Forest to Stove: The Effect of Prices on Firewood Demand. A Two-Sample Instrumental Variable Approach

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Abstract

Firewood use and its environmental and health consequences remain global problems which governments could address by raising the fuel's price. But firewood market informality and lack of systematic price data impede estimating price responsiveness. The paper addresses these obstacles in the case of firewood demand in Chile, using a two-sample IV strategy. We propose a novel price instrument, linked to the marginal cost of supply, derived from satellite-based, distance-weighted forest cover measures. Results show that a 10% increase in firewood prices produces a 6.7% reduction in consumption, directly leading to a policy-relevant annual reduction of 4,500 tons in $PM_{2.5}$ emissions. Beyond Chilean firewood, the analysis demonstrates a price instrumentation method applicable to inadequately observed markets, such as those for local farmers' produce and biomass, illegal logging services in remote areas, artisanal fishing, and other cases where informality and unrecorded transactions obscure quantity and price relationships.

I. Introduction

Air pollution is responsible for an estimated 3.3 million premature deaths globally each year (Lelieveld et al., 2015). In the European Union, exposure to fine particulate matter ($PM_{2.5}$) contributed to over 253,000 deaths in 2021, with the highest burden concentrated in Central and Eastern Europe (OECD/European Commission, 2024). Residential firewood and biomass use remain major contributors to particulate pollution worldwide (Shen et al., 2019; Liu et al., 2016). For example, in Dublin, only 13% of households burn peat and wood, yet account for up to 70% of winter PM_{10} emissions (Lin et al., 2018). In rural China, air pollution caused 570,000 premature deaths in 1992; a transition to cleaner fuels over the following two decades averted approximately 130,000 deaths annually (Shen et al., 2019). In Europe, biomass fuels supply around 20% of residential heating capacity, with shares exceeding 60% in Estonia and Latvia (Directorate-General for Energy, 2016). In Latvia alone, the associated annual health costs reach €126 million – despite a population of under 2 million. Chile presents an especially acute case: 39% of households rely on firewood for residential heating (Ministry of Energy Chile, 2019), with firewood energy representing over a third of the electrical grid's energy supply and a fifth of the entire energy matrix. There is little self-collection, and with few exceptions, households rely on firewood markets (Reyes et al., 2018). Among households that do use firewood, approximately 70% are located in urban areas (see https://simef.infor.cl). Chilean firewood use accounts for 94% of particulate emissions in the country's center-south region, exposing most residents to dangerously high $PM_{2.5}$ concentrations and elevating mortality

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risks, particularly among the elderly (Busch et al., 2024; Huneeus et al., 2020). Yet, despite these substantial costs, the transition to cleaner heating sources remains slow.

When governments regulate firewood-driven pollution, they typically rely on quantitative restrictions or outright bans. Economists, by contrast, often advocate for price-based interventions (Stavins, 2003). Nevertheless, important empirical questions remain, most notably the responsiveness of consumer demand for firewood to price changes. Estimating the demand elasticity is challenging, because firewood markets are largely informal, and systematic price data are scarce, despite the fuel's significance in terms of total household energy expenditures and the number of competitive market participants. Even in more developed countries, firewood markets tend to be informal, and, while firewood use is often observable through household surveys, price information remains limited and is rarely matched directly with demand data.

We demonstrate a method to estimate the price elasticity of demand in such informal markets – markets characterized by low barriers to entry but limited, systematic availability of prices. This exercise holds particular policy relevance for Chile and is applicable to other contexts where informality and unrecorded prices obscure the relationship between quantity and price. Examples include biomass fuel markets in other countries, farmers' markets, and informal taxi and cargo transport services, among others.

To address the challenge of limited price observations, we leverage a novel panel dataset on firewood consumption in Chile at the municipality level, together with all available firewood price data. We implement a Two-Sample Instrumental Variable (TSIV) strategy to overcome two common issues in the literature on biomass use, particularly in informal markets. First, it addresses potential joint endogeneity between price and quantity in estimating the price elasticity of demand. We exploit variation over time and space in a lagged, distance-weighted measure of forest cover as an instrument for local firewood prices, which are closely tied to the variable costs of firewood supply (Miteva et al., 2017; Key et al., 2000). Second, by estimating each stage of the IV model using distinct samples, the strategy resolves the data limitation arising from observing prices in only a subset of the geographic zones and periods, where and when consumption is recorded. In our detailed discussion of the empirical strategy, we argue that this approach is both effective and appropriate. Firewood markets are characterized by low barriers to entry and exit, with suppliers facing minimal fixed costs and requiring little investment in physical or reputational capital (Reyes et al., 2018). Firewood is a search good, supplied in highly atomized and competitive conditions.

