Controlling Urban Air Pollution Caused by Households: Uncertainty, Prices, and Income

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Abstract: We examine the control of air pollution caused by households burning wood for heating and cooking in the developing world. Since the problem is one of controlling emissions from nonpoint sources, regulations are likely to be directed at household choices of wood consumption and combustion technologies. Moreover, these choices are subtractions from, or contributions to, the pure public good of air quality. Consequently, the efficient policy design is not independent of the distribution of household income. Since it is unrealistic to assume that environmental authorities can make lump sum income transfers part of control policies, efficient control of air pollution caused by wood consumption entails a higher tax on wood consumption and a higher subsidy for more efficient combustion technologies for higher income households. Among other difficulties, implementing a policy to promote the adoption of cleaner combustion technologies must overcome the seemingly paradoxical result that efficient control calls for higher technology subsidies for higher income households.

Keywords: Efficiency, urban air pollution, nonpoint pollution, environmental policy, uncertainty

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1. Introduction

Air pollution caused by households burning wood for heating and cooking is a serious concern in many urban areas of the developing world. To illustrate the problem consider the city of Temuco, the capital city of the Araucanía region in southern Chile. This city contains about 350,000 people in about 86,000 households. About 80% of the households in the city report using wood as an energy source. The consumption of wood is not particularly concentrated at any income level. The 30% of the city's households in the middle of the income distribution also account for 30% of the city's annual wood demand. Similarly, the 20% of households with the highest incomes consume about 22% of the total wood fuel annually (Gómez *et. al* 2009). It has been estimated that 90% of total emissions of suspended particulate matter in Temuco is caused by households burning 500,000 cubic meters of wood annually. There are about 100,000 smoke stacks connected to cooking and heating stoves in the city (Comisión Nacional del Medio Ambiente, CONAMA 2007, Chávez *et. al* 2009).

The number of days that the concentration of total suspended particulate matter (PM_{10}) exceeded the 24-hour average Chilean legal limit of $150 \mu g/m^3$ was 11 in 2005, 15 in 2006, 21 in 2007, 36 in 2008, and 37 in 2009. Furthermore, during the 2009 season, the maximum daily average concentration on a 24 hour basis for the city was in the range of 800-1020 $\mu g/m^3$. During the worst day of the 2009 season, the concentration of PM_{10} was measured at about 6090 $\mu g/m^3$ at 5 p.m., increasing to 6240 $\mu g/m^3$ by 11 p.m. that same day. To put these figures in context, the Air Quality Guidelines of the World Health Organization (WHO) call for limiting the mean 24-hour concentration of PM_{10} in urban areas to 50 $\mu g/m^3$ (WHO 2005).

Moreover, there are at least two reasons to be pessimistic about air quality in Temuco. First, generating household energy with kerosene or liquefied gas —the two closest substitutes for wood in central-southern Chile— is about 5 to 8 times more expensive than using fuel wood (Gómez-Lobo 2005). Second, the supply of wood from native forests surrounding the cities is also increasing, as many small-scale farmers harvest wood to sell in urban areas. Even though an official figure of the number of suppliers of wood to Temuco is not available, the National Forest Service had registered about 470 producers. Most of these producers are owners of small plots of land less than 100 hectares (Lobos 2001 and Von Baer et. al. 2002).¹

Situations like this pose major challenges for environmental regulatory authorities at local and national levels. The great number of individual sources of pollution makes direct emissions monitoring impractical; thus, air pollution from households is best characterized as a nonpoint pollution problem. The inability to monitor emissions implies that regulation is likely to be directed at emissions inputs, in particular wood consumption and household combustion technologies. In addition, regulators face a great deal of uncertainty because of stochastic weather effects on the concentration of air pollution and human health, and because of limited information about how households use combustion technologies and the wood input. Finally, choices of wood consumption or more efficient combustion technologies are subtractions from or contributions to a pure public good (i.e., air quality). It is well known by public economists that one cannot separate efficient provision of a public good from the distribution of income. (For

¹ Air pollution problems caused by households burning wood for heating have also occurred in some regions of developed countries. Examples include the city of Christchurch in New Zealand (Barna and Gimson 2002, Environment Canterbury 2009, and Wilton et. al. 2006), the city of Launceston in Australia (Kesby et. al. 2002, Luhar et. al. 2006), Sacramento California (Sacramento Metropolitan Air Quality Management District 2006 and 2008), the town of Libby Montana (HPBA 2008), and British Columbia in Canada (Ministry of Environment-British Columbia 2005).

example, see Laffont 1988, chapter 2). The main objective of this paper is to examine the role that income distribution plays in the determination of policies to control urban air pollution from households.²

Our approach is to consider optimal taxes for wood consumption for household energy and subsidies for more energy efficient (less polluting) combustion technologies. We recognize that wood taxes or technology subsidies may not be implementable in particular instances, because of monitoring, other information problems, and political realities. Nevertheless, deriving the optimal taxes and subsidies can yield important insights into the problem of controlling air pollution from households.³ In particular, we show that if authorities are able and willing to make unrestricted lump sum transfers of income among households, then these prices should be roughly equal across households. However, it is unrealistic to assume that lump sum income redistributions can be made part of a policy to control household air pollution. In the absence of lump sum transfers and assuming diminishing marginal utility of consumption of a private good, an optimal policy will force more of the burden of emissions control onto wealthier households. The reason is that doing so serves to reduce the expected costs of the policy by equalizing the weighted expected marginal disutility of control across households. This is analogous to the standard prescription to minimize aggregate abatement costs of stationary industrial pollution sources by equalizing their marginal abatement costs. Since it is efficient for higher income households to take on relatively more of the abatement burden in our context, an optimal policy

² Our approach might apply, with suitable modifications, to other household pollution issues, including automobile emissions, and households' garbage disposal and recycling behavior. Addressing how income distribution affects optimal policy in these other contexts may be fruitful areas for future research.

