 and 5. Furthermore, after two weeks, the information sign was installed only in the wood stoves of those households in the treatment group (see Figure 4).

[19] Random assignment to treatment and control groups assures that the two groups are virtually identical, at least from a statistical point of view.

[20] The consent form as well as the full design of the experiment was approved by an external ethics review board from the Centre for Experimental Social Sciences of Nuffield College at the University of Oxford (CESS- Nuffield). The application record is ETH-170526299-3 and is titled "Informational Interventions to Reduce Air Pollution in Chile's Southern Cities."

Moreover, the installation of this information sign was supplemented with an information flyer in the form of a refrigerator magnet. This flyer, in addition to clearly explaining the information conveyed by the information sign, contains more detailed information on wood stoves' effect on the city's ambient air pollution (see Figure 5). During the installation visit, the technician explained in detail to the household head the meanings of both the information sign and the flyer and answered any questions household members may have had. We believe that the flyer strengthened the link between the chosen damper setting and their associated effects in term of wood pollution emissions (Fischer, 2008).

Figure 5. Magnetic Flyer Explaining Meaning of the Information Sign

Original Flyer	Translation
	**Damper use of our wood stoves** What is its effect on the air we breathe? Valdivia [city] suffers from high air pollution due to inefficient use of wood stoves. Damper use drives wood stoves' emissions of air pollutants. **How?** A choked wood stove emits much more air pollutants than a wood stove with an open damper. This air pollution also filters inside the dwelling through doors, windows and drafts. **Information sign** The installed signage represents your wood stove's air pollution emissions for each setting of the damper. 

Note: This flyer was provided to all households in the treatment group at the time that the information sign was installed in their wood stoves. The flyer was a magnet that can be posted on their refrigerator, which makes it always visible.

Furthermore, for each participating household, in both the treatment and control groups, an indoor temperature monitoring device was installed approximately 2 meters from the wood stove (at about 2 meters from the woodstove, which is usually located in the living room). The purpose of this temperature monitoring device is to record indoor temperature so that, by contrasting it with outdoor temperature, we are able to determine when the wood stove is actually in use.

In addition, an enumerator applied a survey to each participating household to gather information on socio-economic characteristics of the households, experience of any health-related problems, characteristics of dwellings, quality of wood fuel used and means for acquiring it. The survey also asked questions regarding the household head's opinion on air pollution as well as frequency of use of the wood stove.[21] Moreover, a team of enumerators and technicians paid periodic visits to participating households to ensure that the monitoring devices were readily recording information. A follow-up survey was additionally conducted at the end of the participation period to complement information gathered by the initial survey. After a month, and once the intervention was finished, all monitoring devices were collected, the data from them were downloaded and the survey data were digitized.

5. Results

5.1 Descriptive Statistics for Treatment and Control Groups

The randomization of participating households into treatment and control groups guarantees that there are no systematic characteristics of those participating households that may affect the outcome of the experiment. Table 1 provides descriptive statistics of a selected group of household characteristics from the household survey for those households in the treatment and control group. Table 1 presents mean and standard deviation for the following variables: i) number of household members and distribution of their age groups; ii) whether there is any household member that suffers from respiratory or cardiovascular disease; iii) the average number of hours that the wood stove is in use, both during weekdays and on weekends; iv) a self-reported score of the indoor temperature; v) monthly household income; vi) dwelling characteristics regarding ownership, surface area, number of floors and construction year; and vii) survey respondent's characteristics, such as gender, age, marital status and educational

[21] In the next section we present descriptive statistics of these questions from the household survey.

attainment. We conducted t-tests and Kolmogorov-Smirnov tests on the means of each of those variables and found no statistically significant difference between households in the treatment and control groups. Consequently, the only observed feature that set these households apart is whether they were assigned to the treatment or control group, which occurred via the random process described in the previous section.

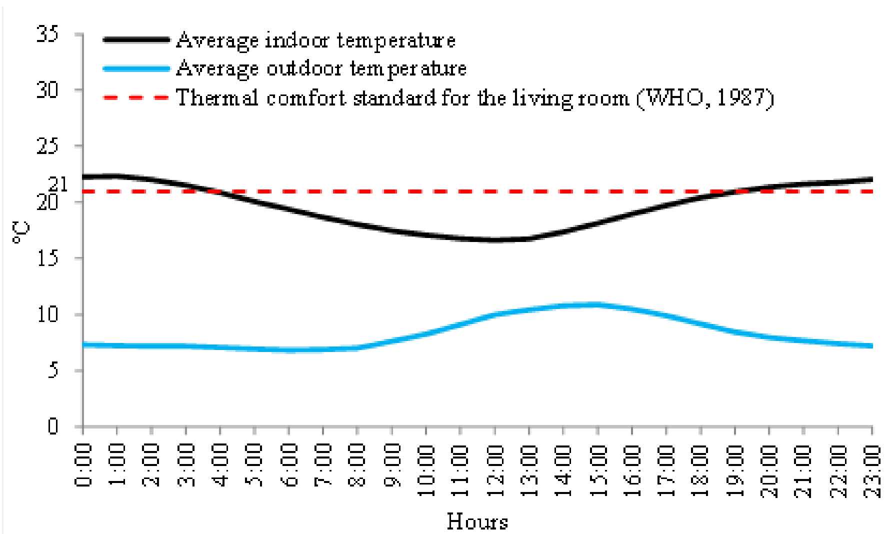
Table 1. Descriptive Statistics of Participating Households (treatment and control groups)

	Treatment Group		Control Group	
Variables	Mean	S.D.	Mean	S.D.
Household members	3.15	1.03	3.37	1.46
Less than 4 years old	0.19	0.48	0.19	0.44
Between 5 and 14	0.30	0.54	0.50	0.75
Between 15 and 65	2.44	1.15	2.33	1.32
65 and older	0.22	0.58	0.35	0.56
HH member suffer from resp. or cardio. disease	0.26	0.45	0.25	0.44
Num. hours woodstove is in use				
Weekdays	13.4	6.3	12.3	5.0
Weekends	14.9	6.5	15.5	4.8
Indoor temp. score (self reported)	0.88	0.12	0.88	0.11
Monthly HH income (perc.)				
Less than USD 800	0.41	0.50	0.42	0.50
Between USD 800 - 1,700	0.33	0.48	0.38	0.49
More than USD 1,700	0.19	0.40	0.19	0.40
Dwelling's				
Ownership = own (perc.)	0.70	0.47	0.71	0.46
Surface area (sq. meter)	70.6	39.2	78.6	39.6
Floors (perc. 1 floor)	0.37	0.49	0.38	0.49
Construction before year 2000	0.56	0.51	0.60	0.50
Const. between 2000 and 2007	0.19	0.40	0.21	0.41
Const. after 2007	0.11	0.32	0.06	0.24
Const. year N/A	0.15	0.36	0.12	0.32
Respondent's				
Gender (1=male)	0.41	0.50	0.40	0.50
Age	43.0	13.8	47.3	14.2
Marital status = single (perc.)	0.33	0.48	0.31	0.47
Marital status = married (perc.)	0.44	0.51	0.58	0.50
Marital status = divorced/widowed	0.22	0.42	0.12	0.32
Educ. attainment = primary (perc.)	0.15	0.36	0.19	0.40
Educ. attainment = secondary (perc.)	0.41	0.50	0.37	0.49
Educ. attainment = Terc. (technical)	0.19	0.40	0.19	0.40
Educ. attainment = Terc. (university)	0.26	0.45	0.25	0.44