We observe average prices in 43 municipalities over an imperfect panel and firewood consumption of 160 municipalities over three years. Satellite-based data on forest cover (a measure of forest stocks), that covers all municipalities and all years for two decades, allows us to instrument firewood prices in one sample and then use this information to predict firewood prices over the consumption sample employing the Two-Sample Instrumental Variable (TS2SLS) approach (Angrist and Krueger, 1992; Inoue and Solon, 2010). We also control (in both samples) for relevant socio-demographic and climatic variables and municipality and year fixed-effects. Our results show that firewood is an inferior good and inelastic, which is consistent with a necessity product, and that kerosene and electricity are its main substitutes.

This study makes both methodological and context-specific contributions. Methodologically, it is the first to apply a two-sample instrumental variables (IV) strategy to firewood markets. By leveraging satellite-derived forest cover data as an instrument for firewood prices, the study overcomes common data limitations in informal markets. This approach demonstrates how spatial and temporal variation in satellite data can bridge gaps between imperfect consumption and price datasets—a strategy that can be extended to other data-scarce informal markets. In the Chilean context, this is the first study to provide a causal estimate of the price elasticity

of firewood demand. It offers a generalizable estimate to inform policies aimed at reducing firewood use and accelerating energy transitions toward cleaner energy sources. The estimated own-price elasticity of -0.67 and income elasticity of -0.34 enable quantitative policy simulations. We present an example, where a *10% increase in firewood prices*—as anticipated under new legislation intended to restrict wood humidity (Ministry of Energy Chile, 2023)—is projected to reduce annual $PM_{2.5}$ emissions by approximately 4,500 tons. This reduction is equivalent to the yearly emissions of a small city of around 200,000 residents in Chile's central valley (e.g., Los Angeles, as estimated by Huneeus et al. 2020, p. 21), based on emission conversion factors from Alamos et al. 2022.

Our study builds on previous literature on the use of biomass fuels. The survey of Muller and Yan (2018) finds that the own-price elasticity of firewood for various uses has a consistent negative effect with a wide variation in magnitude (from about -0.32 to -1.14). But the existing research on firewood demand faces several limitations. Many studies rely on small, region-specific datasets and often lack direct price data, substituting expenditure figures instead (Couture et al., 2012; Arabatzis and Malesios, 2011; Jaime et al., 2020). Broader studies, such as Calvo et al. (2022), tend to emphasize environmental impacts rather than demand estimation. Moreover, much of the literature focuses on developing countries where fuelwood is collected rather than purchased, overlooking market-mediated contexts as in Chile, Canada, the U.S., and parts of Europe (Korteland, 2022; Song et al., 2012). This present study addresses these gaps by focusing on a market-based setting and applying a novel empirical strategy.

The rest of this article is organized as follows, Section II summarizes some relevant literature and presents the basic model and estimation strategy. Section III describes the database-derived municipal aggregates and satellite data employed in the study. Section IV presents forest cover as an instrument of firewood prices and its construction from measures of local and distant forest stocks. Sections V and VI presents and discusses the results of our estimations and some robustness checks. Finally, Section VII concludes with some implications for policy.

II. Background and estimation strategy

The informal nature of the market presents a challenge in estimating the price sensitivity of firewood demand. The majority of research in the literature on household firewood use is based on small-scale studies in the less-developed world, without estimation of market demand price elasticities, and focused mainly on cooking in contrast to this present study on wood for heating (Jeuland et al., 2021). Even in the developed world, the effect of own prices on firewood consumption is largely unobserved, although wood remains a significant energy source. For example, in estimating elasticities of residential electricity demand in Portugal, Silva et al. (2018) exclude firewood prices in the analysis although they point out that firewood is the second-most-used household energy source (following electricity but leading natural gas). Similarly, Song et al. (2012), when estimating the demand for firewood using a sample of 4,382 U.S. households, only include prices of substitutes and not of the own price of the product itself. More relevant to our analysis of the Chilean case, Jaime et al. (2020) examine a survey regarding heating systems and wood consumption of 2761 households in nine urban areas in centre-south Chile. Although the authors have access to a limited cross section of nine data points for firewood prices for the included regions, their analysis finds only weak correlation between prices and the type of household primary heating system and excludes prices altogether from wood demand estimation. We should note that there are a few studies that do employ own-price information in firewood demand analysis. MacKenzie and Weaver (1986) finds a firewood price elasticity of -0.1 across a small sample of households in the U.S. northeast. Couture et al. (2012) employ a survey of 2244 households in the French Midi-Pyrénées, finding

16% with firewood as their primary heating system. Using declared prices to estimate the elasticity of firewood consumption, the authors find a wide range of elasticities depending on the heating system regime,[1] from a high of -1 in the case of wood as the primary system to much lower where wood is a backup to other energy sources. In a similar study, Arabatzis and Malesios (2011) find a smaller (and only significant at 20%) marginal effect of -0.1 between the reported firewood prices and consumption in northern Greece.