³ There is a proposed plan for the city of Temuco that offers subsidies to induce voluntary adoption of more efficient combustion technologies. The main feature is a subsidy-based stove exchange program to induce the renovation of 12,000 stoves over a ten year period (CONAMA 2007, Chapter II, Article 10).

will charge a higher wood tax on wealthier households, as well as offer them a higher subsidy for the purchase of more efficient combustion technologies. This last result may seem paradoxical, but it is important to realize that the technology subsidy is not meant to correct income disparities—its purpose is to aid in the efficient control of household pollution.

While the role that income distribution plays in the setting of environmental taxes has been well-studied by environmental economists, it is usually in the context of uniform taxes. Therefore, the question of how income distribution affects the distribution of control responsibilities is usually not addressed.⁴ One exception is Chichilnisky and Heal (1994) who examine how the global distribution of income affects the efficient distribution of greenhouse gas abatement to confront climate change. They show that the familiar prescription that marginal abatement costs should be equal across countries only holds if countries commit themselves to large-scale transfers of income from richer to poorer nations. In the absence of these transfers the efficient distribution of abatement requires that richer countries undertake more abatement than would be implied by equalizing marginal abatement costs.⁵

Our contribution is that we examine the effect of income distribution on the control of a nonpoint pollution problem generated by households. Chichilnisky and Heal (1994) assume perfect information about all benefits and costs of greenhouse gas control, while regulators have only limited information about these elements in the control of air pollution caused by

⁴ For example, this is true of Sandmo's (1975) classic article on optimal commodity taxation in the presence of an externality. Other examples include Bovenberg and Goulder (2002, section 5) and Fullerton and Wolverton (2005). Income distribution is not an issue in these latter articles because they assume identical households.

⁵ Also see Heal, Chichilnisky and Starret (1993). Sheeran (2006) seeks to clarify certain aspects of Chichilnisky's and Heal's analysis. There are a number of policies that charge differential tax rates, but we are not aware of any that vary by income levels. Differential carbon emissions taxes that vary by industry have been introduced in parts of Europe (Baranzini et. al. 2000 and Bye and Nyborg 2003). Since these taxes are not directed at households they are very different from the taxes we model in this paper.

households. More importantly, Chichilnisky and Heal (1994) assume that greenhouse gas emissions are perfectly observable. For our problem it is not practical to monitor household emissions; thus, control policies are likely to focus on controlling the inputs of the production of pollution, namely the fuel input and the combustion technology. There is an extensive literature on nonpoint pollution control, of which Shortle and Horan (2001) have provided a valuable review. However, we are not aware of any study that considers the impact of income distribution on the optimal control of a nonpoint pollutant. Our work makes this contribution to the nonpoint control literature in general, as well as to the study of the control of air pollution caused by households in the developing world in particular.

The rest of the paper proceeds as follows. In the next section we lay out a model of the control of air pollution caused by households burning wood for energy, and derive the optimal taxes on wood consumption and subsidies for more efficient combustion technologies. The main results of the paper are contained in section 3 where we examine the interdependence between optimal policies and income distribution. We conclude in section 4 with an extended discussion of several implementation issues that our results generate.

2. A model of regulating air pollution from households

Consider an urban area consisting of a large number of households that produce energy by burning wood. Each household makes a small contribution to pollution levels, but the resulting aggregate level is dangerous for the community. Due to the large number of polluting households, an environmental authority is unable to measure emissions from each household.

Consequently, we explore the design of taxes to induce lower wood consumption and subsidies to promote the adoption of cleaner-burning wood combustion technologies.⁶

2.1 Basics of the model

Let there be n households indexed by i . Each household produces energy by combining a combustion technology, which we denote as x_{i1} , and the amount of wood used, x_{i2} . Thus, the production of energy in a household is given by

$$[1] \quad c_i = c_i(x_{i1}, x_{i2}).$$

Assume that c_i is increasing in fuel use x_{i2} . We interpret x_{i1} as an index of available wood combustion technologies and order the technologies according to their effectiveness in producing energy given an amount of fuel. Assume that more effective combustion technologies are indicated by higher levels of x_{i1} so that c_i is increasing in x_{i1} . For analytic convenience we assume that x_{i1} is a continuous variable.⁷ There may very well be uncertainty from a regulator's perspective about c_i , perhaps because of unobservable skill levels or wood quality, but we ignore this possibility because households' energy production is not our primary concern.

⁶ Another option would be to pursue an ambient pollution tax and subsidy as first proposed by Segerson (1988). This policy would involve household-specific penalties if the ambient concentration of air pollution surpasses some limit and subsidies if the concentration is lower than that limit. Despite the interest in these mechanisms for controlling nonpoint pollution, we are not aware of an instance in which they have been applied. Shortle and Horan (2001) discuss several practical limitations of these mechanisms.

⁷ Assuming that the combustion technology is a continuous variable may not be too far from the truth. Combustion technologies can vary along several dimensions including type, size, vintage, and so on. Treating each combination of characteristics as a distinct technology can produce a large number of technologies that, when ordered according to energy-producing efficiency, can be modeled as being on a continuum.

Our main concern is that energy production creates emissions of pollution, r_i , as a byproduct. Thus, household emissions depend on the combustion technology, the wood input, and a random parameter σ_i (from a regulator's point of view) that captures unobserved variation in how the combustion equipment is actually used:

$$[2] \quad r_i = r_i(x_{i1}, x_{i2}, \sigma_i).$$

Suppose that r_i is increasing in the amount of wood used, but is decreasing in the combustion technology (under the assumption that a more productive combustion technology burns more cleanly and uses less wood for the amount of energy generated). The random parameter σ_i represents households' preferences and skills that affect how the combustion equipment is used, and consequently the production of emissions. For example, emissions are an increasing function of the moisture content of the wood used, and households choose wood with varying moisture content.⁸ Furthermore, households can adjust the amount of wood burned per period of time by varying the air flow in and out of the combustion equipment. Reducing airflow increases burn time but also increases emissions. Overfilling the combustion chamber with wood to avoid frequent refilling can also produce higher emissions (Klippel and Nussbaumer 2007; Nussbaumer 2003 and 2006).

