



Nudging for Cleaner Air: Experimental Evidence from an RCT on Wood Stove Usage

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Accepted: 17 July 2021
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Abstract

Air pollution from wood burning is a serious problem in the developing world. In the cities of south-central Chile, households experience extremely high ambient air pollution levels due to massive combustion of wood as fuel for residential heating. To address this problem, in recent years new residential wood stoves—equipped with improved combustion technologies that are designed to be less-polluting—have replaced high-polluting ones. However, users' behaviour in operating these improved stoves is a key factor that drives actual emissions. When users 'choke the damper' to extend the burning time of their wood fuel, it constrains the air flow in the wood stoves and creates a highly polluting combustion process. To address this issue, a behavioural intervention was designed to provide users with real-time feedback on their wood stoves' air pollution emissions with the goal of 'nudging' them to use their stoves in a less polluting way. The intervention consists of an information sign that aligns with the wood stove's damper lever and informs users about pollution emission levels according to the chosen setting of the wood stove's damper. The information sign is complemented by the visit of a field assistant that explains the sign and provides an informational flyer (fridge magnet). To assess the effectiveness of this behavioural intervention a randomized controlled trial was conducted with selected households in the city of Valdivia, Chile. Results from this intervention show that households that were provided with the information sign reduced the frequency with which they used the most polluting settings of their stoves, inducing a behavioural change that results in a 10.8% reduction in residential pollution emissions.

Keywords Air pollution · Behavioural intervention · Environment and development · Field experiment · Wood stoves

We appreciate the financial support of the Inter-American Development Bank (IDB). We additionally benefited from discussions with Bridget Hofmann and Sebastián Miller (both at IDB) that greatly improved the experimental design. We are also grateful to René Reyes (at Instituto Forestal, Sede Los Ríos) and Oscar Pilichi (at Universidad Austral de Chile) for valuable support in conducting the field work. All errors and omissions are our own.

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1 Introduction

Household air pollution from wood fuel burning is a serious problem for many low-income and middle-income countries (Chávez et al. 2011a, b). The incomplete combustion of wood fuel can generate high levels of air pollution, releasing pollutants such as fine particulates, carbon monoxide, nitrogen oxide, and organic compounds. A recent report finds that exposure to household air pollution is linked to 2.6 million annual deaths worldwide (Health Effects Institute 2018). Exposure to air pollution from wood fuel burning, in particular, can also cause various diseases, including respiratory infections (such as acute upper respiratory infections, pneumonia, and chronic obstructive pulmonary disease), cardiovascular diseases, and cancers (American Lung Association 2011; Smith et al. 2013).

Households in Chile's south-central region—the geography where we conducted the field experiment presented in this paper—experience very high levels of ambient (outdoor) air pollution. Unlike households in many developing countries that experience high levels of indoor air pollution from the burning of wood fuels on open fires or traditional stoves, most Chilean households have significantly reduced the problem of indoor air pollution (Chávez et al. 2011a, b). This is due to the widespread adoption of wood stoves equipped with a closed combustion chamber and chimney that carries pollutants from firewood burning outside the dwellings. Consequently, what had largely been a problem of indoor air pollution has turned into a more serious problem of outdoor air pollution in Chile (Chávez et al. 2011a, b).¹ This phenomenon of increasing outdoor air pollution as a consequence of increased adoption of improved wood burning technologies (i.e., closed combustion chambers, chimneys, etc.) is increasingly being experienced by more countries in the developing world, creating a combined problem of indoor and outdoor air pollution (Balakrishnan et al. 2013; Hu et al. 2020). This is also a challenge in some developed countries, especially in rural areas and in the outskirts of cities where households use firewood as a primary or secondary fuel for heating (Hine et al. 2011; US EPA 2013).

Household air pollutants emitted from wood stoves remain suspend in the immediate surrounding areas of their dwellings. When aggregated at the neighbourhood and city level, emissions from individual households create large systemic effects on overall ambient air pollution concentrations. This is reflected in the hazardous levels of ambient air pollution experienced by cities of the south-central region of Chile—where 80 to 95% of households use wood fuel for heating, especially during the cold winter months (Schueftan and

¹ While outdoor air pollution is a more serious problem in Chile, indoor air pollution has not been fully eliminated through widespread household adoption of wood stoves that carry the pollutants outside of dwellings. In fact, indoor pollution is exacerbated by outdoor pollution. 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) elevated levels of outdoor air pollution from wood fuel burning leak back into the interior of many household dwellings. Jorquera et al. (2018) estimate that 68 per cent of indoor air pollution comes from outdoor infiltration in the city of Temuco (one of the most polluted cities, from wood burning air pollution, in south-central Chile). This problem is even more serious in low-income neighbourhoods 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. This problem of neighbourhood pollution created by local household emissions leading to re-entry of pollution back into households has also been documented in other contexts beyond Chile (MacNeill et al. 2014; Smith et al. 1994).

González 2013). Air pollution concentrations in all cities in this region far exceed safe levels, particularly during the wintertime.² According to a 2018 ranking of the world's most polluted cities by fine particulate matter (PM_{2.5}), the top five most polluted cities in South America are found in south-central Chile. Valdivia, the city where we conducted the field experiment, is ranked fourth.³

To address this problem, Chile's environmental authority (the Ministry of Environment) has introduced multiple public policy measures to lower ambient air pollution. A key measure has been the implementation of a policy regulation that only allows for the selling of newer models of wood stoves that are equipped with a “double combustion” technology. This technology allows for a secondary burning of air pollutants in the combustion chamber that, when operated ‘optimally’, can significantly reduce emissions. However, despite policy measures and high market penetration of these cleaner stoves, ambient air pollution concentrations have continued to rise in all major cities of this region (Schueftan and González 2015).

A major reason for this is that users' behaviours in how they operate their wood stoves in real life settings has a significant effect on pollution emissions. Outdoor pollution emission from these cleaner wood stoves vary largely according to the setting of the stove's damper, which regulates airflow inside the combustion chamber (Jordan and Seen 2005). When users “choke the damper” to close the airflow in the combustion chamber and keep the wood burning longer—as they often do for fuel cost savings—they create smouldering. This is a combustion process that is significantly more polluting as compared to when users set the stove's damper open (or partially open) to allow for more air flow that generates combustion with a vivid flame, which re-burns the pollutants in the secondary combustion described above.

As brought to attention by Hanna et al. (2016), it is very important to assess how users' behaviours in operating their stoves in real-life settings impact the effectiveness of improved stove technology in reducing pollution and improving health. To-date, there has not been an assessment of how users' behaviours of the cleaner stoves in Chile impacts pollution emissions (Chávez and Gómez 2017; Gómez et al. 2017; Schueftan et al. 2016). This paper contributes to the literature by providing experimental evidence on the links between behavioural change in the usage of improved wood stove technology and reduction in outdoor household air pollution.

In this paper we examine whether households can be *nudged* through a behavioural intervention to change how they use their wood stoves so that they emit less outdoor pollutants. We do this by providing an information sign that informs users, in real-time, about their wood stove's emissions according to how they chose to set their stove's damper setting. Our hypothesis is that users will respond to this visual aid by decreasing the frequency of the choking of their wood stoves towards using a more open, less emitting damper settings.

² For example, Fig. 6 (in Appendix A) shows the average concentrations of ambient fine particulate matter (PM_{2.5}) from 2008 to 2019 for the city of Valdivia, Chile. The figure shows that during the cold winter months ambient PM_{2.5} pollution concentrations far exceed both national standards and WHO guidelines. Moreover, most cities in south-central Chile show similar patterns (Molina et al. 2017).

³ The cities in Chile's south-central region listed in this 2018 ranking are: Padre Las Casas (Rank #1), Osorno (#2), Coyhaique (#3), Valdivia (#4), Temuco (#5), Linares (#10), Rancagua (#13) and Puerto Montt (#15). Santiago, which is Chile's largest city, but not located in the south-central region, is ranked #7. An updated ranking for year 2020 shows a similar ranking. Source: www.airvisual.com/world-most-polluted-cities

We assessed the effectiveness of this information sign by conducting a randomized controlled trial (RCT) with 80 households in the city of Valdivia, Chile. We provided households in the treatment group with an information sign that attached to the levers of their wood stove's dampers. Households in the treatment group also received a visit from a field assistant to install and explain the information sign and to provide an informational flyer (fridge magnet). Users in the control group were not provided with this information sign (and neither the installation visit nor the fridge magnet). Users in both the treatment and control groups were free to set their wood stove's damper in any way they wanted: choking the airflow in the combustion chamber to save on wood fuel expenditure, opening the airflow to decrease outdoor pollution emissions, or any setting in between. We monitored and recorded the actual setting of wood stoves' dampers for both treatment and control groups.