5.2 Effect on Frequency of Wood Stove's Damper Setting

In this section we present results from the analysis of the data on wood stove use obtained with the damper setting monitoring device. We restrict our analysis to only those hours of the day when the wood stove was in use. According to our survey data, participating households report that their wood stoves are in use an average of 13.32 hours a day (that is, about 55.5 percent of the time). To establish whether a wood stove is in use during any given period of time we contrast the outdoor city-wide temperature with the indoor temperature in the room where the wood-stove is located (as recorded by a temperature monitoring device). We determine that a wood- stove is in use when the difference between outdoor and indoor temperature is greater or equal to 11.31 degrees Celsius, which corresponds to the 55.5 percentile of the temperature difference.[22]

Figure 6. Indoor and Outdoor Temperature Profile for Participating Households in Valdivia, Chile: Average for August and September 2017



Note: The black line denotes average hourly indoor temperature (in Celsius degrees) for participating households and the light blue line denotes average hourly outdoor temperature (in Celsius degrees) for the city of Valdivia. Whereas the outdoor temperature is obtained from Chile's meteorological service, the indoor temperature is obtained from the Speck sensors, which were located in each of the dwelling's living room at a distance of about two meters from the household's wood stove.

[22] Figure 6 shows average indoor and outdoor temperature for those participating households. The indoor temperature corresponds to the recorded temperature of the Speck sensor, which was located in the dwelling's living room at a distance of about two meters from the wood-stove. This means that when the wood-stove is in use, the indoor temperature as recorded by this device is considerable higher than that of the rest of the dwelling. Figure 7 shows that the average indoor temperature peaks soon after midnight and drops monotonically until about 13:00 hrs. (when it reaches its lowest temperature). This temperature profile reflects the most common pattern of household wood stove in Valdivia. Most wood stoves are lit in the late afternoon or evening, and households usually fully load them with wood fuel before going to bed (between 22:00 and 24:00 hrs.), so that the wood stove reaches its peak temperature about an hour later. Then, the wood stove slowly cools down until loaded and started again in the morning, or in the afternoon. On the other hand, outdoor temperature drops overnight slowly until dawn (around 8:00 hrs. during winter), to slowly increase and peak at around 15:00 hrs.

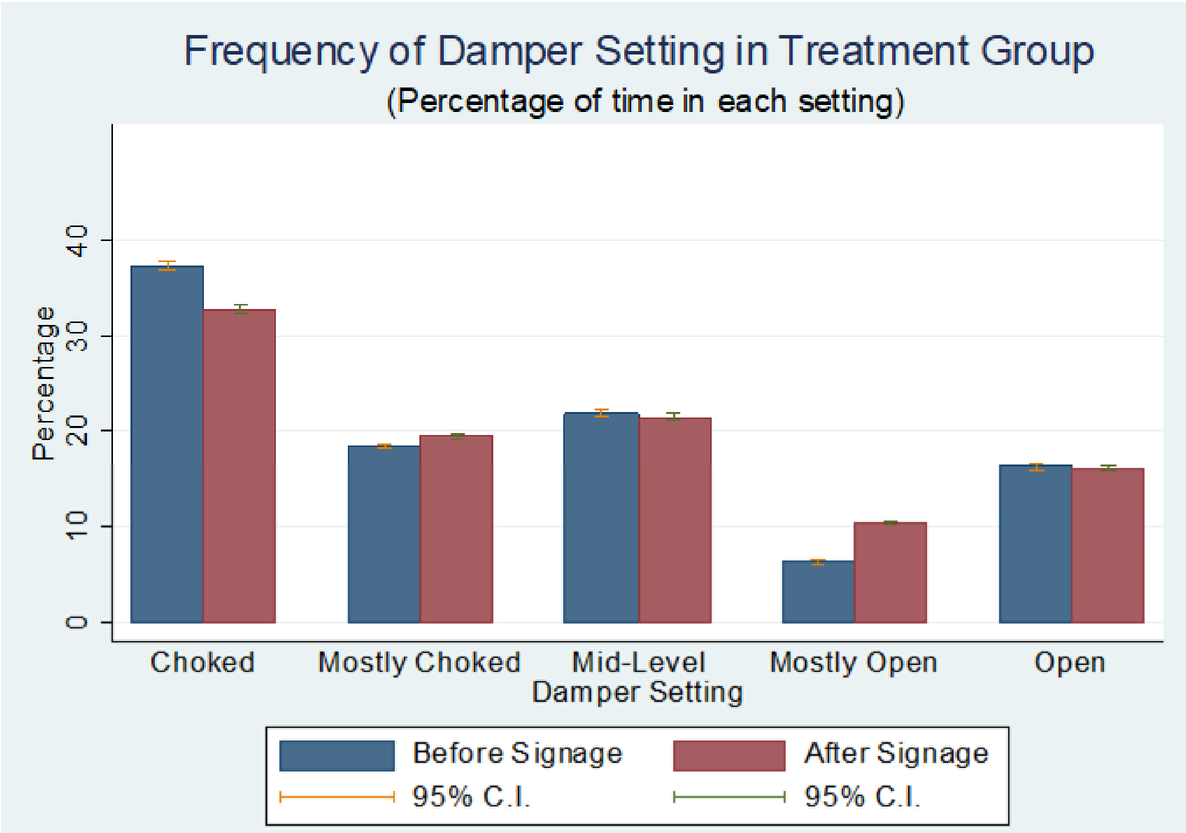
Results of the behavioral intervention are presented in Figures 7-9 below.[23] Figures 7 and 8 show the frequency of use of the damper setting for the treatment group (Figure 7) and control group (Figure 8), and Figure 9 summarizes the main results by showing the magnitude of the effect of the information sign.