Environmental quality in a city depends on the ambient concentration of pollution. The main pollutants produced from burning wood are nitrogen oxide, carbon monoxide, and fine particulate matter. To simplify matters, we assume that household emissions produce a single pollutant. In addition we assume that this pollutant is uniformly mixed; that is, the ambient concentration of the pollutant depends only on the sum of household emissions. This assumption

⁸ It has been reported in the city of Temuco that some households actually prefer to use wetter wood even though it has lower caloric content, because moist wood burns slower and lasts longer (Chávez et. al. 2009, CONAMA-DICTUC 2008, CONAMA 2007, Nussbaumer 2006).

makes the location of emissions irrelevant, which is a reasonable approximation for pollution problems in the cities that motivate this work.⁹ Let the ambient concentration of the pollutant be

$$[3] \quad a = a \left(\sum_{k=1}^n r_k(x_{k1}, x_{k2}, \sigma_k), \theta \right),$$

which is increasing in aggregate household emissions so it is increasing in individual household emissions as well. (We use k to index households in specific summations, in this case the sum of emissions is over households, to avoid potentially confusing notation at certain points in the paper. The population of households consuming wood is the same as the population affected by exposure to the pollutant). The parameter θ is a random factor that captures the effect of weather conditions on air quality. For example, windy days result in lower ambient pollution for a given level of emissions because pollution is blown away and dispersed. However, cold can produce a thermal inversion that traps pollutants at ground level, resulting in higher ambient concentration of pollution.

The utility function for a household is denoted by

$$[4] \quad u_i = u_i(c_i, y_i, a, \mu, \eta_i).$$

Suppose that utility is increasing in energy use c_i and the consumption of a private commodity y_i , but is decreasing in ambient pollution a . Note that since the ambient concentration of pollution affects each household's utility, their choices of combustion technology and wood consumption can be viewed as contributions to and subtractions from the local public good of air quality. The variable μ is a random parameter that captures the notion

⁹ As noted in the introduction our work is motivated by household pollution problems in urban areas of the central-southern region of Chile. Most of these areas are located in the central valley, on relatively flat land surrounded by small hills, away from the Los Andes mountain range. The many emission points are quite uniformly distributed within each city. We should note that the model can be easily modified to consider non-uniformly mixed pollutants.

that weather affects household energy choices. Think of households generating more energy to heat their homes when it is colder. We assume for simplicity that the distributions of the random weather parameters, μ and θ , are known to all households as well as to the regulator. The last term in a household's utility function, η_i , is a random term from the regulator's perspective that represents unobservable household characteristics that affect its production of energy, like the insulation of the house, preferences for the type of combustion equipment, and preferences for warmth.

Each household faces a set of prices for the combustion technology and wood input, which we denote as p_1 and p_2 , respectively. To keep the model tractable and focused we assume that these prices are fixed throughout. Relaxing this assumption would not change the fundamental insights of this paper about the role of income distribution in the design of policies to control household air pollution. The price of the private consumption good is equal to one.

We further simplify the analysis by assuming that each household i has exogenous income $\bar{w}_i$, which is taxed at an exogenous rate z_i . Income taxes are fixed because real environmental agencies do not have the authority to make income transfers a part of environmental regulations. We will see later that this assumption plays a very important role in policy formation.

We can obtain principles for controlling urban air pollution from households by deriving the optimal subsidies on combustion technologies and taxes on wood. Anticipating that optimal taxes/subsidies could vary across households, denote the subsidy on household i 's combustion technology as $t_{i1} \leq 0$, and its tax on each unit of wood used as $t_{i2} \geq 0$. Household specific after subsidy/tax prices on combustion technologies and wood are $p_1 + t_{i1}$ and $p_2 + t_{i2}$, $i = 1, \dots, n$, respectively.

Given the after subsidy/tax prices on combustion and wood, a household's budget constraint is

$$[5] \quad \bar{w}_i(1 - z_i) = y_i + (p_1 + t_{i1})x_{i1} + (p_2 + t_{i2})x_{i2}.$$

We do not examine how income taxes affect the optimal prices on combustion technologies and wood input, but we do assume that the government can fund the household pollution control program. To that end assume

$$\sum_{i=1}^n \bar{w}_i z_i \geq \sum_{i=1}^n t_{i1} x_{i1} + \sum_{i=1}^n t_{i2} x_{i2};$$

that is, the government's income tax receipts are sufficient to meet the revenue requirements of the household pollution control program. If aggregate subsidy payments exceed the aggregate taxes on the wood input, then the difference is financed out of income tax receipts. If wood tax receipts exceed subsidies for more efficient combustion technologies, then the excess is simply added to the government's budget.