Our results show that households can be nudged to use their stoves in a less polluting way. Households in the treatment group showed a reduction in the frequency with which they used the most polluting settings of their stoves (the choked settings on their stove dampers), leading to a significant drop in household emissions of $\text{PM}_{2.5}$ pollution. As a result, deploying information signs on existing (and future) wood stoves and educating users on low-polluting usage have the potential to be cost-effective measures to address the problem of air pollution in the near term.

The rest of the paper is organized as follows. The next section discusses the related literature. Section 3 describes the problem of household air pollution in cities in south-central Chile, the design of improved woodstove technology, and targeted public policies to address this problem. Section 4 presents our testable hypothesis through a simple analytical model. Section 5 describes the experimental design, and Sect. 6 presents the main results. Section 7 discusses our findings in reference to the related literature. Finally, Sect. 8 provides policy recommendations and concluding remarks.

2 Literature Review

To the best of our knowledge, this paper is the first to conduct an RCT to examine whether households using improved wood stoves can be nudged to reduce air pollution through an informational intervention. It addresses a gap in the experimental literature about the relationship of household behaviour in using improved stove technology and its impact on ambient air pollution emissions. Additionally, this paper contributes more generally to the growing literature on the broader topic of 'green nudges' in the field of energy and the environment. We discuss these two branches of literature below.

2.1 Improved Stoves and Household Air Pollution

One of the most significant air pollution problems in the world today occurs due to the burning of solid fuels, such as wood fuel, and use of inefficient stoves by approximately 3 billion people in low- and middle-income countries (Jeuland et al. 2015; WHO 2007; WHO 2014a; WHO 2014b). To address this important issue, there have been increasing efforts to design a variety of improved stoves with technologies that emit less air pollution and to promote their adoption by households across a range of low- and middle-income settings (Bensch et al. 2015; Jagger and Jumbe 2016; Lewis and Pattanayak 2012; Miller and Mobarak 2014).

Most of the literature related to less-polluting stove technologies focuses on the topics of household adoption of improved cookstoves and its impact on reducing indoor pollution and improving health outcomes. For example, in an RCT study about the take-up and impact of improved cookstoves in Senegal, Bensch and Peters (2015) provide experimental evidence of increased adoption of improved stoves and significant reductions in smoke exposure and respiratory and eye diseases. Similarly, Pattanayak et al. (2019)'s RCT intervention of improved cookstoves adoption in northern India presents experimental evidence of increased adoption of these improved cookstoves. However, several randomized evaluations of improved stoves, including that by Pattanayak et al. (2019), find that household adoption subsides in the long-term and many households resort back to using traditional stoves or a combination of their new and old stoves (Hanna et al. 2016; Burwen and Levine 2012; Romieu et al. 2009). In the experimental studies that do find evidence of increased household uptake of improved stoves, these studies do not address the predicament that while household adoption of improved stove technology can reduce indoor pollution, it can exacerbate the problem of outdoor air pollution.⁴ Improved stoves are generally designed with new wood burning technologies (i.e., a closed combustion chamber and a chimney) that carry most of the air pollutants generated by the combustion process outside of the dwellings, suspending pollutants in the immediate surrounding areas.

Our study is framed within the broader literature context that discusses how the problem of indoor air pollution is more recently changing into a problem of outdoor air pollution for developing and emerging economies that are experiencing increased adoption of improved stoves (Balakrishnan et al. 2013). This problem has been documented for countries such as Chile, China, and India, where large-scale stove replacement programmes incentivize the adoption of stoves with these new wood burning technologies that channel air pollutants outside dwellings (Gómez et al. 2017; Balakrishnan et al. 2013; Hu et al. 2020). This problem has also been documented in some developed country contexts such as Australia, Canada, New Zealand, United Kingdom, United States, and other countries where peri-urban and rural households use wood fuel burning as a main source of heating (Hine et al. 2011; Rokoff et al. 2017; US EPA 2013).

Furthermore, Hanna et al. (2016) raises the critical point that the effectiveness of improved stoves depends on changes to household behaviour to ensure the stoves' sustained usage, proper use, and maintenance. User behaviour of how individuals operate their stoves in real-life settings poses limits to the effectiveness of improved stoves adoption programmes in reducing pollution. For instance, Hanna et al. (2016)'s RCT evaluation in India finds that households used their improved stoves improperly and irregularly and failed to maintain them.⁵ The authors conclude that more studies are needed to assess whether the benefits of improved stoves—usually evaluated under controlled laboratory conditions—persist under “typical use” of households in field settings.

⁴ Hanna et al. (2016) speculates that one potential explanation for why reducing indoor air pollution had limited effects on improving health outcomes of the households in their treatment group could be because these households are exposed to ambient air pollution emitted from chimneys with pollutants remaining in the village. However, they do not directly measure this in their study.

⁵ Hanna et al. (2016)'s study assesses household use of cookstoves as it relates to indoor air pollution. For instance, they assess whether households cover the second pot opening, when it is not in use, to minimize smoke emissions. The authors also assess whether households clean the chimney so that it does not block the smoke. While this study was conducted in the context of indoor pollution emissions, similar principles apply to the context of ambient pollution emissions because in both instances the focus is on the relationship between how user behaviour impacts emission levels.

In the context of Chile, the existing literature that examines ambient air pollution from burning wood fuel acknowledges that the real effect on emissions reductions from adoption of cleaner stove technologies is uncertain due to the impact of users' behaviour when operating their wood stoves (Chávez et al. 2009, 2011a, b; Chávez and Gómez 2017; Gómez et al. 2014; Gómez et al. 2013; Gómez et al. 2017; Schueftan et al. 2016; UFRO-CONAMA 2009). This paper contributes to this gap in the literature by providing field-based experimental evidence of how users' behaviour of the cleaner stoves in Chile impacts pollution emissions.

2.2 Information Feedback Behavioural Interventions and 'Green Nudges'

In recent years, researchers and policymakers have shown increased interest in behavioural incentives that stimulate voluntary actions to address negative externalities (Croson and Treich 2014; Kesternich and Rübhelke 2017; Carlsson et al. 2019). As a result, there has been a rapidly growing literature on 'green nudges' and information feedback strategies.⁶

However, other than a few exceptions, there are limited field studies about behavioural interventions in the context of household usage of improved stoves and impact on air pollution emissions. One of the closest studies in the existing literature is that of Zhou et al. (2006), and subsequently Yu (2011). These studies assessed a programme that consisted of adoption of improved cookstoves and a health education intervention to raise awareness among rural households in China about the adverse effects of indoor air pollution from cookstoves. Another closely related study is Hine et al.'s (2011) field experiment, in a small city in Australia, that assessed the effectiveness of an education campaign describing the negative health effects of wood smoke pollution and providing advice to households about best practices for wood heater operation. Their results show that the education campaign was associated with significant reduction in wood smoke emissions. Hine et al. (2011) indeed recommend that future field experiments examine whether providing households with descriptive feedback about their own emissions and the average emissions for their neighbourhood, a topic not addressed by their experiment. Our experiment addresses this research question.

For our experimental intervention, we draw from the relevant implications from recent studies that assess information feedback strategies (a.k.a., 'green nudges') to induce savings in residential energy and resource consumption in the developed world. For example, Fischer (2008) notes that information feedback is more effective when the action that aims to affect occurs with high frequency and feedback is given soon after this action. Likewise, in a review of studies, Delmas et al. (2013) observe that significant energy conservation is triggered only when information is given in real-time (such as when using smart meters in-home displays) or when information strategies include higher involvement interventions (such as home energy audits). In fact, this literature 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).⁷

⁶ These strategies evaluate the effectiveness of (social comparison-based) home energy reports, smart meters and in-home displays in promoting more efficient patterns of consumption, and thus achieving reductions of residential electricity and water consumption (Allcott 2011; Ferraro and Price 2013; Jessoe and Rapson 2014; Schultz et al. 2015).

⁷ Moreover, Asensio and Delmas (2015) show that information strategies that communicate the environmental and public health externalities of electricity production outperform information strategies that only emphasize monetary savings. For the case of India, a developing country experiencing high levels of air

Using insights from this literature, we designed our informational-based behavioural intervention to include similar elements of giving real-time feedback to households about the pollution emissions that their wood stoves generate according to how they use their stoves' damper. In our intervention households could see how their action impacted emission levels through the display of a colour-coded information sign that aligns with their stove's damper setting. Our design and implementation of this experimental approach adds a new application of 'green nudges'—more specifically, informational-based behavioural science—to the assessment of household usage of stove technology.

3 Background on Household Air Pollution and Wood Stove Technology in South-Central Chile

Cities in south-central Chile have climatic and structural conditions that create high demand for residential heating.⁸ During the cold winter season, households in the region rely on firewood as the main fuel for heating. 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; MMA 2014a; CDT 2010), making it particularly challenging to switch to different sources of energy for residential heating. As discussed in the Introduction, the incomplete combustion of wood fuel generates hazardous levels of air pollution in this region.