Our objective is to estimate the correlation between observed household consumption of firewood and observed market prices, controlling for other relevant factors. This will allow an estimation of the effect of possible higher consumer prices on both total firewood use and its associated contamination due to some policy change, such as the recent introduction of stringent legal restrictions on wood humidity.[2] As noted, however, there two practical problems to address in estimating the price elasticity of demand in the context of a market of the type analyzed here: potential endogeneity and the infrequency of observable price data. Concerning the first problem, the estimation of the demand relationship requires addressing the potential empirical issue of identification due to simultaneity. The usual approach to resolve the joint endogeneity of prices with quantities involves estimating the demand curve with one or more instrumental variables to control for shifts in supply. The conceptual framework of partial equilibrium offers a clear analytical structure to identify a successful instrument: a variable determinant of supply that affects demand only through its influence on the variation of the supply curve, and thus of equilibrium price. Formally, we require three basic conditions for a successful instrument candidate (Angrist and Pischke, 2009): (1) The instrument has a causal effect on the endogenous variable of interest (i.e., price), known as the relevance restriction. (2) The instrument is effectively random with respect to the treatment, known as the independence restriction. And (3) there is a single channel through which the instrument affects the outcome, the exclusion restriction.

To estimate the demand for firewood, we use a panel of 168 municipalities in center-south Chile in the years 2003, 2010 and 2020. The model of interest, measured at the municipality level, relates the annual demand (cubic meters, total or per capita) for firewood in municipality m, in year t, Q^d_{mt}, to a corresponding price per m^2, p^d_{mt}, a set of covariates $\mathbf{X^d_{mt}}$, which include relevant demand shifters, and appropriate municipality and time fixed effects:

$$\ln Q^d_{mt} = \alpha^d + \beta \times \ln p^d_{mt} + \theta' \mathbf{X}^d_{mt} + \gamma^d_m + \gamma^d_t + \epsilon_{mt} \tag{1}$$

where ϵ_{mt} is a random error term and γ^d_m and γ^d_t represent fixed effects. The superscript d in equation 1 makes explicit two aspects of the statistical modelling effort: it refers to the demand side of market equilibrium and, relevant for our estimation strategy, it also refers to the observed data to estimate the demand curve. An additional data set will be introduced to instrument the average market price of firewood, p^d_{mt}. The set of covariates $\mathbf{X^d_{mt}}$ include, prices of substitutes and complementary energy sources, income level, and other socio-demographic and climatic characteristics at the municipal level. We discuss these data below.

The key problem to estimate the demand equation 1 is the absence of price data for the complete sample for which the quantities of firewood are available. The rest of the variables in the demand model and the instrument for prices based on forest cover (discussed below) perfectly overlap in the two samples. There is a clear link between the distance to forest

[1] Couture et al. (2012) define different regimes of the combination of primary and "backup" heating systems to control for the selection bias in estimating the demand equations. They do not attempt, however, to control for potential endogeneity of consumption and prices.

[2] Details of this new legislation can be found in Ministry of Energy Chile (2022)

stocks and local firewood prices.[3] That is, we can observe the stock of forest, and all controls in every year (2000-2023) and for all municipalities with data in both samples. Given the data composition, we can use a Two-Sample, Two-Stage Least Squares approach (TS2SLS) to estimate the demand curve. Initially developed by Angrist and Krueger (1992) as a Split-Sample Instrumental Variable (SSIV), the TS2SLS method allows IV estimation in scenarios where outcomes and endogenous variables are not found within the same set of data (Angrist and Pischke, 2009). In the analysis presented below we improve the efficiency of the standard error of the TS2LS estimator, accounting for the differences in the size of the two samples, using the correction proposed by Inoue and Solon (2010).[4]

In the first stage, using the price sample (represented in the following by superscript p), we estimate the relationship between the endogenous variable, p^p_{mt}, firewood prices in municipality m and year t, and our instrument – Forest Cover Potential, $FCP^p_{m,t-1}$. We discuss in detail how we construct this instrument and its rationale in section IV. We include other exogenous variables, $\mathbf{X}^p_{mt}$, and fixed effects γ^p_m for each municipality and γ^p_t for each year in the sample.[5] The first stage regression model is

$$\ln p^p_{mt} = \alpha^p + \phi \times \ln FCP^p_{m,t-1} + \varphi' \mathbf{X}^p_{mt} + \gamma^p_m + \gamma^p_t + \eta_{mt} \tag{2}$$

where η_{mt} a random error term. Note that the controls, $\mathbf{X}^p_{mt}$, are the same set included in Equation 1.