Figure 8 shows that, for wood stoves in the treatment group, the most frequent setting of the wood-stoves' damper before the sign was installed (blue bars) was "Choked" (37.8 percent of the time). On the other hand, the least frequent setting of the wood-stoves' damper before the sign was installed was "Mostly Open" (6.3 percent of the time). Figure 8 shows an almost identical pattern for wood stoves in the control group. The most frequent damper setting prior to installation of the information sign (dark green bars) was "Choked" (37 percent of the time), and the least frequent setting "Mostly Open" (5.4 percent of the time). Furthermore, by conducting a Kolmogorov-Smirnov test on the distribution of the damper setting before the information sign was installed, we cannot reject the null hypothesis of equal distributions of both control and treatment groups. In other words, according to the labelling and color marks in the information sign, our data shows that most of the time wood stove users set the damper to "Very High" pollution emissions (red mark—see Figure 3).

Figure 7 shows that, after information signs were installed on wood stoves in the treatment group, there was a statistically significant reduction in the frequency the damper was set at "Choked" ("Very High" pollution emissions). The figure also shows that, after information signs were installed, there was a statistically significant increase in the frequency at which the damper was set at "Mostly Open" ("Low" pollution emissions). More precisely, the frequency of the "Choked" setting decreased 4.8 percentage points (from 37.8 to 33 percent), and the frequency of the "Mostly Open" setting increased by 4.2 percentage points (from 6.3 to 10.5 percent). Conversely, for all other damper settings no statistically significant difference occurred in the treatment after information signs were installed.

[23] Whereas when presenting results we combined results from the two phases, an analysis for each phase (not shown here) yields the same result. Results by phase are available upon request.

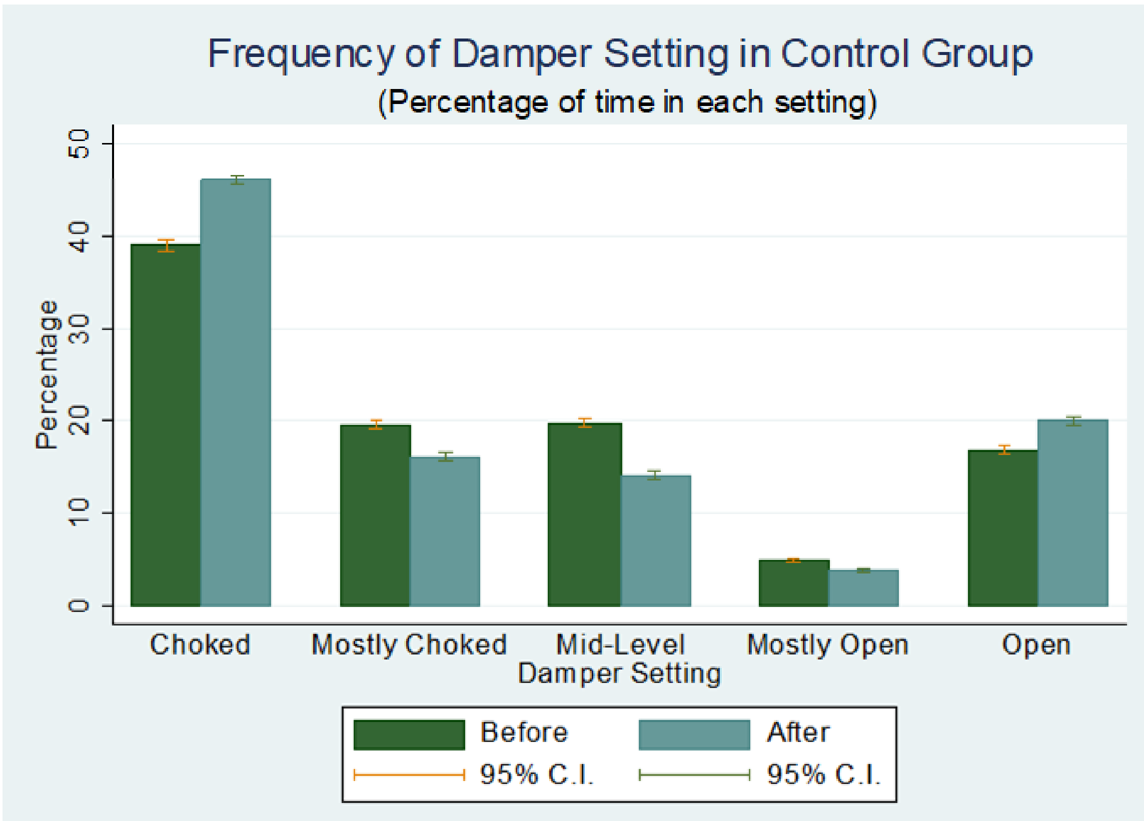
Figure 7. Frequency of Damper Setting for Treatment Group, Percentage of Time the Wood Stove Is On



Note: Blue bars denote the distribution of damper settings of households in the treatment group before the information sign was installed. Red bars denote the distribution of damper settings of the same households after the information sign was installed. The settings are grouped into five categories (Choked, Mostly Choked, Mid-Level, Mostly Open, and Fully Open), and these distributions are calculated based on the percentage of time the wood stoves are actually on. In addition, capped lines denote 95% confidence intervals (C.I.) of these distributions for each damper setting.

On the other hand, in order to assess what would have happened without information signs, we examine the control group during the same period. Figure 8 shows that the frequency of the "Choked" setting ("Very High" pollution emissions) experienced a statistically significant increase for wood stoves in the control group. That is, the frequency of the "Choked" setting increased by 7.9 percentage points (from 37.0 to 44.9) on the days that followed the installation of the sign on wood stoves in the treatment group. Our data also show an increase in the frequency of the "Open" setting during that same period of time. Conversely, during that period, there was a decrease in the frequency of all intermediate settings ("Mostly Choked," "Mid-Level" and "Mostly Open").[24]

Figure 8. Frequency of Damper Setting for Control Group, Percentage of Time the Wood Stove Is On