To mitigate emissions from wood fuel burning, Chile's Ministry of Environment has designed and implemented Air Pollution Control and Prevention Plans (PPDAs, according to the Spanish acronym) in most of the cities in this region.⁹ Under these PPDAs, it has mandated that only high efficiency "double combustion" stoves to be available in the market since the early 2000s. In addition, over the last decade, the government has pushed for a large-scale stove replacement programme that largely subsidises household adoption of these cleaner technologies. Under this programme, eligible households could buy a "double combustion" wood stove at a fraction of the cost (paying about USD 50 for a wood stove that has a market value of approximately USD 700), so long as they properly dispose of their old wood stove. As a result of these policies, thousands of households in Chile's south-central region have upgraded to this new stove technology over the last decades.

Figure 1 shows one of the most popular wood stoves currently available in the Chilean market, which was also part of the government-subsidised wood stoves replacement

Footnote 7 (continued)

pollution—of which a large part originates in electricity generation—the reduction in electricity consumption using these strategies has been found to be even more pronounced than in the U.S. (Chen et al. 2017).

⁸ Valdivia, the city where we conducted the field work, has a temperate humid climate with an average temperature of 12° C and abundant rainfall (Castillo 2001). The cold season extends from April through November (late autumn, winter and early spring in the Southern Hemisphere), in which July is the coldest month with average temperature of 8 °C. Given these climatic conditions, one of the leading factors explaining the high consumption of wood fuel is the poor thermal insulation of dwellings, which makes them require more fuel for heating (MMA, 2014a).

⁹ 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).

programme.¹⁰ The figure shows that these wood stoves have a closed combustion chamber with a seal-tight door that effectively prevents from indoor emissions. In addition, these wood stoves are installed together with a chimney that directs air pollutants outside the dwelling. Thereby, the technology in these wood stoves allows for combustion in which almost all air pollutants exit through the chimney and have virtually no emissions of indoor air pollutants.¹¹ Figure 1 also illustrates the wood stove's embedded "double combustion" technology for efficient wood burning and low outdoor pollution emissions. As described in the note in Fig. 1, this technology allows for a secondary burning of air pollutants in the combustion chamber before being emitted outdoors through the chimney, designed to significantly reduce emissions under optimal operation of these wood stoves (which largely varies according to usage of the damper settings). It is important to underscore that this "double combustion" technology is fairly standard across different brands and models currently available in the Chilean market.¹²

Overall air intake is controlled by the wood stove's damper, which is a lever located on top of the wood stove (right above the main chamber door). The damper allows users to adjust the airflow in the combustion chamber which regulates 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, users incur higher wood fuel expenses because the wood burns more quickly at this setting, consequently, users will use more wood fuel when the damper is "open" or "partially open". Through the higher air inflow from a more open damper setting, the combustion of the wood fuel is cleaner leading to less emissions, despite more usage of wood fuel. On the other hand, choking the wood stove creates smouldering, which is a highly polluting combustion process with no vivid flame, and thus effectively preventing from the secondary combustion of pollutants (for which these stoves are specially designed for). Choking thus slows down combustion, which allows users to save on wood-fuel expenses, but it dramatically increases outdoor pollution emissions.¹³

Due to their design, 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. The amount of emissions depends on user behaviour of the stove damper settings. When users "choke the damper" of their wood stoves—dramatically limiting the airflow in the combustion chamber and thus preventing clean and efficient combustion—emissions from these newer technologies can be 77% (for low moist wood fuel) to 103% (for high moist wood fuel) as

¹⁰ This wood stove is a Bosca model Eco 360, and it is one of the models we targeted in this behavioural intervention.

¹¹ This is unlike recent interventions in the developing world (India, East Africa, West Africa, and Central America) in which 'clean' cook stoves do not have a seal-tight door that effectively prevents from indoor pollution emissions. See for example the RESPIRE cook stoves replacement program in Guatemala (Envirofit cook stoves) documented in World Bank (2011), or the long-term analysis by Hanna et al. (2016) of 'clean' cook stove replacement programs in India (Gram Vikas cook stoves).

¹² 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 a former Bosca engineer who left to start his own company, taking with him the wood burning combustion technology that he had originally designed.

¹³ These emissions present a highly non-linear relationship with respect to the damper setting, in a way that wood stove emissions when fully choked are many times larger than emissions in any other setting (even compared to emission when only partially choking them). Users' choking of wood stoves can result in outdoor pollution emissions as much as five times greater than wood fuel burning from more efficient usage of the stoves when users set the damper to open or partially open (Jordan and Seen 2005).

much as emissions from the old wood stoves that they are replacing. Conversely, when users allow for plenty of air flow in the combustion chamber through an open damper setting, these figures are only 36 to 31% (for low moist wood fuel and high moist wood fuel, respectively) as much as emissions from old wood stoves.

4 Theoretical Framework and Testable Hypothesis

Users' decision on whether to choke their own wood stove can be characterized as a voluntary contribution to a local public good in which wood stove users face individual 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 neighbouring population (regardless of who emits air pollutants). Moreover, those costs are not always perceptible and do not necessarily produce immediate consequences, but they are likely to be cumulative over time.¹⁴

4.1 A Simple Model of Household Woodstove Pollution Emissions

We can characterize the problem of woodburning air pollution by means of a utility maximizing household-level model. Let us assume that, during the cold months of winter, household i obtains utility from indoor temperature comfort (T) and from consumption of other goods (Z). Meanwhile, the household members suffer from the adverse effects of woodburning air pollution, so that they perceive negative utility from exposure to local ambient air pollution (E). Let U_i represent the utility by household i , such that $U_i = U_i(T, Z, E)$.

Indoor temperature comfort is a function of wood-fuel usage (w) and the choking of the woodstove's damper (c), $T = T(w, c)$. Similarly, household-level emissions (e_i) are also a function of w and c , such that $e_i = e_i(w, c)$. Wood stove pollution emissions increase with choking, so that $\partial e_i / \partial c > 0$. Air quality (i.e., the absence of air pollution) can be characterized as a local public good, so that aggregate ambient air pollution (E) is the sum of emissions across N households in the same locality, that is $E = \sum_i^N e_i(w, c)$.

Households face a budget constraint in which disposable income I must be no less than their total expenditure in consumption goods and wood fuel: $I \geq wP_w + Z$, where the price of the compound consumption goods Z has been set equal to one, for simplicity, and P_w denotes the price of wood fuel.

Therefore, in this household-level utility maximizing problem, household i chooses w, c and Z so that to maximize utility U_i subject to its budget constraint. The Lagrangian and first order condition for the household maximization problem are given by,

$$\mathcal{L} = U_i(T(w, c), Z, E(e_i(w, c))) + \lambda_i(I - Z - wP_w)$$

F.O.C.

¹⁴ 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.

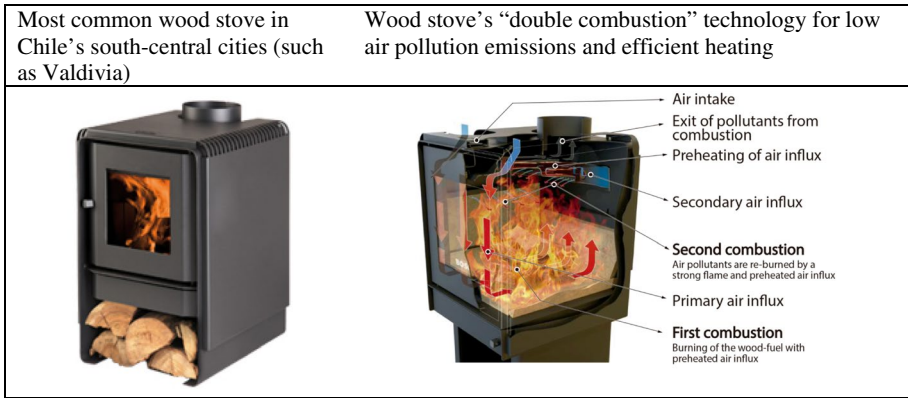


Fig. 1 Wood stoves' combustion technology and outdoor pollution emissions. *Note:* The "double combustion" process of these wood stoves refers to an efficient airflow in the combustion chamber. This airflow creates a strong flame so that, after the wood fuel is burned at the bottom of the chamber (in 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")

$$\frac{\partial U_i}{\partial T} \frac{\partial T}{\partial w} + \frac{\partial U_i}{\partial E} \frac{\partial e_i}{\partial w} \leq \lambda_i P_w \quad (1)$$

$$\frac{\partial U_i}{\partial T} \frac{\partial T}{\partial c} + \frac{\partial U_i}{\partial E} \frac{\partial e_i}{\partial c} \leq 0 \quad (2)$$

$$\frac{\partial U_i}{\partial Z} \leq \lambda_i \quad (3)$$

On the other hand, the social planner chooses w , c and Z that maximizes aggregate utility across all N households, $\sum_i^N U_i$. This is made evident by having the social planner choosing on the level of aggregate emissions E , rather than household-level emissions e_i . Therefore, assuming (for simplicity) that the social planner sets the same level of emissions across all households i (so that $e_i = e$, for all i), then local ambient air pollution is given by $E = Ne$. The FOCs equations of the social planner problem are given by,