2.2 Household energy input choices

A household's decision problem is to choose a combustion technology, wood input, and consumption of the private good to maximize its expected utility subject to [1], [3], and [5]. That is, a household chooses x_{i1} , x_{i2} , and y_i to solve:

$$[6] \quad \max E_i(u_i(c_i, y_i, a, \mu, \eta_i))$$

$$\text{s.t.} \quad c_i = c(x_{i1}, x_{i2})$$

$$w_i = y_i + (p_1 + t_{i1})x_{i1} + (p_2 + t_{i2})x_{i2}$$

$$a = a\left(\sum_{k=1}^n r_k(x_{k1}, x_{k2}, \sigma_k), \theta\right),$$

235 where $w_i = \bar{w}_i(1 - z_i)$ is the household's after tax income, E_i denotes the expectation operator for
 236 household i . This expectation is with respect to the joint distribution of
 237 $(\mu, \theta, \eta_1, \dots, \eta_{i-1}, \eta_{i+1}, \dots, \eta_n, \sigma_1, \dots, \sigma_{i-1}, \sigma_{i+1}, \dots, \sigma_n)$, conditional on η_i and σ_i . Substituting the
 238 constraints of [6] into its objective allows us to write the household's problem as choosing x_{i1}
 239 and x_{i2} to maximize

$$240 \quad [7] \quad E_i \left\{ u_i \left(c_i(x_{i1}, x_{i2}), w_i - (p_1 + t_{i1})x_{i1} - (p_2 + t_{i2})x_{i2}, a \left(\sum_{k=1}^n r_k(x_{k1}, x_{k2}, \sigma_k), \theta \right), \mu, \eta_i \right) \right\}.$$

241 Assume that [7] is continuously differentiable, that it is strictly concave in x_{i1} and x_{i2} , and that
 242 optimal choices of these inputs are not zero. Then, the following first-order conditions determine
 243 each household's optimal choices of combustion technology and wood consumption, given these
 244 choices by all the other households in the city:

$$245 \quad [8] \quad E_i \left\{ \frac{\partial u_i}{\partial c_i} \frac{\partial c_i}{\partial x_{ij}} - \frac{\partial u_i}{\partial y_i} (p_j + t_{ij}) + \frac{\partial u_i}{\partial a} \frac{\partial a}{\partial r_i} \frac{\partial r_i}{\partial x_{ij}} \right\} = 0, \quad i = 1, \dots, n, \quad j = 1, 2.$$

246 These first order conditions implicitly define Bayes-Nash best response functions, and the
 247 solution to these $2n$ equations, assuming that one exists, gives us a Bayes-Nash equilibrium
 248 distribution of wood use and combustion technologies in the urban area. The first-order
 249 conditions reveal that each household will optimally choose the level of combustion technology
 250 and input use considering three elements; the marginal utility of the combustion technology or
 251 wood use in the generation of energy, the marginal reduction in utility from the reduction in
 252 spending on other private goods, and the marginal impact that the choice of technology or wood
 253 use has on the pollution damage the household experiences. To the extent that the household can
 254 detect a change in ambient pollution from its own emissions (i.e., $\partial a / \partial r_i > 0$), the choice of a
 255 more efficient combustion technology reduces the pollution damage it suffers (because

256 $\partial r_i / \partial x_{i1} < 0$) while an increase in its use of wood increases the damage it suffers (because
 257 $\partial r_i / \partial x_{i2} > 0$), holding the choices of all other households constant. Note that $\partial a / \partial r_i > 0$ is the
 258 same for all i , because of our assumption that ambient pollution depends only on the sum of
 259 households' emissions.

260

261 **2.3 Efficient household choices**

262 Optimal wood taxes and combustion technology subsidies internalize the external costs and
 263 benefits of the households' choices. To determine the taxes and subsidies that will induce an
 264 efficient allocation of energy choices, we first derive an efficient allocation of wood use and
 265 combustion choices by maximizing an expected Bergson-Samuelson social welfare function.¹⁰
 266 That is we choose (x_{i1}, x_{i2}) , $i = 1, \dots, n$, to solve

$$\begin{aligned}
 267 \quad [9] \quad \max \quad & E_g \left(\sum_{i=1}^n \lambda_i u_i(c_i, y_i, a, \mu, \eta_i) \right), \\
 268 \quad \text{s.t.} \quad & c_i = c(x_{i1}, x_{i2}), \quad i = 1, \dots, n, \\
 269 \quad & w_i = y_i + p_1 x_{i1} + p_2 x_{i2}, \quad i = 1, \dots, n, \\
 270 \quad & a = a \left(\sum_{k=1}^n r_k(x_{k1}, x_{k2}, \sigma_k), \theta \right),
 \end{aligned}$$

271 In the objective of [9], $\lambda_i > 0$, $i = 1, \dots, n$, are exogenous household utility weights. If every
 272 household's utility has equal weight in the social welfare function, then the utility weights
 273 are $\lambda_i = 1/n$ for $i = 1, \dots, n$, but other distributions of the weights are possible.

¹⁰ The alternative method for finding efficient allocations is to maximize the expected budget-constrained utility of one household while holding the expected budget-constrained utilities of the other households constant. Our results do not depend on maximizing a social welfare function, because the alternative methods are functionally equivalent.

274 E_g refers to the expectation operator for the environmental authority, which is with respect to the
 275 joint distribution of $(\mu, \theta, \sigma_1, \dots, \sigma_n, \eta_1, \dots, \eta_n)$. Our inclusion of household budget constraints in
 276 this problem (instead of, for example, posing production functions for combustion technologies
 277 and fuel wood) reflects the notion that an environmental agency with limited authority must
 278 design a control policy, given the existing distribution of income and income taxes, and the
 279 supplies of combustion technologies and fuel wood. In particular, we do not aggregate the
 280 community's income because the authority cannot make lump sum transfers of income among
 281 households.

282 Given the utility weights, if a solution to the program exists it will identify one of the
 283 many possible efficient allocations. Utility weights are important, because particular efficient
 284 outcomes are associated with particular weights. That is, all of the efficient allocations
 285 obtainable given the existing distribution of income can be identified by varying the utility
 286 weights.