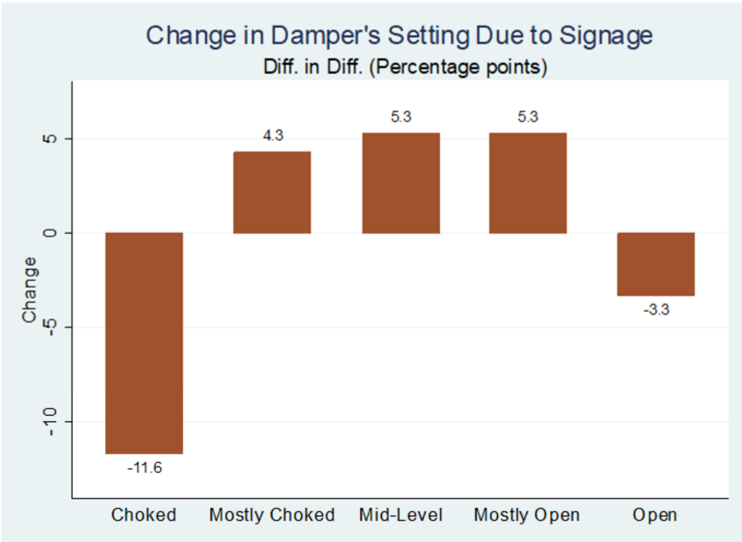
Note: Green bars denote the distribution of damper settings of households in the control group before the information signage was installed. Turquoise bars denote the distribution of damper settings of the same households after the information sign was installed. The wood stove's damper settings are grouped into five categories (Choked, Mostly Choked, Mid-Level, Mostly Open, and Fully Open), and these distributions are calculated based on the percentage of time the wood stoves are actually on. In addition, capped lines denote 95% confidence intervals (C.I.) of these distributions for each damper setting.

To assess the overall effect of the information sign on wood stove users' behavior we contrast the difference in frequencies in each setting before and after installing the information

[24] These results from the control group could be interpreted as evidence of an experimenter effect or Hawthorne effect, which vanishes over time. Whereas households in both treatment and control groups received long visits from our team of technicians and enumerators at the onset of the experiment (and thereafter only brief check-in visits), only those households in the treatment group received a second long visit two weeks into the experiment (to install the information sign, hand out the flyer and provide instructions on how to interpret it). That is, whereas all households may have perceived that their behavior regarding the use of their wood-stoves was being observed during the entire length of the experiment, this perception may have vanished over time for those households in the control group. If this vanishing experimenter effect holds true, then, as time went by, households in the control group should have gradually returned to their normal wood stove use.

sign and the difference between treatment and the control group. This strategy is commonly known as a difference-in-difference approach (Diff-in-Diff). Figure 9 shows the results of the Diff-in-Diff approach in terms of change in percentage points for each damper setting. Figure 9 shows a reduction of 12.7 percentage points in the frequency of the “Choked” setting, as well as a reduction of 3.4 percentage points in the frequency of the “Open” setting.[25] On the other hand, Figure 9 shows increases of 4, 6.3 and 5.8 percentage points, respectively, in the frequency of the “Mostly Choked,” Mid-Level” and “Mostly Open” damper settings. Therefore, our results suggest that the information sign effectively *nudged* wood-stove users to choosing less-polluting damper settings. That is, whereas we observe a large drop in the frequency of the setting that emits “Very High” pollution (“Choked” setting), we also observe an important increase in the frequency of damper settings for “Moderate” and “Low” pollution (“Mid-level” and “Mostly Open” damper settings).

Figure 9. Change in Frequency of Damper Setting for Induced by Information Sign: Percentage Points for Each Damper Setting



Note: Maroon bars denote the difference-in-difference distribution of the damper setting. That is, the bars show the distribution of the difference in frequencies in each setting before and after installing the information sign and the difference between treatment and the control group (shown in Figures 8 and 9). As noted above, the settings are grouped into five categories (Choked, Mostly Choked, Mid-Level, Mostly Open, and Fully Open), and this distribution is calculated based on the percentage of time the wood stoves are actually on.

[25] Recall that the information sign notes that the “Open” damper setting should be used *only* during ignition, and not at other times. Only those households in the treatment group received this information, which is made explicit on the sign as well as in the magnetic flyer. Therefore, the observed reduction in the frequency of use of the “Open” damper setting attributed to the information sign may likely reflect the fact that wood stove users effectively learned not to use this setting at times other than during ignition.

5.3 Regression Analysis

We use the data from the household survey to check whether the results of the previous section hold once we control for observable household characteristics (those presented in Table 1 above). To do this, we use a multinomial logit regression framework in which we model the probability of the wood-stove's damper setting.

Let $\Pr(Damper\ Setting = j \mid Sign, Group)$ denote the probability that the damper setting equals j (where j = Choked, Mostly Choked, Mid-level, Mostly Open or Open) given whether the household belongs to the treatment or control group, and given whether the information sign is on or off. Using $Choked$ as the baseline in a multinomial logit framework, then the probability of the damper setting equal to $Choked(C)$ is given by the following expression

$$\Pr(\, j \mid S, G, j = C) = \frac{1}{1 + \sum_{j \neq C} \exp\left(\beta_0^{(j)} + \beta_1^{(j)} Sign + \beta_2^{(j)} TreatGr + \beta_3^{(j)} Sign\_TrGr + \gamma^{(j)} X\right)} \tag{1}$$

and the probability of a damper setting equal to $Mostly\ Choked$, $Mid\ Level$, $Mostly\ Open$, or $Open$ is given by the expression

$$\Pr(\, j \mid S, G, j \neq C) = \frac{\exp\left(\beta_0^{(j)} + \beta_1^{(j)} Sign + \beta_2^{(j)} TreatGr + \beta_3^{(j)} Sign\_TrGr + \gamma^{(j)} X\right)}{1 + \sum_{j \neq C} \exp\left(\beta_0^{(j)} + \beta_1^{(j)} Sign + \beta_2^{(j)} TreatGr + \beta_3^{(j)} Sign\_TrGr + \gamma^{(j)} X\right)} \tag{2}$$

where $Sign$ is a dummy variable that takes on value equal to 1 when the sign is on, and 0 otherwise. Similarly, the variable $TreatGr$ takes on value equal to 1 when the household belongs to the treatment group, and 0 otherwise. Furthermore, the variable $Sign\_TrGr$ takes on value 1 when the household is in the treatment group and the sign is on, and 0 otherwise. Finally, X is a vector of observable household characteristics and $\gamma^{(j)}$ its associated parameter vector.

Running a multinomial logit regression, we obtain parameter estimates for $\beta_i^{(j)}$ (i = 0,1,2,3) and the parameter vector $\gamma^{(j)}$. With these parameter estimates and equations (1) and (2) above we obtain estimates of the damper setting proportion for each of the following four cases (see Table 2 for the algebraic expressions): (a) Treatment group, before sign; (b) Treatment group, after sign; (c) Control group, before sign; (d) Control Group, after sign.