$$\frac{\partial U_i}{\partial T} \frac{\partial T}{\partial w} + N \frac{\partial U_i}{\partial E} \frac{\partial e}{\partial w} \leq \lambda P_w \quad (4)$$

$$\frac{\partial U_i}{\partial T} \frac{\partial T}{\partial c} + N \frac{\partial U_i}{\partial E} \frac{\partial e}{\partial c} \leq 0 \quad (5)$$

$$\frac{\partial U_i}{\partial Z} \leq \lambda \quad (6)$$

The problem of externalities of air pollution emissions is made apparent by comparing Eq. 1 with 4, and Eq. 2 with 5. Whereas the optimization problem of household i only accounts for the effect of its direct emissions e_i , the optimization problem of the social planner internalizes the disutility from aggregate emissions E . The nature of aggregate emissions E as a public bad greatly amplifies the marginal disutility of emissions (as shown in Eqs. 4 and 5 above). As a result, the social planner's solution calls for a much lower level of emissions e than a household i would otherwise choose. The social planner achieves this by setting a lower level of wood fuel consumption w (Eq. 4) and less choking of the damper lever c (Eq. 5).

4.2 Implications for Analysing Actual Household Behaviour

If due to imperfect information actual households ignore the effect of choking on their wood stoves' emissions (say, by treating $\partial e_i / \partial c$ as if it were equal to zero) then they will choose c so that to set comfortable indoor temperature T , while satisfying their budget constraint. Because choking generates savings in wood fuel expenditure, and thus relaxes the budget constraint, households will choke their woodstove to a larger degree than if they were to fully account for the effect of choking on its own emissions e_i —and thereby, the effect on exposure to local ambient air pollution E . By providing information on user's effective emissions according to their wood stoves' damper setting, the information sign in our experiment aims to correct for this information failure. Therefore, we expect that households in the treatment group would consider the effect of the damper setting in their wood stoves' emissions and would shift the damper away from fully choking, closer to intermediate and open settings instead.

Moreover, to the extent that actual households in our sample may present pro-social behaviour, they may deviate from the household maximization solution, towards the social planner's solution. If so, they would further reduce choking c . Thus, if the overall effect of the treatment promotes pro-social behaviour (say, through moral suasion), then we should expect that households in the treatment group may choose to set the damper towards less emitting settings (i.e., away from fully choked).

4.3 Testable Hypothesis

This analysis allows us to state our hypothesis: *Wood stove users respond to the provision of the information sign by (at least, partially) considering the negative effects that choking creates on the quality of the air they breathe, as well as the effects on others.*

Thus, the information sign—and more broadly, the assignment to treatment (including receiving a visit from a field assistant to install and explain the information sign and to provide a fridge magnet)—should induce a change in the way users operate their wood stove's damper setting: less choking and lower air pollution emissions. In the next section we explain how the behavioural intervention designed for this field experiment allows us to test our hypothesis.

5 Behavioural Intervention for Reducing Wood Stoves' Air Pollution Emissions

5.1 Information Sign

The information sign that we assess in this paper effectively provides feedback to wood stove users by visually showing them whether emissions levels are low or high, depending on how they chose to set their stove's damper settings. The information sign aligns to the wood stove's damper lever, thus providing real-time feedback on wood stove's emissions at each damper setting.

The information sign consists of a metallic plaque that attaches to the top of the wood stove and that aligns precisely with the setting of the damper's lever (see Figs. 2, 3). The sign shows that when the damper setting is all the way to the left (i.e., fully 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.¹⁵

In addition, to effectively register the actual position of the damper setting, a custom-made monitoring device was developed for the purposes of this research project (see Fig. 3). 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 min and saves this information in 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). The information sign was installed so that it aligned with the five positions of the damper. 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.

5.2 Field Experiment

We recruited 80 households to participate in a field experiment.¹⁶ All participating households had a "double combustion" wood stove that they used as the only source of heating

¹⁵ 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 field assistants when they visited participating households to install the information sign.

¹⁶ The recruitment consisted of contacting households by phone from a database of wood stove users from our implementing partner, INFOR (Chile's Forestry Institute). In the year prior to the field experiment, INFOR had participated in a public fair, in which they had conducted a raffle and collected household contact information on wood stove users (this formed the basis of the households we contacted). During the first call, a field assistant explained that we were conducting a study on wood stove usage and asked whether these households had a wood stove of one of the models for which we could potentially mount the damper setting monitoring device (the black box shown in Fig. 3). For those households that seemed 'recruitable', the field assistant scheduled an appointment to visit the household at a later time. At this visit, the field assistant explained the purpose of the visit in more detail and confirmed that the household's stove was workable for the monitoring device.

for 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.¹⁷

The experiment was conducted in two phases of 40 households each, and each phase lasted 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). Adding up both phases there were 52 households randomly assigned to the treatment group and 28 household randomly assigned to the control group. 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. We believe that there was no communication among participating households.¹⁸ All participating households signed an informed consent form before starting the experiment which informed them of the different phases of the experiment.¹⁹ As an incentive for participation, each participating household received one cubic meter (1 m³) 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' behaviour regarding the setting of the woodstove's damper.

The wood stove's damper setting was recorded for a full month for all participating households (both in the treatment as well as in the control group). We did this by means of the damper setting monitoring device shown in Fig. 3. Furthermore, an indoor temperature monitoring device was installed at approximately two meters from the wood stove (which is usually located in the living room). The purpose of this temperature monitoring device was to record indoor temperature so that, by contrasting it with outdoor temperature, we can determine when the wood stove was in use. Figure 4 depicts a timeline of the field experiment.

The installation of these devices marked the beginning of the experiment. At this time, a field assistant also applied a survey to gather information on socio-economic characteristics of the household members, experience of any health-related problems, characteristics of dwellings, quality of wood fuel used and means for acquiring it.²⁰ The survey also asked questions regarding the household head's opinion on air pollution as well as frequency of use of the wood stove.

¹⁷ The damper setting monitoring device was effectively 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.

¹⁸ During the first phone call, the field assistant asked whether the household head had heard of anyone else participating in this a study, and no participant responded affirmatively (although no record of this question was kept). Given that this field experiment was conducted in a city with a population of 150 thousand people, we believe it is unlikely that two households participating in this study knew one another.

¹⁹ 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."

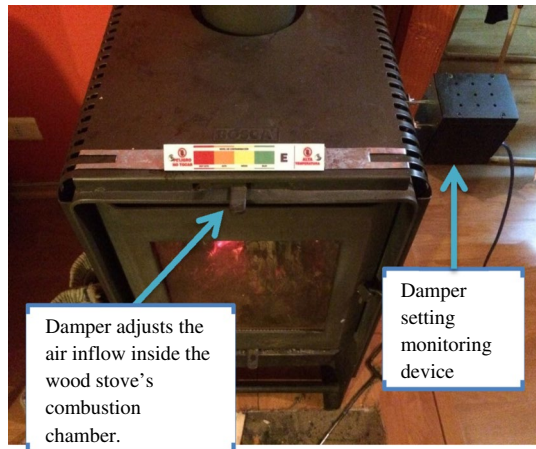
²⁰ The field assistant position had dual roles. One of the roles was to serve as enumerator in administering household surveys and conducting the follow-up check-in calls with participating households. The second role was to serve as technician in installing the information sign on the wood stoves. As part of the installation visit, the role also entailed explaining the information sign, answering questions, and giving households the informational flyer (fridge magnet). After the installation visit, the technician role also entailed household visits to troubleshoot any technical problems when the monitoring device was not working.



Fig. 2 Information sign. *Note:* The information sign shows wood stoves' "Pollution Levels" ("Nivel de Contaminación", in Spanish) for each setting of the damper (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

Fig. 3 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



Two weeks later, the information sign was installed only in the wood stoves of those households in the treatment group (see Fig. 3). 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 aggregate wood stoves' effect on the city's ambient air pollution (see Fig. 8, in the Appendix B).²¹ During the installation visit, the field assistant explained in detail to the household head the meaning of both the information sign and the flyer and answered any questions household members may have had. Throughout the experiment, a team of field assistants made periodic check-in phone calls and paid occasional visits (when troubleshooting was required), to both households in the treatment and control group, to ensure that the monitoring devices were readily recording information.²²

²¹ The flyer was meant to both explain and remind users of the effect of aggregate wood stove emissions. Thus, strengthening the link between the chosen damper setting and their associated effects in term of wood pollution emissions.

²² It is important to note that the field assistants made periodic check-in calls with households in both the treatment and control groups. The check-in calls were conducted with the same frequency with both groups. Therefore, we would not expect the monitoring from the calls to be driving household behaviour for the treatment differently than it would for the control group. Moreover, the visits from the field assistants were rare and focused on troubleshooting the monitoring device when problems arose.