287 For the existing distribution of income and utility weights, assume that the solution to [9]
 288 is characterized by the following first order conditions:

$$289 \quad [10] \quad \lambda_i E_g \left\{ \frac{\partial u_i}{\partial c_i} \frac{\partial c_i}{\partial x_{ij}} - \frac{\partial u_i}{\partial y_i} p_j + \frac{\partial u_i}{\partial a} \frac{\partial a}{\partial r_i} \frac{\partial r_i}{\partial x_{ij}} \right\} + \sum_{k \neq i} \lambda_k E_g \left(\frac{\partial u_k}{\partial a} \frac{\partial a}{\partial r_i} \frac{\partial r_i}{\partial x_{ij}} \right) = 0, \quad i = 1, \dots, n \text{ and } j = 1, 2.$$

290 To interpret the first order condition it may be more informative to rewrite them in the following
 291 way:

$$292 \quad [11] \quad \lambda_i E_g \left\{ \frac{\partial u_i}{\partial c_i} \frac{\partial c_i}{\partial x_{ij}} - \frac{\partial u_i}{\partial y_i} p_j \right\} = -E_g \left\{ \sum_{k=1}^n \lambda_k \frac{\partial u_k}{\partial a} \frac{\partial a}{\partial r_i} \frac{\partial r_i}{\partial x_{ij}} \right\}, \quad i = 1, \dots, n \text{ and } j = 1, 2.$$

293 This is a modification of the usual Lindahl-Bowen-Samuelson conditions for the efficient
 294 provision of a public good. The modifications come from two sources: (1) the context of

household heating and cooking decisions that affect the public good of urban air quality in the developing world, and (2) the uncertainty in the model—the stochastic weather effects on air pollution and household utility as well as uncertainty about the use of combustion technologies and wood input.

The left side of [11] is the government's weighted expectation of a household i 's marginal non-environmental net benefit of employing input j . On the right side of [11] is government's expectation of the impact of that decision on the weighted sum of marginal disutilities from urban air pollution. Note that the sign of the right side of [11] depends on whether the energy input is the combustion technology or the wood input. For the combustion technology ($j = 1$), the right side of [11] is negative because $\sum_{k=1}^n \lambda_k (\partial u_k / \partial a) < 0$, $\partial a / \partial r_i > 0$, and $\partial r_i / \partial x_{i1} < 0$. The negative sign indicates that the environmental authority's expectation of aggregate pollution damage is decreasing when a household employs a more efficient combustion technology. On the other hand, the right side of [11] is positive for the wood input ($j = 2$), because $\partial r_i / \partial x_{i2} > 0$. The positive sign indicates that expected aggregate pollution damage is increasing in a household's use of wood.

2.4 Efficient wood taxes and combustion technology subsidies

Having characterized efficient allocations of combustion technologies and wood consumption, we now determine optimal taxes on wood consumption and subsidies for more efficient combustion technologies that will induce these choices. Clearly, these will be second-best optimal policies because of the authority's inability to make lump sum income transfers.

A simple modification of [8] gives us the government's expectation of how households will respond to taxes and subsidies, t_{ij} $i = 1, \dots, n$ and $j = 1, 2$. Simply replace the E_i 's in [8] with

318 E_g to reflect the fact that government uses its own expectation of households' decision criteria to
 319 determine optimal taxes and subsidies.¹¹ After doing this substitute the result into [10] and
 320 rearrange terms to obtain

$$321 \quad [12] \quad t_{ij} = \frac{-E_g \left\{ \sum_{k \neq i} \lambda_k \frac{\partial u_k}{\partial a} \frac{\partial a}{\partial r_i} \frac{\partial r_i}{\partial x_{ij}} \right\}}{E_g \left\{ \lambda_i \frac{\partial u_i}{\partial y_i} \right\}}, \quad i = 1, \dots, n \text{ and } j = 1, 2.$$

322 The denominator of [12] is the regulator's expectation of household i 's marginal utility of
 323 consumption of the private good times the weight assigned to that household. This term is
 324 positive. The numerator is the environmental authority's expectation of the marginal impact of
 325 household i 's choice of input j on weighted aggregate damage experienced by all the other
 326 households. This is the expected external cost (in the case of wood consumption) or benefit (in
 327 the case of combustion technology) from household i 's decision. This term is negative if j is the
 328 combustion technology, confirming that $t_{i1} < 0$ is a subsidy for the purchase of more efficient
 329 combustion technologies. The numerator is positive if j is the wood input, confirming that $t_{i2} > 0$
 330 is a tax on wood use.

331

332 **3. The control of urban air pollution and the distribution of household income.**

333 The presence of welfare weights and the marginal utility of private good consumption in the
 334 taxes/subsidies in [12] means that the distribution of income will play an important role in
 335 optimal policies to control urban air pollution.

336 To understand how income disparity affects policy design, use [12] to subtract t_{hj} from

¹¹ Obviously, we require that the government and households hold symmetric beliefs about the stochastic relationships between pollution damage, household emissions, and household choices.

337 t_{mj} for an arbitrary pair of households h and m and for both energy inputs $j = 1, 2$. Carrying out
 338 this subtraction and rearranging terms yields

$$339 \quad [13] \quad t_{mj}\lambda_mE_g\left(\frac{\partial u_m}{\partial y_m}\right) - t_{hj}\lambda_hE_g\left(\frac{\partial u_h}{\partial y_h}\right) = -\lambda_hE_g\left(\frac{\partial u_h}{\partial a}\frac{\partial a}{\partial r_m}\frac{\partial r_m}{\partial x_{mj}}\right) - \left(-\lambda_mE_g\left(\frac{\partial u_m}{\partial a}\frac{\partial a}{\partial r_h}\frac{\partial r_h}{\partial x_{hj}}\right)\right).$$