In the first stage of the TS2SLS model, we use the information regarding prices to estimate Equation 2, and then employ the estimated coefficients and second data set to predict firewood prices for estimating the demand curve based on the instrument and covariates. These predicted prices are then incorporated in Equation 1, replacing the endogenous variable p_{mt}, to estimate the final model:

$$\ln Q^d_{mt} = \alpha^d + \beta \times \ln \widehat{p}^d_{mt} + \theta' \mathbf{X}^d_{mt} + \gamma^d_t + \gamma^d_i + \epsilon_{mt} \tag{3}$$

The resulting estimate of β, $\widehat{\beta}_{TS}$, is the price elasticity of demand estimated thorough the TS2SLS model. The standard errors are corrected for the inclusion in the second-stage –Equation 3– of the predicted variable $\widehat{p}^d_{mt}$ derived from the price sample regression - Equation 2.[6]

The data sample relating prices to forest cover –the price sample– includes 122 observations from a set of 45 municipalities (of the 168 total) with observed prices between 2000 and 2023 (an imperfect panel). Only twenty-eight municipalities are included in both datasets; within those overlapping, only a small fraction of prices coincide with consumption data in the same years. The use of a simple 2SLS, therefore, is impractical due to the small sample where outcome, endogenous and instrumental variables overlap. Figure 1 shows consumption quantities and prices in their respective sub-samples. The box plot in the upper panel shows the distribution of the

[3] For example, Jaime et al. (2020) note (pp. 7) that "fuelwood prices appear to respond to a very large extent to wood availability; as can be observed, prices are higher in northern areas and lower in southern counties, where most of the native forest are located."

[4] Pacini and Windmeijer (2016) also present a method to adjust the standard errors of estimated coefficients under heteroskedasticity.

[5] Given the imperfect panel nature of our price sample, we are unable to include a full set of year fixed-effects, because some municipalities are only observed over one or two years in the price sample

[6] We use the adjustment proposed by Inoue and Solon (2010), which corrects the variance of $\hat{\boldsymbol{\beta}}_{TS}$ by multiplying the sample mean squared residual, $\hat{\sigma}^2_d$, from the second-stage regression by $1 + [(n_d/n_p)\hat{\beta}'_{TS}\hat{\Sigma}_\eta\hat{\beta}_{TS}/\hat{\sigma}^2_d]$, where $\hat{\Sigma}_\eta$ is a consistent estimate of the variance for the first-stage disturbances (see p. 559 of Inoue and Solon 2010).

consumption data observed in the three years available. On average, there is a slight reduction over time in per-capita consumption (after removing municipality and year fixed-effects). The scatter-plot in the lower panel shows the price sample, after removing the municipality fixed effects. On average, prices show a weak-increasing trend after 2010. Moreover, as observed in Appendix Figure A.1, the geographical distribution of the two samples lie within the same geographical area.

Half of firewood production derives from native forests and other half as a byproduct of forest plantations (Reyes et al., 2018). Local commercialization of firewood is mainly by intermediaries aggregating wood from thousands of small-scale producers. This competitive market process generates a direct relationship between firewood market prices and production decisions at the level of forest owners. Considering the highly competitive nature of this market without barriers to entry, there is every reason to take the two datasets as representing the same population (see Angrist and Pischke 2009). The rest of the variables in the demand model (Equation 1) and the instrument, perfectly overlap in the two samples. This means we can observe the stock of forest, and all controls in every year (2000-2023) and for all municipalities with data in both samples.

In the next section III we review the data used in these two estimation stages, and in the following section IV we present a detailed discussion of the construction and justification of the price instrument.