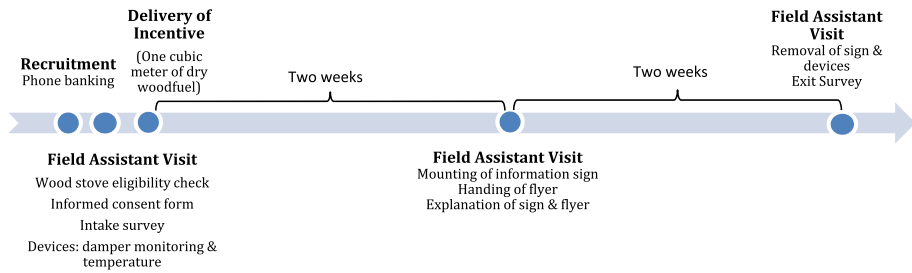


Fig. 4 Timeline of the field experiment

At the end of the experiment, an exit survey was conducted to complement information gathered by the initial survey. Once the intervention was finished, all monitoring devices were collected, the data from them were downloaded and the survey data were digitized.

Therefore, the intervention was a bundle that consisted mainly of the information sign attached on top of the wood stoves, but the information sign was complemented by the visit of a field assistant that explained the sign and provided the informational flyer (fridge magnet). It is possible that part of the effect we present in the next section may be driven by these visits acting as a more salient audience to the treatment than to the control group, thus modifying the effect of the information sign alone.

6 Results

6.1 Descriptive Statistics for Treatment and Control Groups

The randomization of participating households into treatment and control groups makes it highly unlikely that there is any systematic characteristic of those participating households that affects 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. More specifically, it presents mean and standard deviation for the following group of 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 indoor temperature; (v) monthly household income; (vi) dwelling characteristics (such as ownership, surface area, number of floors and construction year); and (vii) survey respondent's characteristics, such as gender, age, marital status and educational attainment. We conducted a test of joint orthogonality to assess that these baseline variables are unrelated to the treatment status. We did this by running a Probit of the treatment dummy on all the variables presented in Table 1, and then conducted a joint hypothesis test for the null that all parameters are equal to zero. We fail to reject the null (chi-squared p value equals 0.99).

6.2 Effect on Usage of Wood-Stove's Damper Setting

In this section we present results from the analysis of the data on wood stove's damper use obtained with the damper setting monitoring device (shown in Fig. 3). We restrict

our analysis to only those hours of the day when the wood stove was in use. 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, not shown in the pictures). 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.²³ As a robustness check, we also conducted the analysis at the 40th and 70th percentile of the temperature difference, finding qualitatively and quantitatively similar results.

We compute the aggregate distribution of damper settings by averaging households' distributions of the damper setting in control and treatment groups as well as before and after installation of the information sign. Figure 5 presents these distributions for control group (left graph) and treatment group (right graph). The distribution for the control group before the information sign (blue bars) is similar to that after the information sign (red bars). Furthermore, the distribution for the control group before the information sign was installed (blue bars) is similar to that of the treatment group (brown bars).

We conducted Wilcoxon's paired signed-rank test (for equality of distributions for those in the control group, before and after the information) and rank-sum test (for equality of distributions across control and treatment groups, before the information sign was installed). We failed to reject equality of distributions in both cases. The Wilcoxon rank-sum test for equality of distributions across control and treatment group, before the information sign was installed, yielded a p value = 0.8469. Thereby we fail to reject the null. Similarly, the Wilcoxon paired signed-sum test for equality of distributions for the control group, before and after the information sign, yielded a p value = 0.7672, failing to reject the null.²⁴

To assess the effect of the information sign on user's damper setting, we then contrasted the distribution before and after the information sign for the treatment group. We find that the distribution after the information sign (green bars) is shifted towards

²³ According to our survey data, participating households report that their wood stoves are in use an average of 13.32 h a day (that is, about 55.5% of the time). Figure 7 (in the Appendix) 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 short distance from the wood stove 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 A2 shows that the average indoor temperature peaks soon after midnight, and drops monotonically until about 13:00 h. (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 h.), 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 7:00 h. during winter), to slowly increase and peak at around 15:00 h.

²⁴ To conduct this test, we proceeded in two steps. First, we conducted a pairwise rank-sum across all households, by contrasting household i 's distribution of the damper setting against that of every other household (say, every household j , where $i \neq j$). This allowed us to generate a *score* of pairwise contrasts containing the count in which household i 's distribution ranked higher than that of household j (where $i \neq j$). With this *score* we constructed a *ranking* of those household-level distributions most 'shifted' (highest *score*) towards the "Choked" setting to those most 'shifted' towards the "Open" setting (lowest *score*).

Then, using the *scores* obtained in the first step, in the second step we conducted both a Wilcoxon paired signed-rank and a Wilcoxon rank-sum test.

Table 1 Descriptive statistics of participating households (treatment and control groups)

Variables	Control group		Treatment group	
	Mean	Std. Dev	Mean	Std. Dev
Household members	3.19	1.02	3.34	1.45
Less than 4 years old	0.19	0.49	0.19	0.44
Between 5 and 14	0.31	0.55	0.49	0.75
Between 15 and 65	2.46	1.17	2.32	1.31
65 and older	0.23	0.59	0.34	0.55
HH member suffer from resp. or cardio. Disease	0.27	0.45	0.25	0.43
Num. hours wood stove is in use				
Weekdays	13.5	6.31	12.1	4.96
Weekends	14.9	6.55	15.4	4.71
Indoor temp. score (self-reported)	0.88	0.12	0.88	0.11
Monthly HH income (percent)				
Less than USD 800	0.46	0.51	0.42	0.50
Between USD 800 and 1700	0.33	0.48	0.40	0.49
More than USD 1700	0.21	0.41	0.19	0.39
Dwelling's				
Ownership = own (percent)	0.73	0.45	0.70	0.46
Surface areas (sqrd. meters)	69.9	40.1	78.8	39.2
Floors (percentage 1 floor)	0.36	0.49	0.40	0.49
Construction before 2000	0.54	0.51	0.62	0.49
Const. between 2000 and 2007	0.19	0.40	0.21	0.41
Const. after 2007	0.12	0.33	0.06	0.24
Const. year N/A	0.15	0.37	0.12	0.32
Respondent's				
Gender (1 = male)	0.42	0.50	0.40	0.49
Age	42.7	14.0	47.4	14.1
Marital status = single (percent)	0.35	0.49	0.30	0.46
Marital status = married (percent)	0.46	0.51	0.57	0.50
Marital status = divorced/widowed	0.19	0.40	0.13	0.34
Educ. attainment = primary (percent)	0.15	0.37	0.19	0.39
Educ. attainment = secondary (percent)	0.42	0.50	0.36	0.48
Educ. attainment = terc (technical)	0.19	0.40	0.19	0.39
Educ. attainment = terc. (university)	0.23	0.43	0.26	0.45

less polluting damper settings. Whereas the frequency of the “Choked” and “Mostly Choked” drops 8.7 and 2.7 percentual points, respectively, the frequency of “Mostly Open” and “Open” increase 4.5 and 5.4 percentual points, respectively. We conducted a Wilcoxon paired signed-rank tests and we rejected equality of distributions, in favour of the alternative hypothesis that the distribution after the information sign is shifted to the right (i.e., it has a lower ranking). The Wilcoxon paired signed-sum test for the treatment group, before and after the information sign, yielded a p value = 0.0000. Therefore,

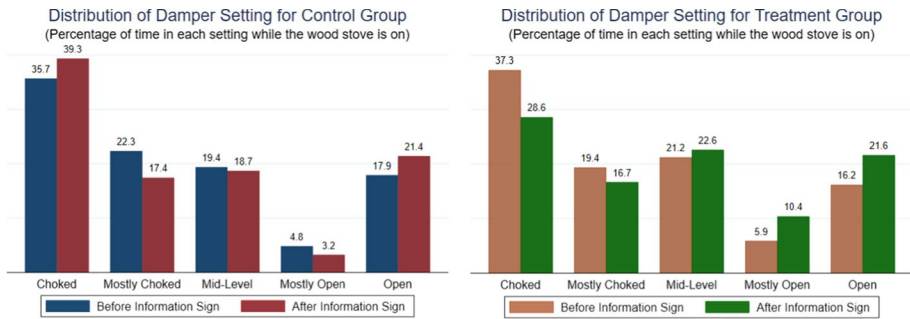


Fig. 5 Distribution of damper setting for control and treatment groups. *Note:* Graph on the left graph shows the distribution of the damper setting for households in the control group and the graph on the right show the distribution for those in the treatment group. Blue and orange bars denote the distribution before the information sign was installed and red and green bars denote the distribution 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

we reject the null in favour of the alternative that the distribution after the information signed is shifted towards less polluting settings.²⁵

As a robustness check we conducted a regression analysis. More specifically, we ran an ordered logit, in which we further control for those household characteristics presented in Table 1 as well as controlling for household-level fixed effects. Results are presented in columns 1 through 3 of Table 5 (see Appendix C). This analysis shows that households in the treatment group shifted the setting of their wood stove damper towards less polluting settings after the information sign was installed on their wood stoves. Conversely, we find no evidence of such shift before the information sign was installed, nor among those households in the control group.