340 On the right side of [13], $-\lambda_hE_g\left(\left(\partial u_h/\partial a\right)\left(\partial a/\partial r_m\right)\left(\partial r_m/\partial x_{mj}\right)\right)$ is the authority's expectation of
 341 the weighted impact of household m 's choice of wood consumption or more efficient combustion
 342 technology on household h 's disutility from pollution. Therefore, one potential source of
 343 variation of wood taxes and combustion technology subsidies across households stem from
 344 differences between the impacts of each household's choices on the pollution damage suffered
 345 by every other household. Since we are motivated by mid scale urban areas like Temuco, Chile
 346 with more than 80,000 households, the marginal impact of one household's choices on some
 347 other's utility is probably very small.¹² Hence, we think it is reasonable to assume that right
 348 hand side of [13] is approximately zero so that

$$349 \quad [14] \quad t_{hj}\lambda_hE_g\left(\partial u_h/\partial y_h\right) \approx t_{mj}\lambda_mE_g\left(\partial u_m/\partial y_m\right), \text{ for all household pairs } h \text{ and } m, \text{ and } j = 1, 2.$$

350 For some household i and with j being the wood input, $t_{ij}\lambda_iE_g\left(\partial u_i/\partial y_i\right)$ is the
 351 government's weighted expectation of the household's marginal cost of the wood tax in terms of
 352 utility of consuming the private good. For the combustion technology, the term is the authority's
 353 weighted expectation of the household's marginal benefit of the technology subsidy. The result
 354 in [14] indicates that the weighted expectation of the marginal cost of the wood tax in utility
 355 terms should be approximately equal across households. The same is true of the combustion

¹² This, of course, does not imply that the expected marginal damage from a single household's emissions (i.e., the numerator of [12]) is also small.

technology subsidy. This is reminiscent of the requirement to equate marginal abatement costs of commercial point pollution sources to minimize the aggregate abatement costs of pollution control.

Our result in [14] also indicates that taxes and subsidies vary across households as $\lambda_i E_g (\partial u_i / \partial y_i)$ varies over households. Of course, the marginal utility of consumption of the private good, $\partial u_i / \partial y_i$, varies with household income. Diminishing marginal utility of consumption of the private good implies that $\partial u_i / \partial y_i$ decreases as household i 's income increases. Therefore, [14] indicates that the distribution of income plays an important role in formulating policies to control urban air pollution from households.

In fact, $\lambda_i E_g (\partial u_i / \partial y_i)$ only varies across households if the authority is unable or unwilling to make unrestricted lump sum income transfers. When an authority makes these transfers, $t_{hj} \approx t_{mj}$ for all household pairs h and m , and $j = 1, 2$. To see this, modify the social decision problem [9] by eliminating the individual household budget constraints and replacing them with the single aggregate income constraint,

$$[15] \quad \sum_{i=1}^n w_i = \sum_{i=1}^n y_i + p_1 \sum_{i=1}^n x_{i1} + p_2 \sum_{i=1}^n x_{i2}.$$

This modification allows an authority to distribute the aggregate income of the community in any way it wants. Let $\phi > 0$ be the multiplier attached to the aggregate wealth constraint for the Lagrange equation for the problem. Then, the first order conditions for determining the allocation of wood use and combustion technologies are:

$$[16] \quad \lambda_i E_g \left(\frac{\partial u_i}{\partial c_i} \frac{\partial c_i}{\partial x_{ij}} + \frac{\partial u_i}{\partial a} \frac{\partial a}{\partial r_i} \frac{\partial r_i}{\partial x_{ij}} \right) + \sum_{k \neq i} \lambda_k E_g \left(\frac{\partial u_k}{\partial a} \frac{\partial a}{\partial r_i} \frac{\partial r_i}{\partial x_{ij}} \right) - \phi p_j = 0, \quad i = 1, \dots, n \text{ and } j = 1, 2,$$

and the first order conditions for determining consumption of the private good are

377 [17] $\lambda_i E_g (\partial u_i / \partial y_i) - \phi = 0, i = 1, \dots, n.$

378 Combine [16] and [17] to obtain

379 [18] $\lambda_i E_g \left(\frac{\partial u_i}{\partial c_i} \frac{\partial c_i}{\partial x_{ij}} + \frac{\partial u_i}{\partial a} \frac{\partial a}{\partial r_i} \frac{\partial r_i}{\partial x_{ij}} \right) + \sum_{k \neq i} \lambda_k E_g \left(\frac{\partial u_k}{\partial a} \frac{\partial a}{\partial r_i} \frac{\partial r_i}{\partial x_{ij}} \right) - \lambda_i E_g \left(\frac{\partial u_i}{\partial y_i} \right) p_j = 0,$

380 $i = 1, \dots, n \text{ and } j = 1, 2.$

381 Note that [18] is the same as [10]. Therefore, combining this with [8] with E_i replaced by
 382 E_g yields [12] and ultimately [14]. However, the major difference in assuming the government
 383 has the unrestricted ability to make lump sum transfers comes from [17], which implies

384 [19] $\lambda_h E_g (\partial u_h / \partial y_h) = \lambda_m E_g (\partial u_m / \partial y_m),$ for all household pairs, h and m .

385 This implies that the efficient pollution control policy would include income transfers so that
 386 households' weighted expected marginal utilities of consumption of the private good are equal.
 387 For given utility weights and diminishing marginal utility of private good consumption, these
 388 income transfers would tend to be from richer households to poorer ones. If these transfers are
 389 made, [19] indicates that $\lambda_i E_g (\partial u_i / \partial y_i)$ plays no role in how an optimal control policy treats
 390 different households. That is, efficient lump sum income transfers would imply that household
 391 wood taxes and combustion technology subsidies satisfy $t_{hj} \approx t_{mj}$, for all household pairs h and
 392 m , and $j = 1, 2$.