Panel A of Table 3 below presents parameter estimates from the multinomial logit regression.[26] Setting Choked as the baseline, columns 2 through 5 present parameter estimates for $\beta_i^{(j)}$, for the probability of the damper setting other than choked, for the case in which we do not add further controls. Similarly, columns 7 through 10 present parameter estimates for $\beta_i^{(j)}$ when controlling for observable household characteristics (X). Panel A of Table 3 shows that adding controls for observable household characteristics had little effect on the $\beta_i^{(j)}$ estimates.

In addition, using the estimates of $\beta_i^{(j)}$ (as illustrated in Table 2 above), Panel B of Table 3 presents predicted probabilities for each of the four cases above (a through d). Furthermore, Panel B of Table 3 adds a row at the bottom that calculates the Diff-in-Diff estimate from these predicted probabilities. Panel B of Table 3 shows that there is little difference of adding controls for observable household characteristics, both for the predicted probabilities as well as the Diff-in-Diff estimate. This is evidence that the effect of the information sign on wood-stove users' behavior is not contaminated by observable household characteristics and that the randomization process effectively yields causal estimates.

[26] We also conducted this regression analysis for each phase, independently, yielding basically the same results (not shown here). When estimating jointly the dummy variable associated to the phase turns non-significant.

Table 2. Probabilities for Each Damper Setting Using Parameter Estimates from Multinomial Logit Regression[27]

	Probability Choked $\Pr(j \mid S, G, j = C)$	Probability any other setting $\Pr(j \mid S, G, j \neq C)$
(a) Treatment Group, Before Sign $Sign = 0, TreatGr = 1, Sign\_TrGr = 0$	$\frac{1}{1+\sum_{j\neq C}\exp\left(\beta_0^{(j)}+\beta_2^{(j)}\right)}$	$\frac{\exp\left(\beta_0^{(j)}+\beta_2^{(j)}\right)}{1+\sum_{j\neq C}\exp\left(\beta_0^{(j)}+\beta_2^{(j)}\right)}$
(b) Treatment Group, After Sign $Sign = 1, TreatGr = 1, Sign\_TrGr = 1$	$\frac{1}{1+\sum_{j\neq C}\exp\left(\beta_0^{(j)}+\beta_1^{(j)}+\beta_2^{(j)}+\beta_3^{(j)}\right)}$	$\frac{\exp\left(\beta_0^{(j)}+\beta_1^{(j)}+\beta_2^{(j)}+\beta_3^{(j)}\right)}{1+\sum_{j\neq C}\exp\left(\beta_0^{(j)}+\beta_1^{(j)}+\beta_2^{(j)}+\beta_3^{(j)}\right)}$
(c) Control Group, Before Sign $Sign = 0, TreatGr = 0, Sign\_TrGr = 0$	$\frac{1}{1+\sum_{j\neq C}\exp\left(\beta_0^{(j)}\right)}$	$\frac{\exp\left(\beta_0^{(j)}\right)}{1+\sum_{j\neq C}\exp\left(\beta_0^{(j)}\right)}$
(d) Control Group, After Sign $Sign = 1, TreatGr = 0, Sign\_TrGr = 0$	$\frac{1}{1+\sum_{j\neq C}\exp\left(\beta_0^{(j)}+\beta_1^{(j)}\right)}$	$\frac{\exp\left(\beta_0^{(j)}+\beta_1^{(j)}\right)}{1+\sum_{j\neq C}\exp\left(\beta_0^{(j)}+\beta_1^{(j)}\right)}$

$Sign$ is a dummy variable that takes on value equal 1 when the information sign is on, and 0 otherwise. Similarly the variable $TreatGr$ takes on value equal to 1 when the household belongs to the treatment group, and 0 otherwise. Furthermore, the variable $Sign\_TrGr$ takes on value 1 when the household is in the treatment group and the information sign is on, and 0 otherwise.

[27] For brevity of exposition we have set the parameter vector X equal to zero.

Table 3. Parameter Estimates from Multinomial Regression (Panel A), Predicted Probabilities and Diff-in-Diff Estimate (Panel B). Dependent variable: damper setting.

Panel A: Parameter Estimates from Multinomial Logit Regression

	Choked	Mostly Choked	Mid-Level	Mostly Open	Open	Choked	Mostly Choked	Mid-Level	Mostly Open	Open
VARIABLES	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)
Sign On		-0.0456**	-0.00639	0.148***	-0.114***		-0.0486**	0.165***	0.390***	0.0110
		(0.0210)	(0.0200)	(0.0332)	(0.0214)		(0.0217)	(0.0205)	(0.0343)	(0.0221)
Treatment Group		-0.332***	-0.585***	-0.553***	-0.0372		-0.344***	-0.567***	-0.506***	-0.0167
		(0.0242)	(0.0243)	(0.0423)	(0.0234)		(0.0247)	(0.0246)	(0.0427)	(0.0237)
Sign On & Treatment Gr.		0.551***	0.693***	1.193***	0.148***		0.539***	0.717***	1.188***	0.144***
		(0.0294)	(0.0291)	(0.0482)	(0.0293)		(0.0300)	(0.0296)	(0.0488)	(0.0298)
Constant		-0.690***	-0.554***	-1.932***	-0.731***		-1.956***	0.941***	-2.380***	-0.289***
		(0.0170)	(0.0163)	(0.0276)	(0.0173)		(0.0665)	(0.0654)	(0.107)	(0.0700)
Controls	No	No	No	No	No	Yes	Yes	Yes	Yes	Yes
Observations	173,157	173,157	173,157	173,157	173,157	173,157	173,157	173,157	173,157	173,157

Standard errors clustered at the household level. *** p<0.01, ** p<0.05, * p<0.1

Panel B: Frequency of Damper Setting Using Parameter Estimates from Multinomial Logit Regression (percentages)

	Choked	Mostly Choked	Mid-Level	Mostly Open	Open	Choked	Mostly Choked	Mid-Level	Mostly Open	Open
Treatment Gr., Before	37.8	18.1	21.6	6.3	16.2	38.1	17.4	22.6	6.0	16.0
Treatment Gr., After	33.0	19.7	21.0	10.5	15.8	33.0	18.3	22.7	10.3	15.7
Control Gr., Before	37.0	18.6	21.3	5.4	17.8	39.9	19.1	20.1	4.3	16.6
Control Gr., After	44.9	16.1	14.4	3.7	20.8	47.7	16.2	13.6	3.1	19.5
Diff-in-Diff	**-12.7**	**4.0**	**6.3**	**5.8**	**-3.4**	**-12.8**	**3.9**	**6.6**	**5.5**	**-3.1**

Variables in Panel A are defined as follows: *Sign On* is a dummy variable that takes on value equal 1 when the information sign is on, and 0 otherwise. Similarly, *Treatment Group* takes on value equal to 1 when the household belongs to the treatment group, and 0 otherwise. Furthermore, Sign On & Treatment Gr. takes on value 1 when the household is in the treatment group and the information sign is on, and 0 otherwise. Controls refer to observable household characteristics such as those presented in Table 1.