6.3 Effect on Emissions of Fine Particulate Matter (PM_{2.5})

The previous section provides evidence suggesting that the assignment to treatment effectively nudged wood stove users towards less-polluting damper settings by reducing the frequency of very polluting damper settings while increasing the frequency of the less polluting settings.

To express the change in the use of the damper's setting in terms of changes in air pollution emissions by these wood stoves we use estimates of emission factors of PM_{2.5} pollution obtained by recent lab tests conducted for Chile's environmental authority (Díaz-Robles 2014).²⁶ 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

²⁵ We employed the same approach as detailed in the previous endnote.

²⁶ As mentioned in Sect. 4.b. 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.

2015) so that to arrive a figure for a representative household in Valdivia.²⁷ The emission factors from the lab tests conducted by Díaz-Robles (2014) are presented in Table 2, both for burning dry (certified) wood fuel and for burning wood fuel with high moist content. These emission factors show the nonlinearity of wood-stove pollution emissions for different settings of the damper. Whereas the pollution emission of PM_{2.5} by a woodstove in optimal operating conditions (burning dry wood-fuel with a “mostly open” damper setting) is 4.8 g per hour (g/h), partially choking the wood stove slightly increases emissions to 5.9 g/h, and emissions from a fully choked wood stove burning the same type of wood fuel can be as high as 17.2 g/h. For the case of wood fuel with high moist content, those figures are 9.3, 9.5 and 40.6 g/h, respectively.

In addition, using survey data for households in Valdivia (INFOR 2015), we calculate a weighted average for these emission factors (third row of Table 2) weighing the percentage of households that use either dry wood fuel (75% of households) or high moist wood fuel (25% of households). Thus, using the emission factors from Table 2 we impute emissions to the wood stoves in our analysis. To do so, we imputed “Choked” to Choked in Table 2; “Mid-Level” to ‘Intermediate’ and “Open” to Open in Table 2. For the remaining categories, namely “Mostly Choked” and “Mostly Open”, we split them in halves and imputed them to the nearest neighbour category from Table 2.

Table 3 presents household-level average PM_{2.5} emissions, according to the imputation mechanism explained above, for those in the treatment and control groups both before and after installation of the information sign. Whereas average emissions before the information sign are not statistically different across those in the treatment and control groups, we observe that average emissions for those in the treatment group declined by 10.8% after installation of the information sign (and 12.6% lower than those for the control group).²⁸ We conducted a paired t-test of equality of means for the treatment group, rejecting the null hypothesis in favour of the alternative that mean emissions are lower after the information sign. Conversely, we did not find a statistically significant difference for those in the control group.

Additionally, we ran an OLS regression for imputed wood stove emissions, while controlling for those household characteristics presented in Table 1, as well as household-level fixed effects. Results presented in columns 4 through 6 of Table 5 (Appendix C) show that the information sign significantly reduces imputed wood stove emissions.

6.4 Effect on Increased Wood Fuel Expenditure Due to Behavioural Intervention

The premise that wood stove users would tend to choke their woodstoves rests largely on incentives for saving on wood fuel expenditure. In this section we examine whether households in the treatment group changed the amount of wood fuel used during the intervention. Although we did not directly measure the amount of wood fuel used, because we do not have the technology to monitor such use, in a follow up survey we asked household

²⁷ Furthermore, to convert these emission factors from PM₁₀ emissions to PM_{2.5} emissions we used a proportionality factor of 93.2% according to the proportionality factor found in Chow and Watson (1998) for wood fuel emissions from wood stoves for residential use. That is, 93.2% of the total PM₁₀ emissions of these wood stoves corresponds to PM_{2.5} emissions.

²⁸ Results discussed below are robust to different ways to impute wood stove emissions (in Table 2) to each setting of the damper. Indeed, the emission reduction due to the information sign in the control group vary from 10 to 12.5%.

heads whether they had changed the amount of wood fuel used during the weeks of the experiment (see Table 4).

Results shown in Table 4 show that most participants, both in the treatment and control groups, reported either not changing the amount of wood fuel (56% for the control group and 41.5% for the treatment group) or using less wood fuel than before (32 and 35.8% for control and treatment group, respectively). On the other hand, participants in the treatment group more frequently reported increasing the amount of wood fuel (22.6%) than those in the control group (12%). However, none of these differences is statistically significant (at 95% confidence) across treatment and control group. Thereby, this indicates that there is no strong evidence either in favour or against an increase in wood fuel expenditure of those households assigned to the treatment group. In other words, we find no evidence that the reduction in emissions reported in the previous section are countervailed by an increase in wood fuel usage.

On the other hand, we examined whether pro-environment change induced by the treatment would result in increased wood fuel expenditure. That is, whether ‘green shifter’ households in the treatment group traded-off less emitting wood stove setting operation for increase expenditure in wood fuel. To this end, we analysed whether, conditional on significantly shifting their damper usage behaviour towards less polluting settings, households in the treatment group spent more on wood fuel. Thus, we calculated the average position of the damper setting—among only those households in the treatment group—and we split the sample in two halves: the half that shifted the most their behaviour towards less polluting settings (‘Greenest shifters’, in Table 4) and the half the shifted the least (‘Others’, in Table 4). Results in Table 4 show that a larger proportion of those that shifted most towards less polluting settings (‘Greenest shifters’) state to having used more wood fuel than the ‘Others’ group (30.8 vs. 11.5). This difference is statistically significant (at 95% confidence), suggesting that, conditional on large shifts towards less polluting settings, those households report spending more on wood fuel.²⁹

Therefore, evidence from the follow up survey points to increased wood fuel expenditure only among those households in the treatment group for which the treatment induced a larger pro-environment behavioural change (i.e., only for the ‘greenest shifters’).³⁰ This would suggest that some households may be willing to trade-off increased household expenditure for cleaner operation and fewer emissions of their wood stoves.

6.5 Additional Analysis: Effect of Behavioural Intervention on Indoor Air Pollution

In the previous section, we assessed the effect of the information sign on wood stove’s outdoor air pollution emissions, the focus of this paper. We did not expect to find an effect of the information sign on indoor air pollution emissions directly from the stove inside the dwellings. Instead, we expected we may have seen an indirect effect on indoor pollution.

²⁹ In addition, we tested whether those ‘greenest shifters’ would change the amount of time their woodstove is on (perhaps increasing or decreasing wood stove usage time). We tested this hypothesis using the same method to determine whether a woodstove is on as detailed in Sect. 6.1. We fail to reject the null hypothesis that, comparing the ‘greenest shifters’ to ‘Others’ in the treatment group, the amount of time their wood stove is on is equal across these two groups (not shown on Table 4).

³⁰ However, the follow up survey question did not ask specifically whether these households increased their wood fuel consumption before or after the information sign was installed on their wood stoves. Therefore, we have no evidence on whether the information sign caused this increase in wood fuel expenditure.

Table 2 PM_{2.5} emission factors by damper setting and wood fuel type (grams/hour)

Wood fuel's type	Damper setting		
	Choked	Intermediate	Open
Dry (certified)	17.2	5.9	4.8
High moist	40.6	9.5	9.3
Weighted average ^a	23.0	6.8	5.9

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 species (10%)

^aWeighted average according to type of wood fuel used by households in Valdivia: certified dry wood fuel (75%) and high moist wood fuel (25%)

Table 3 Average PM_{2.5} emissions (imputed grams/hour) by treatment and control groups, before and after installation of the information sign

	Before Info. Sign	After Info. Sign	Paired T-test (p-value) ^(a)
Control group	14.42 [0.89]	14.37 [0.99]	0.4632
Treatment group	14.06 [0.71]	12.55 [0.71]	0.0002

Average PM_{2.5} emissions using emissions factors from Díaz-Robles (2014) (shown in Table 2). The table shows household-level average wood stove emissions for those households in the Treatment and Control group, both before and after installation of the information sign. Standard errors in brackets. (a): p-value of the paired t-test against H_a: average emissions before sign are greater than average emissions after sign

As previously stated, the wood stoves of those households that participated in this study have a sealed “double combustion” chamber that is designed to leak little pollution indoors. However, we may have seen an indirect impact of the sign on indoor air pollution through the filtering of ambient pollution into the dwellings through the drafts (through doors, windows, and ceilings from poor insulation). If the sign induces less outdoor emissions from the stoves externally, then the aggregate neighbourhood pollution might decrease, consequently marginally lowering the concentration of ambient pollution from the immediate neighbourhood filtering back into the dwellings.