393 However, as we noted earlier it is unlikely that these income transfers would be made a
 394 part of policies to control household air pollution. In this case, the effect of income disparity on
 395 the efficient pollution control policy cannot be dealt with directly, but instead must be dealt with
 396 through the specification of household utility weights or through the variation in wood taxes and
 397 technology subsidies across households. The first option would involve choosing a wood tax and

technology subsidy that is uniform across households and adjusting the utility weights so that $\lambda_i E_g(\partial u_i / \partial y_i)$ is the same for all households. Since $\partial u_i / \partial y_i$ will be higher for lower income households, this strategy would assign lower weights in the social welfare function to these households. It is hard to imagine a strategy that is more arbitrary and unfair. However, our analysis suggests that we should recognize that the choice of uniform taxes involves an implicit assignment of utility weights that are biased against low income households.

Varying the wood taxes and combustion technology subsidies seems to us to be more defensible. From [14] it is easy to see that both the wood tax and the subsidy for more efficient combustion technologies will tend to be higher for higher income households. That is, if h is a wealthier household than m , then the combustion technology subsidies satisfy $-t_{h1} > -t_{m1}$, and the wood consumption taxes satisfy $t_{h2} > t_{m2}$.

At first glance it may seem paradoxical that income differences call for a higher subsidy for wealthier households. However, the reason that efficiency calls for wealthier households to take on more of the burden of reducing air pollution than less wealthy households is to distribute the expected marginal utility costs of wood taxes and benefits of technology subsidies so they are equal. With lump sum transfers this equilibration is accomplished by income redistribution. In the absence of these transfers it is accomplished by pushing more of the control burden onto wealthier households.¹³ To see why wealthier households take on more of the burden let us

¹³ Our result that the subsidy is larger for high income households does not depend on any assumption about the marginal impact of a household's combustion technology on its emissions; in particular, we do not assume that differences in this value are independent of income. [The same is true of the wood input.](#) These differences are eliminated because they are part of how emissions of one household affect the damage experienced by one other household, which is likely to be small in large communities. In the case of a small number of households, we acknowledge that optimality might call for making the low income households bear most of the burden of pollution control. This could occur if low income households own the least efficient

416 assume that we can tax household emissions directly. We will show that the emissions tax is
 417 higher for wealthier households in the absence of lump sum income transfers, thereby
 418 demonstrating that efficiency calls for wealthier households to take on more of the burden of air
 419 pollution control.

420 Assume that the i^{th} household faces an emissions tax t_i on its emissions r_i , instead of tax
 421 on its wood consumption and a subsidy for more efficient combustion technologies. Then the
 422 household's decision problem is to choose x_{i1} , x_{i2} , and y_i to solve

$$\begin{aligned}
 423 \quad [20] \quad & \max E_i(u_i(c_i, y_i, a, \mu, \eta_i)) \\
 424 \quad & \text{s.t.} \quad c_i = c(x_{i1}, x_{i2}), \\
 425 \quad & w_i = y_i + p_1 x_{i1} + p_2 x_{i2} + t_i r_i(x_{i1}, x_{i2}, \sigma_i), \\
 426 \quad & a = a\left(\sum_{k=1}^n r_k(x_{k1}, x_{k2}, \sigma_k), \theta\right).
 \end{aligned}$$

427 The first-order conditions are:

$$428 \quad [21] \quad E_i \left\{ \frac{\partial u_i}{\partial c_i} \frac{\partial c_i}{\partial x_{ij}} - \frac{\partial u_i}{\partial y_i} \left(p_j + t_i \frac{\partial r_i}{\partial x_{ij}} \right) + \frac{\partial u_i}{\partial a} \frac{\partial a}{\partial r_i} \frac{\partial r_i}{\partial x_{ij}} \right\} = 0, \quad i = 1, \dots, n, \quad j = 1, 2.$$

429 As before, replace the E_i 's in [21] with E_g to reflect the fact that government uses its own
 430 expectation of the households' decision criteria to determine optimal taxes and subsidies. After
 431 doing this, substitute the result into [10] and rearrange terms to obtain

combustion technologies and that a subsidy for an upgrade can produce a larger reduction in emissions than if the subsidy was given to higher income households with more efficient combustion devices. [We also acknowledge that optimal taxes and subsidies might vary with income if pollution is not uniformly mixed and the spatial distribution of damages is correlated with income. Our model does not account for this possibility, but it can be modified in a straightforward way to do so.](#)

$$[22] \quad t_i = \frac{-\sum_{k \neq i} \lambda_k E_g \left(\frac{\partial u_k}{\partial a} \frac{\partial a}{\partial r_i} \frac{\partial r_i}{\partial x_{ij}} \right)}{\lambda_i E_g \left(\frac{\partial u_i}{\partial y_i} \frac{\partial r_i}{\partial x_{ij}} \right)}, \quad i = 1, \dots, n.$$

To simplify matters, assume that the uncertainty in $\partial r_i / \partial x_{ij}$, $j = 1, 2$ is uncorrelated with the uncertainty in $\partial u_i / \partial y_i$ and in $(\partial u_k / \partial a)(\partial a / \partial r_i)$, for all $i = 1, \dots, n$. This allows us to eliminate $\partial r_i / \partial x_{ij}$ from [22].¹⁴ Once this has been done, subtract t_{hj} from t_{mj} to obtain

$$[23] \quad t_m \lambda_m E_g \left(\frac{\partial u_m}{\partial y_m} \right) - t_h \lambda_h E_g \left(\frac{\partial u_h}{\partial y_h} \right) = -\lambda_h E_g \left(\frac{\partial u_h}{\partial a} \frac{\partial a}{\partial r_m} \right) - \left(-\lambda_m E_g \left(\frac{\partial u_m}{\partial a} \frac{\partial a}{\partial r_h} \right) \right).$$

Again, the right side expression is likely to be very small, so [23] implies $t_h \lambda_h E_g (\partial u_h / \partial y_h) \approx t_m \lambda_m E_g (\partial u_m / \partial y_m)$, for all household pairs h and m . If the authority can tax household emissions but cannot make lump sum transfers of income across households, [23] suggests that the efficient tax on emissions is higher for higher income households. Thus, optimality calls for making higher income households bear more of the burden of controlling household air pollution.