Row *Treatment Gr – Before* in Panel B refers to the distribution of the damper setting of those households in the treatment group before the information signage was installed. A similar interpretation should be given to the three subsequent rows (*Treatment Gr – After*, *Control Gr – Before, and Control Gr – After*). The wood stove's damper settings are grouped into five categories: Choked, Mostly Choked, Mid-Level, Mostly Open, and Fully Open (as also shown in the column headings), and these distributions are calculated based on the percentage of time the wood stoves are actually on. Columns (1) through (5) correspond to the bars presented in figures 8 and 9, whereas columns (6) though (10) account for further controls. Row *Diff-in-Diff* refers to the distribution of the difference in frequencies in each setting before and after installing the information sign and the difference between treatment and the control group.

5.4 Analysis of Rebound Effect

Studies on the effects of efficiency programs often find a *rebound effect* in which more efficient technologies are used more intensively, partially offsetting the overall effect. In this section we examine whether households in the treatment group changed their wood fuel use in a way that may have offset the emission reductions resulting from changes in the use of wood stove damper setting.

We did not directly measure the amount of wood fuel actually used throughout the intervention, which would have been challenging as we do not have the technology to monitor such use. In a follow-up survey, however, we asked participants whether they had changed the amount of wood fuel use during the weeks of the experiment (see Table 4 below). Most participants, both in the treatment and control groups, reported either not changing the amount of wood fuel (40.7 percent for the treatment group and 57.7 percent for the control group) or using less wood fuel than before (37 and 30.8 percent, respectively, for treatment and control groups). This result would be at odds with a rebound effect. On the other hand, participants in the treatment group more frequently reported increasing the amount of wood-fuel (22.2 percent) than those in the control group (11.5 percent), which would be consistent with a rebound effect. Therefore, taking these two observations together we conclude that there is no strong evidence either in favor or against a rebound effect as a result of the information sign.

Table 4. Tabulation of Wood Stove Users' Response to Survey Question *Have you changed the amount of wood-fuel you use for your wood-stove?* (percentage)

	No	Yes	
	Same as before	Less than before	More than before
Treatment Gr.	40.7	37.0	22.2
Control Gr.	57.7	30.8	11.5

5.5 Effect on Wood-Stove Emissions of Fine Particulate Matter (PM2.5)

To interpret the change in the use of the damper's setting as a result of the information sign we use estimates for emission factors of Fine Particulate Matter ($PM_{2.5}$) obtained for wood-stoves by recent lab tests conducted for Chile's environmental authority (UCT, 2014).[28] Emission factors were obtained for wood-stoves similar to the ones that participated in this experiment and for burning of different types of timber as wood-fuel. To obtain an average emission factor, we weighted these emission factors by the frequency of each type of timber effectively used for wood fuel by households in Valdivia (INFOR, 2015) to arrive at a weighted average for the average household in Valdivia. Furthermore, to convert these emission factors from PM_{10} emissions to $PM_{2.5}$ emissions we used a proportionality factor of 93.2 percent according to the proportionality factor found in Chow and Watson (1998) for wood-fuel emissions from wood stoves for residential use.[29] The emission factors from the lab tests conducted by (UCT, 2014) are presented in Table 5 below, both for burning dry (certified) wood fuel and for burning wood fuel with high moisture content. Table 5 shows the nonlinearity of wood-stove pollution emissions for different settings of the damper. For example, Table 5 shows that, whereas the pollution emission of fine particulate matter ($PM_{2.5}$) by a woodstove in optimal operating conditions (burning dry wood-fuel with a "mostly open" damper setting) is 4.4 grams per hour (g/h), partially choking the wood stove slightly increases emissions to 6.1 g/h, and emissions from a fully choked wood stove burning the same wood fuel can be as high as 17.1 g/h. For the case of wood-fuel with high moisture content of moist, those figures are 8.7 g/h, 9.8 g/h and 40.5 g/h, respectively.

Table 5. $PM_{2.5}$ Emission Factors by Damper Setting (g/h)[1]

	Damper Setting		
Wood-fuel's moisture	Choked	Mid-Level	Mostly Open
Dry (certified)	17.1	6.1	4.4
High moist content	40.5	9.8	8.7

(1): Emission factors (g/h) for wood-stoves used in Chile's south-central region (double-combustion, similar to those used in the experiment) when burning different types of timber for wood-fuel. Figures weighted according to frequency of use of each timber used for wood-fuel: Nothofagus obliqua (34%), Eucalyptus nitens (33%), Eucryphia cordifolia (7%), Acacia sp. (5%), and Canelo and other speciec (10%).

(2): Weigthed average according to average frecuency of use, for the city of Valdivia, of certified dry wood-fuel (75%) and high moisture wood-fuel (25%).

[28] As mentioned in Section 4.2. above, all woodstoves currently available in the Chilean market are embedded with the "double-combustion" technology. Air pollution emissions are therefore fairly similar across different brands and models.

[29] That is, 93.2 percent of the particulate total PM10 emissions of these wood-stoves correspond to PM2.5 emissions.

In Table 6 we summarize the information presented in Figures 8 through 10 (or equivalently, that of Panel B of Table 3) and compute the effect of the information sign on reductions in wood stove emissions of fine particulate matter ($PM_{2.5}$). The first row of Table 6 presents the frequency of damper setting, as shown in Figures 8 and 9, where we have re-grouped the categories into "Choked," "Mid-level" and "Mostly Open" to match those used in the lab studies conducted by Díaz-Robles (2014). Likewise, we also re-grouped the categories of damper setting in the second row of Table 6, which presents the change in the frequency of use of the damper setting induced by the information sign (as shown in Figure 9).