We collected data on indoor particle pollution for those participating households and conducted a regression analysis for the effect of the information sign on indoor air pollution. Although we had initially expected to find an effect on directly measurable air pollution concentrations, we found no statistically significant effect on indoor air pollution. The results are not surprising considering that the sample size of this experiment is too small to make a significant reduction in neighbourhood-level ambient pollution if the large majority of the other households are emitting pollutants at high levels. Nonetheless, should this type of intervention be conducted at scale, then we may be able to observe effects on

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
Control Gr	56.0 [10.1]	32.0 [9.5]	12.0 [6.6]
Treatment Gr	41.5 [6.8]	35.8 [6.7]	22.6 [5.8]
Greenest shifters	26.9 [8.9]	42.3 [9.9]	30.8 [9.2]
Others	57.7 [9.9]	30.8 [9.2]	11.5 [6.4]

Standard errors in brackets

neighbourhood ambient air pollution as well as indirect indoor pollution through filtering inside of the dwellings.

7 Discussion

Much of the existing literature focuses on adoption of improved wood fuel technologies with the assumption that household dissemination of cleaner stoves will lead to reduced pollution emissions. However, few of these studies examine actual stove-use behaviours in field settings to evaluate if households are using cleaner stoves in ways that are less-emitting. As emphasized by Hanna et al. (2016), users' behaviour in operating improved stoves is a key factor that drives actual emissions. For instance, users' low-polluting stove-usage behaviours—such as not choking the stove damper, not letting the fire smoulder overnight, cleaning the chimney, not over-filling the heater, etc.—reduce the degree of actual emissions from wood stoves. As such, it is important to design and assess interventions that influence households to use new stove technologies in appropriate ways that effectively reduce emissions.

The improved-technology "double-combustion" wood stoves assessed in this experiment are designed to emit 76% fewer $PM_{2.5}$ pollution than old conventional wood stoves, but only when used under optimal operating conditions (i.e., open air flow in the combustion chamber and burning of dry wood fuel). However, under real-world operating conditions (as surveyed by monitoring device employed for this research), these double-combustion wood stoves emit only 44% fewer $PM_{2.5}$ pollution than old wood stoves.³¹

³¹ According to official figures from Chile's Ministry for the Environment, under optimal operating conditions these "double-combustion" wood stoves emit 3540 mg of $PM_{2.5}$ per KWh. This compares to the estimated average emissions of the old wood stoves, at 14,862 mg of $PM_{2.5}$ per KWh (Min. Hacienda 2019). That is, as compared to old wood stoves, "double combustion" wood stoves emit 76% fewer emissions. On the other hand, using our data on actual operation of the damper of these "double combustion" wood stoves (as presented in Fig. 5) in combination with emission factors (Table 4), yields that under real-world operation these "double combustion" wood stoves emit only 44% fewer emission than the old wood stoves.

In this paper, we assessed the effect of a behavioural intervention bundle (an information sign attached to the stove, accompanied by a visit of a field assistant to install and explain the sign and a fridge magnet informational flyer) designed to nudge users to adopt less-polluting usage behaviour. We conducted a field experiment to assess the effect of this intervention on user's damper setting. Our findings show that households in the treatment group reduced the frequency with which they used the most polluting damper settings of their stoves, suggesting that the intervention induced a behavioural change that results in 10.8% reductions in $PM_{2.5}$ emissions. This is a significant reduction in emissions that is highly cost effective. The intervention bundle evaluated in this experiment costs approximately USD 9.³² This represents only a small fraction of the USD 700 that these “double-combustion” wood stoves cost in Chile.

Therefore, our findings indicate that addressing the imperfect information households face about the relationship between their stove usage and the impact on pollution emissions through an information-based behavioural intervention is effective in nudging households to practice less-polluting behaviours in how they operate their wood stoves. Prior to our intervention, most households lacked information about the negative effects that choking creates on the quality of the ambient air they breathe outside their dwellings, as well as the effect on others. Indeed, at the beginning of this intervention, we asked household heads whether they agree with the following statement: “The usage of my wood stove's damper drives pollution emissions outside my dwelling”. Only 12.6% [s.e. 3.7] responded that they ‘agree’, whereas the large majority, 82.3% [s.e. 4.3], responded that they ‘neither agree not disagree’ or that they ‘don't know’. Our findings suggest that the behavioural intervention in our experiment corrected for this information problem by providing information on user's effective outdoor emissions according to their wood stoves' damper setting.

As noted in the literature discussion, insights from the behavioural literature related to nudge strategies to induce savings in residential energy and resource consumption can help explain how information feedback strategies (a.k.a., ‘green nudges’) influence household behaviour towards pro-environmental actions. Our findings provide empirical support to the hypothesis posed by our theoretical model. That is, households can be induced to less frequently choking their stove's damper setting and to lower air pollution emissions through real-time information feedback that educates them about pro-environment outcomes related to their stove usage behaviour.

Nonetheless, several limitations should be considered when interpreting the present findings. Firstly, the results are from a sample of households in south-central Chile who rely on wood burning as the primary source of domestic heating. We expect that the findings of this study will shed some light on other contexts that experience wood smoke pollution from cooking as well as heating. However, whether these results are fully transferable to the context of cookstoves remains an empirical question, and additional field experiments in diverse contexts are needed given the limited experiments examining household

³² The breakdown of the costs of the intervention bundle are the following: USD 3 for the cost of the information sign that is attached on top of the wood stoves; USD 1 for the informational flyer (fridge magnet); and USD 5 for the labour cost of one hour's time of the field assistant to install and explain the information sign. The labour cost is the most variable and will vary based on the labour rates in different countries. In Chile, we estimated the average monthly wage for field assistant salary is about two times the minimum wage.

stove-usage behaviours in field settings. Secondly, given common measurement challenges in the field, our measurement of wood stoves' air pollution is based on imputed emissions, not on direct emissions. Thirdly, our interpretation of the findings is that the information sign informing users about emissions produced by each damper setting is a main driver of users' behaviour change. It is also our interpretation that the complimentary parts of the 'intervention bundle' that accompany the information sign play a supplemental role in influencing users' behaviour change. It is possible that, either the handing out of the flyer, the visit by a field assistant to install the information sign and explain the meaning of the sign and flyer (with the possibility these visits act as a more salient audience to the treatment than to the control group), or both, modify the effect of the information sign alone. Future field experiments should further test for any possible interactive effect between these complimentary aspects of the intervention and that of the information sign. Particularly, we suggest future experiments evaluate whether the field assistant explaining the meaning of the information sign and complimentary flyer is required, or whether comparable results can be achieved through the information sign and flyer alone.

8 Policy Recommendations and Concluding Remarks

Our findings have implications for public policies designed to reduce ambient air pollution by promoting or legislating the adoption of improved wood burning technologies. Government officials of countries that faced air pollution problems such as Chile, India, China, the United Kingdom, and the United States, among others, have implemented large-scale measures to subsidize cleaner stoves, implement stove replacement programs swapping old stoves with newer models, and regulate the marketplace only allowing for stoves that meet certain standards (US EPA 2013; MMA 2014a; Defra 2019). For instance, in Chile, government officials mandated that only high efficiency "double combustion" stoves to be available in the market since the early 2000s, and the government has further implemented a large-scale replacement programme that highly subsidizes adoption of these cleaner technologies. Despite these measures, ambient air pollution concentrations have continued to rise in all major cities of Chile's south-central region (Schueftan and González 2015). Public policy has led to increased household adoption of cleaner stoves, but user behaviour may temper the effectiveness of clean stove adoption policies.

Based on our findings, we recommend that measures to promote dissemination of improved stove technology should be accompanied with information-based behavioural interventions that nudge households to adopt low-polluting practices when they operate different features of their wood stoves, such as the stove damper settings. Our field experiment suggests that household stove-operating practices are an important contributing factor to why newer, less-polluting stoves are not working as effectively as their design envisioned.

The findings of our paper also suggest that dedicated communications campaigns should educate users on less polluting operation of their wood stoves. Communications campaigns can be effective in modifying users' behaviour towards less polluting operation of their stoves. For example, Hine et al. (2011)'s field experiment in Australia shows that households who received an education pack—that educated users about the health risks

associated with wood smoke pollution and provided practical best practice advice about proper wood heater operation—practiced better wood heater behaviours, which were associated with a significant reduction in household wood smoke emissions.³³ Additionally, lessons from the U.S., the Environmental Protection Agency (EPA)’s “Burn Wise” education and outreach programme could provide practical insights into how to design and implement regional and local wood smoke reduction campaigns (EPA 2013).