Of course, we have maintained that the main difficulty in this policy problem is that household emissions cannot be observed. When an authority can control wood consumption and combustion technologies it pursues policies that place more of the air pollution control burden on higher income households by placing a higher tax on their wood consumption and offering a higher subsidy for their purchase of more efficient combustion technologies. It is important to

¹⁴ This lack of correlation could come about if, for example, there was no regulatory uncertainty about how household choices of wood consumption and combustion technology produce emissions. If we are not able to eliminate $\partial r_i / \partial x_{ij}$ from the right side of [22], a household's emission tax would depend on the input j . In this case, no emissions tax could simultaneously satisfy [21] for both the wood input and the combustion technology. This problem is discussed in another context by Shortle and Horan (2001).

realize that a higher technology subsidy for wealthier households is not meant to correct income inequality. The purpose of the subsidy is to motivate the purchase of more efficient combustion technologies. A higher technology subsidy for wealthier households is a part of how more control burden is optimally placed on wealthier households. It bears repeating, however, that the technology subsidy is only needed because household emissions cannot be controlled directly. Thus, it is the nonpoint nature of the problem combined with the inability of an authority to make unrestricted lump sum income transfers that lead to higher technology subsidies for wealthier households.

4. Concluding remarks about implementation

We have derived a set of efficient household-specific taxes on wood consumption and subsidies for more efficient combustion technologies. Our most important result is that these interventions are dependent of the distribution of income; in fact, efficiency requires that these taxes and subsidies be structured so that wealthier households take on more of the control burden. In this section we discuss some practical implementation issues associated with our results.

Although we have assumed that taxes on wood consumption and subsidies for combustion technologies are available, in many settings in the developing world wood consumption is not observable. This may be due to the absence of formal markets for wood for heating, which is the case of wood used by urban households in central southern Chile. The market for wood is mainly informal and no regulatory authority has actual control or transaction records. In a recent survey of a sample of urban households in the city of Temuco, about 90% of the respondents acknowledged buying wood without paying taxes (CONAMA-DICTUC 2008).

In the absence of the ability to monitor wood consumption, air pollution control policy would then focus on promoting cleaner combustion technologies. However, our result that

471 income disparities imply that higher technology subsidies should be provided to higher income
472 households becomes problematic. It is hard to imagine that there would be much political
473 support for our recommendation.

474 In fact, it may be the case that subsidies are only feasible if they are targeted at lower
475 income groups. This is likely to be true in Chile where subsidies that are part of social welfare
476 programs are targeted at the poor. We are not aware of any environmental policy intervention in
477 Chile that uses subsidies for household choices; however, it seems likely that such a policy
478 would be implemented in concert with social policies that define how subsidies are allocated.
479 Providing a higher technology subsidy to higher income households might appear to be at odds
480 with other social welfare objectives.

481 While higher technology subsidies for higher income households may be part of an
482 efficient control program, they may not be part of a control policy that pursues other reasonable
483 objectives. For example, an authority may be motivated to get the largest improvement in air
484 quality with a limited budget to pay subsidies for more efficient combustion technologies. Then
485 it may be the case that these subsidies should be directed mainly at poorer households if this is
486 where the marginal reduction in emissions from a dollar of technology subsidy is highest.
487 Pursuing the biggest environmental improvement for a fixed implementation budget is a
488 reasonable policy objective, even though it will not lead to the theoretically efficient solution.
489 However, it may be easier to understand than the idea of efficiency, and hence, easier to sell to
490 lawmakers and the public.

491 There is another reason to target combustion technology subsidies to low income
492 households, which is perhaps more specific to the developing country context of the problem we
493 explore. While in our model households are able to choose or may be induced to choose the

optimal combustion technology, liquidity constraints can make that choice difficult for some households. Chávez, et al. (2010) conducted a survey of a sample of Temuco's households to determine their willingness to change combustion equipment with a government subsidy. They found that responses depended on whether or not there was credit available for the part of the cost of the combustion equipment not covered by the subsidy.

Even though we have assumed that combustion technologies are observable, and therefore can be subsidized, there is still a costly enforcement problem to manage. A monitoring and penalty program needs to be designed along with the incentive policy to make sure that those who take advantage of the subsidy actually purchase approved equipment and use it properly.

Our results suggest that optimal technology subsidies and wood taxes vary continuously according to household incomes. While continuity is possible because authorities are likely to have income information for tax purposes, it is more likely that authorities will group households into a relatively small number of income classes and apply different subsidies and taxes to each class. Differentiated after-tax or after-subsidy prices produce the risk of developing so-called "black markets" in wood or combustion equipment. Black markets could also develop across communities that move efficient combustion equipment intended for one community to another. If this problem proves difficult to deal with, then authorities could be forced to consider implementing a uniform technology subsidy or wood tax despite the efficiency consequences.

Our results also suggest that the efficient subsidies (and wood taxes if they are available) should vary across cities. Although we have illustrated the problem of concern with the case study of Temuco in southern Chile, the same type of air pollution is a serious problem in several medium and small size cities in the valley south of the Chilean capital of Santiago. Because of the heterogeneity across these cities in terms of population, income distribution, distribution of

517 combustion technologies, the use of wood, and general environmental conditions, it is highly
518 unlikely that the same control policy will be appropriate for different cities.

519 A coordinated plan may also be required to manage the flow of retired equipment across
520 communities. An effective equipment subsidy program will generate a stock of discarded stoves.
521 If these are not destroyed, they may be available to other communities at significantly reduced
522 prices. Because of this a stove replacement program in one community can have environmental
523 impacts in other communities; hence, the potential need for coordinated air quality programs.

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