Table 6. Damper Setting Usage, $PM_{2.5}$ Emissions by Wood Fuel Type and Effect of Information Sign on Reducing $PM_{2.5}$ Emissions

	Total	**Damper Setting**		
		Choked	Mid-Level	Mostly Open
Frequency of damper setting usage (%)[1]		37.4	39.7	22.9
Change of damper setting usage due to sign (percentage points)[2]		-12.7	10.3	2.4
		Dry Wood-Fuel (certified)		
$PM_{2.5}$ emissions before sign (g/h)[3]	**9.8**	6.4	2.4	1.0
Reductions in $PM_{2.5}$ emissions due to sign (g/h)[4]	**1.4**	2.2	-0.6	-0.1
		High Moisture Wood-Fuel		
$PM_{2.5}$ emissions before sign (g/h)[3]	**21.0**	15.1	3.9	2.0
Reductions in $PM_{2.5}$ emissions due to sign (g/h)[4]	**3.9**	5.1	-1.0	-0.2

(1): Average damper setting across treatment and control groups before signage. Settings 'mostly choked' and 'Mid-level' were agregated into column 'Mid-Level', and setting 'Mostly Open' was agregated with 'Open'. See Figure 8 and Figure 9, or Panel B Table 3.

(2): Settings 'mostly choked' and 'choked' were agregated into column 'Mid-Level', and setting 'Mostly Open' was agregated with 'Open'. See Figure 10 or Panel B Table 3.

(3): Average $PM_{2.5}$ emissions in grams per hour (g/h). Emissions for each damper setting is a weighted average calculated by multiplying frequency of damper setting (first row) by emission factors from Table 4.

(4): Reductions in $PM_{2.5}$ emissions in grams per hour (g/h). Emissions for each damper setting is a weighted average calculated by multiplying change of damper setting due to signage (second row) by emission factors from Table 4.

The results on wood-stove emissions of $PM_{2.5}$ are presented in the third, fourth, fifth and sixth rows of Table 6. Whereas the third and fourth rows presents results for the case of burning (certified) dry wood-fuel, the fifth and sixth rows present results for burning wood fuel with high moisture content. For the case of certified dry wood fuel, and given the actual setting of the wood-stove's damper, the third row of Table 6 shows that average $PM_{2.5}$ emissions for a wood stove like those used in Valdivia is 9.8 g/h. Furthermore, our results show a reduction in $PM_{2.5}$ emissions drop of 1.4 g/h due to the information sign (fourth row total). This represents a 14.7 percent decrease in $PM_{2.5}$ pollution emissions with respect to the baseline (absence of information sign). On the other hand, for the case of wood fuel with high moisture content, the fifth row of Table 6 shows that wood stove's $PM_{2.5}$ emissions amount to 21.0 g/h, and that the information sign induces a reduction in $PM_{2.5}$ emissions of 3.9 g/h (sixth row total). This represents an 18.7 percent reduction with respect to the baseline for wood fuel with high moisture content.

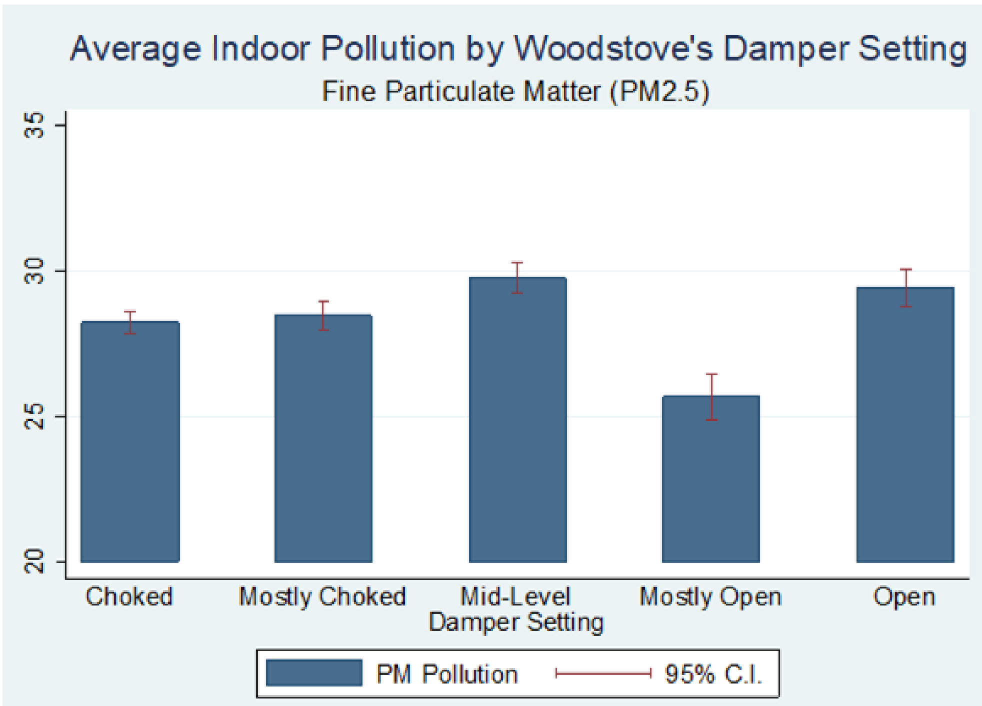
To obtain an overall effect for the effect of the information sign on $PM_{2.5}$ emission reductions we weight these estimates by the percentage of consumption of certified dry wood fuel and wood fuel with high moisture content. According to survey data for households in Valdivia, about one third of households use certified dry wood fuel for heating, whereas about two-thirds use wood fuel with high moisture content (INFOR, 2015). Using these proportions to obtain a weighted estimate for the average household in Valdivia, we estimate that the information sign can reduce wood stove $PM_{2.5}$ pollution emissions by 17.3 percent on average.

5.6 Effect on Indoor Concentrations of Fine Particulate Matter (PM2.5)

In the previous section we considered the effect of the information sign on wood-stove outdoor air pollution emissions and assessed the change in these emissions that was induced by change in the damper setting. Once pollution from a given wood stove is emitted outdoors, those pollutants combine with those emitted by neighboring dwellings, making it difficult to establish a direct link between the emissions of an individual wood stove and ambient air pollution concentrations.

As stated earlier, however, much of the pollution emissions that are emitted outdoors filter into dwellings through drafts entering doors, windows and ceilings. As individuals spend a large amount of their time indoors (particularly during the cold winter months), we are also interested in learning whether there is an effect of the information sign intervention on indoor pollution concentrations. To do so, in this experiment we additionally measured indoor concentrations of particle pollution with the Speck sensor (the same that measures indoor temperature in the living room of each of the participating dwellings). Figure 10 below shows average indoor particle concentrations for each damper setting. The figure shows that households those that largely use the damper in the "Mostly Open" setting also experience lower indoor particle pollution.