A communications campaign should visually show users that they can considerably reduce their pollution emissions by simply adjusting the damper setting away from fully choked. For example, at the end of this intervention, we asked users whether they would be willing to choke their wood stoves less frequently to reduce their wood stoves’ pollution emissions. Only 3.8% [s.e. 3.8] of those in the control group and 28.3% [s.e. 6.2] of those in the treatment group said they would do so. We asked if they would do less choking if other neighbours were to do so as well, and the figures were not different. However, when asked whether they would choke their wood stoves less frequently if there were a large-scale government led campaign that educates and encourages the community towards choking their wood stoves damper less frequently, 88.6% [s.e. 3.6] of respondents in both groups said they would do so. Implementing this type of communications campaign that encourages reducing the choking of wood stoves has the potential to be a cost-effective measure.³⁴

Another recommendation relates to regulations for wood stove design and production. For example, as Chile’s Ministry of Environment sets pollution emission standards of the wood stoves currently available in the market, it could mandate that all new wood stoves be manufactured with a built-in information sign, like the one assessed in this study. It could even mandate for a wood stove technology that does not allow for fully choking the damper setting. This should only slightly increase production costs and could prove to be a highly cost-effective policy measure to combat ambient air pollution. Moreover, as most double-combustion wood stoves have an extended lifetime (of about 20–30 years), attaching an information sign on existing wood stoves could result in low-cost intervention that does not lock-in households into new expensive long-lasting technologies. This can be an effective tool to address the problem of air pollution in the near term in south-central Chile.

In the European context, this research is also relevant for the UK as it shapes its post-Brexit environmental policy. The government’s clean air strategy specifically addresses residential air pollution by regulating biomass burning in the outskirts of cities and rural areas (Defra 2019). The strategy plans for having only Ecodesign-ready wood stoves to be available for sell in the market, from year 2022 (as is the case for the European Union). These stoves allow for combustion higher up in the combustion chamber, just like the ‘double combustion’ ones in south-central Chile. Whereas the strategy acknowledges the importance of wood stove users’ behaviour—indeed it states that “the way in which we use our stoves can have a big impact on air

³³ The pack in Hine et al. (2011)’s experiment consisted of pamphlets, a DVD (providing behavioural modelling of proper wood heater operation) and a fridge magnet.

³⁴ Under the current air pollution control strategy in the PPDAs, Chile’s Ministry of Energy is currently undertaking communications campaigns in all cities suffering from high levels of wood stove air pollution. Indeed, a communications campaign that stresses the importance of correct use of the damper setting was introduced for the first time in the winter of 2019 in a nearby city, Temuco (one of the most polluted cities in south-central Chile), but only for a small subgroup of wood stove users: those low-income elderly residents.

quality” (Defra 2019)—it focuses mostly on acquisition of Ecodesign-ready stoves and optimal operation regarding both maintenance of the chimney and purchase of dry wood fuel. However, the strategy does not stress the importance of day-to-day operation in terms of users controlling the air flow inside the combustion chamber via the stove’s damper. We believe that there are some clear lessons to be drawn here from this paper and the Chilean experience.

To conclude, to effectively address the problem of wood burning air pollution, it is key to account for real-world operating conditions (Hanna et al. 2016). This is particularly important when implementing policy to transition towards cleaner residential wood burning technologies. We believe that governments in developed and developing countries, as well as development assistance organizations fighting the problem of high levels of wood burning ambient air pollution, can learn from the recent experience of wood stoves with cleaner technology in south-central Chile.

Appendix A: Supplementary Figures on PM Concentrations and Indoor/Outdoor Temperature

See Figs. 6 and 7.

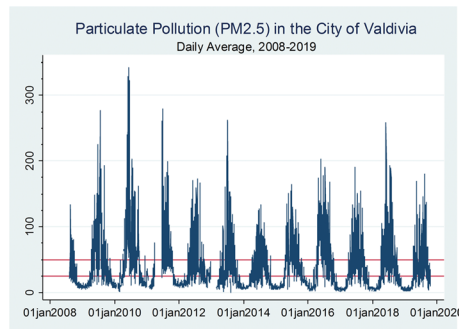


Fig. 6 Concentrations of fine particulate matter ($PM_{2.5}$) in the City of Valdivia, Chile. Daily Average, 2008–2019. *Note:* WHO guidelines recommend a maximum 24-h concentration of $PM_{2.5}$ not to exceed $25 \mu g/m^3$ (WHO 2005), while EPA sets a standard for 24-h concentration of $PM_{2.5}$ not to exceed $35 \mu g/m^3$ (USEPA 2016). The Chilean standard for 24-h $PM_{2.5}$ is $50 \mu g / m^3$ (MMA 2011). *Source:* <http://sinca.mma.gob.cl/> (Chile’s Ministry for the Environment)

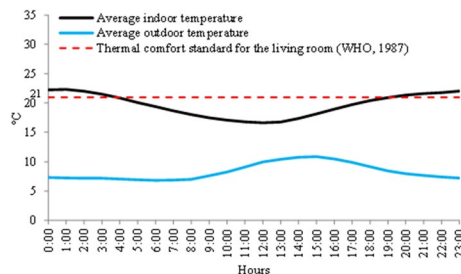


Fig. 7 Indoor and outdoor temperature profile for participating households in Valdivia, Chile: Average for August and September 2017. *Note:* The black line denotes average hourly indoor temperature (in Celsius degrees) for participating households and the light blue line denotes average hourly outdoor 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

Appendix B: Supplementary Experimental Material

See Fig. 8.

Original Flyer	Translation
<p>USO DEL TIRAJE DE NUESTRAS ESTUFAS A LEÑA ¿CÓMO AFECTA AL AIRE QUE RESPIRAMOS?</p> <p>Valdivia sufre de altos niveles de contaminación, debido al uso ineficiente de las estufas a leña.</p> <p>El uso del tiraje incide en la contaminación que éstas emiten.</p> <p>¿CÓMO?</p> <p>El tiraje cerrado emite mucho más contaminación que el tiraje abierto.</p> <p>Esta contaminación, también entra al interior de la vivienda a través de puertas, ventanas y filtraciones.</p> <p>SEÑALÉTICA</p> <p>La señalética instalada, representa los niveles de contaminación de su estufa en las distintas posiciones del tiraje.</p> <p>MUY MALO MALO REGULAR BUENO ENCENDIDO</p>	<p>Damper use of our wood stoves</p> <p>What is its effect on the air we breathe?</p> <p>Valdivia [city] suffers from high air pollution due to inefficient use of wood stoves.</p> <p>Damper use drives wood stoves' emissions of air pollutants.</p> <p>How?</p> <p>A choked wood stove emits much more air pollutants than a wood stove with an open damper.</p> <p>This air pollution also filters inside the dwelling through doors, windows and drafts.</p> <p>Information sign</p> <p>The installed signage represents your wood stove's air pollution emissions for each setting of the damper.</p> <p>Very Bad Bad Fair Good Ignition</p>

Fig. 8 Magnetic flyer explaining meaning of the information sign. *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 visible. It is designed to serve as a memory prompt alongside the information sign. The colour-coded system on the woodstove sign aligns with the colour-coded system in the information flyer. For instance, the information sign for the choked damper setting states “High” alongside the red colour, and the magnet flyer reminds the wood stove user that red signifies “Very bad” for pollution emission levels. Conversely, the information sign for the open damper setting states “Low” alongside the green colour, and the magnet flyer reminds the wood stove user that green signifies “Very good” for pollution emissions levels

Appendix C: Regression Analysis

See Table 5.

Table 5 Parameter estimates from ordered Logit and OLS regressions

	Probability of shifting damper towards less polluting settings			Imputed wood stove emissions		
	(1)	(2)	(3)	(4)	(5)	(6)
Treatment Gr. & Sign On	0.540** −0.261 (0.304)	0.609** (0.287)	0.603** (0.267)	−2.885*** (1.065)	−1.937** (0.952)	−1.844** (0.802)
Treatment Gr	0.166 (0.304)	0.0245 (0.298)	−0.663 (0.390)	−0.437 (1.381)	−0.254 (0.976)	−0.329 (0.568)
Sign on	−0.31 (0.203)	−0.258 (0.227)	−0.222 (0.223)	1.272 (0.815)	1.105 (0.773)	0.767 (0.656)
Constant	13.12*** (1.136)	8.219 (6.240)	10.257 (9.36)			
HH-level controls	No	Yes	Yes	No	Yes	Yes
HH-level fixed effects	No	No	Yes	No	No	Yes
Observations	116,913	116,913	116,913	116,913	116,913	116,913

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

The table shows parameter estimates from two regression models, an ordered logit for the position of the damper setting (columns 1 through 3), and an OLS regression for imputed pollution emissions (columns 4 through 6). Household level controls include those shown in Table 1. The ordered logit is justified by the ordinal nature of the different damper settings (i.e., the amount of air flow inside the combustion chamber is ordered according to “Choked” < “Mostly Choked” < “Mid-level” < “Mostly Open” < “Open”). The OLS regression uses imputed emissions for each damper setting, according to emission factors presented in Table 2, weighted by the type of wood fuel consumed by households in Valdivia from survey data on household wood fuel consumption (INFOR, 2015).

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