Figure 10. Average Indoor PM Pollution by Wood Stove Damper Setting



Note: Blue bars denote average indoor pollution (fine particulate matter concentrations) for each damper setting. As noted above, settings are grouped into five categories (Choked, Mostly Choked, Mid-Level, Mostly Open, and Fully Open), and average indoor pollution is computed only for when the wood stoves are actually on. In addition, capped lines denote 95% confidence intervals (C.I.) for each damper setting.

To examine whether the information sign effectively induced a change in indoor particle pollution concentrations, we run an ordinary least square regression for the following regression equation

$$IndoorPM = \alpha_0 + \alpha_1 Sign + \alpha_2 TreatGr + \alpha_3 Sign\_TrGr + \delta X + \varepsilon \tag{3}$$

where $IndoorPM$ refers to the particle count of indoor air pollution and the rest of the variables are the same as in equations (1) and (2) above, with ε denoting the error term.

The average indoor pollution for each of the groups is given by: (a) Treatment group, before sign = $\alpha_0 + \alpha_2$; (b) Treatment group, after sign = $\alpha_0 + \alpha_1 + \alpha_2 + \alpha_3$; (c) Control group, before sign = α_0 ; and (d) Control Group, after sign = $\alpha_0 + \alpha_1$. Therefore, the Diff-in-Diff estimate [(b-a)-(d-c)] is captured by the parameter α_3.

Table 7 below presents parameter estimates for the α's in equation (3) above, both without further controls for household characteristics (column 1) and adding those controls (column 2). Results from Table 7 show that the information sign had no significant effect on indoor particulate pollution of participating households. This is result is not surprising. As stated above, outdoor pollution from surrounding emitting sources mixes outside with that of other emitters (neighbors' wood stoves) and then enters indoors through drafts. In this work we did not attempt to model and directly account for the mixing of ambient air pollutants. In addition, as stated earlier, the wood stoves of those participating households have a sealed combustion chamber that is designed to leak little air pollution inside the dwelling. Because of this, we did not expect to find significant effects of the information sign on indoor particle pollution.

Table 7. Parameter Estimates for OLS Regression
Dependent Variable: Particle Pollution

VARIABLES	(1)	(2)
Sign On	-4.117	-3.754
	(2.654)	(2.500)
Treatment Group	-2.838	-1.451
	(4.966)	(5.791)
Sign On & Treatment Gr.	0.274	0.372
	(3.056)	(2.818)
Constant	33.09***	56.20**
	(4.019)	(21.42)
Observations	98,880	98,880
R-squared	0.004	0.016

Standard errors clustered at the household level.
*** p<0.01, ** p<0.05, * p<0.1

Sign On is a dummy variable that takes on value equal to 1 when the information sign is on, and 0 otherwise. Similarly, *Treatment Group* takes on value equal to 1 when the household belongs to the treatment group, and 0 otherwise. Furthermore, Sign On & Treatment Gr. takes on value 1 when the household is in the treatment group and the information sign is on, and 0 otherwise. Column (1) presents results without controlling for observable household characteristics (such as those from Table 1), whereas column (2) explicitly accounts for household characteristics.

6. Concluding Remarks and Policy Recommendations

To address the problem of high concentrations of ambient air pollution in cities in south-central Chile, the environmental authority has pushed for a large-scale wood stove replacement program. Under this program, eligible households receive a free wood stove with state-of-the-art combustion technology so long as they effectively dispose of their old (dirty) wood stoves. These new wood stoves have a market value starting at about USD 200. In addition, the only new wood stoves now available are wood stoves with the same combustion technologies as those under the government replacement program. However, because of the way consumers use these new wood stoves, reductions in pollution emissions from upgrading to these new wood-stoves have not been realized. Unless users change the way they operate their woodstoves, upgrading to new wood stoves alone cannot effectively address the problem of high ambient air pollution in this region.

In this work we assessed an information sign that aims to induce a behavioral change in the way users operate their wood stoves, so that to reduce air pollution emissions. We found that reductions in wood stoves' pollution emissions vary from 14.7 to 18.7 percent, depending on the type of wood fuel that is burned (either certified-dry or high-moisture wood fuel), and a weighted average yields reduction of 17.3 percent. Current government policies have focused on inducing users to choose cleaner wood fuels, such as certified-dry wood fuel and pellets. However, as mentioned earlier, these policies have not proven very successful at tackling the problem of air pollution in cities in this region. We believe that a policy measure that attaches an information sign to existing wood stoves can be complementary to current efforts by Chile's environmental authorities.

We see a big potential in reduction of wood-stove pollution emissions from a large-scale program that *nudges* wood stove users into changing the way they operate their devices. For example, at the end of the intervention we asked in our survey whether users would be willing to choke their wood stoves less frequently in order to reduce their wood stoves' pollution emissions. Only 7.4 percent of those in the control group and 26 percent of those in the treatment group said they would. However, when asked whether they would choke their wood stoves less frequently if there were an educational campaign to educate and motivate the community, 88 percent of respondents in both groups said they would. Therefore, the data and analysis conducted in this work allow for a better understanding of users' behavior regarding actual operation of their wood stoves. This can be used for predicting realistic scenarios of the impact of a similar large-scale intervention that provides wood stove users with an information sign similar to the one assessed in this work.

Moreover, the information sign evaluated in this work costs only a small fraction of the cost of these new wood stoves, at about USD 3 (plus costs of installation and information flyer). We believe that a large-scale intervention has real potential to tackle a substantial portion of the problem of air pollution in cities of south-central Chile. It is simple and low-cost so that it can be scaled up in a relatively short period of time and at little additional cost. Moreover, it can be complementary to other existing policies and programs.

Significant gains in reducing air pollution emissions could additionally be achieved by a large-scale communications campaign that teaches users that fully choking their wood stoves is highly polluting and informs them that they can considerably reduce their pollution emissions by simply adjusting the damper setting away from fully closed. Chile’s Ministry of Energy is currently undertaking communications campaigns in all cities suffering from wood stove air pollution, and adding this layer should be quite affordable. Indeed, this sort of communications campaign is currently for a small subgroup of users, low-income elderly residents, in a nearby city (Temuco).

Furthermore, as the government (Ministry of Environment) dictates the technology and pollution emission standards of the wood stoves currently available in the market, it could simply mandate that all new wood stoves come with a built-in information sign similar to the one assessed in this study. This should only slightly increase manufacturers’ costs and could prove to be a cost-effective policy measure.

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