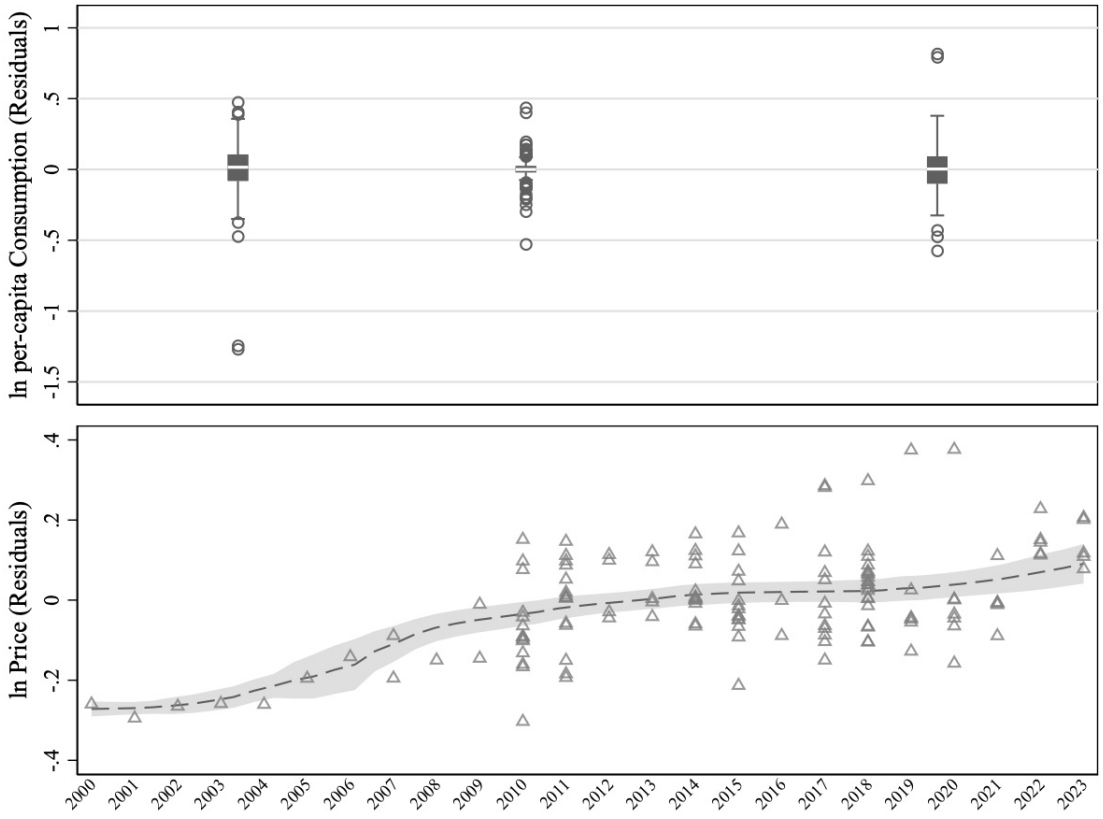


Figure 1: Firewood consumption and prices in two samples.

Note: **Upper panel**: Box plot of the residuals from a regression of log per-capita consumption on municipality and year fixed-effects. The sample contains information for 168 municipalities in the years 2003, 2010 and 2020. **Lower panel**: The triangle dots are residuals from a regression of log firewood prices on municipality fixed effects. The dashed line, illustrating the trend in prices is derived from the fitted values of the residuals from a kernel-weighted local polynomial smoothing regression. The sample contains information of 45 municipalities for the period between 2000 and 2023 (imperfect panel).

III. Data

Municipal-level consumption estimates from the Chilean Forest Institute (Spanish acronym INFOR) are combined with a novel dataset on firewood prices. Sociodemographic information are from Chilean national household survey (CASEN) and the Institute of Statistics (INE). Prices of substitute energy sources are from the National Energy Commission (CNE). Satellite-based data to account for weather characteristics and forest cover are from Copernicus Climate Change Service (2022) and Hansen et al. (2013).

A. *Consumption*

The estimations of consumption at the municipal level come from the Chilean Forest Institute's *Observatory of Forests, Energy and Society* (Spanish acronym BES).[7] These estimations are based on a series of regular regional studies accounting for hundreds of surveys. To generate the total annual municipal consumption in cubic meters (m^3), the results of the surveys are cross-linked with three levels of demographic statistics: Urban/Rural occupied dwellings (not including apartment buildings) based on census data[8] (1992, 2002 and 2017); percent of households using firewood based on the periodic sociodemographic survey CASEN (rounds 1994, 2006 and 2013) and the studies from INFOR since 2015; and the average household firewood consumption-based on studies by INFOR and CASEN. Table 1 shows descriptive statistics of all relevant variables employed this study. The average municipality's firewood consumption is around 31 thousand cubic meters, equivalent to 1.1 m^3 per capita.

B. *Prices*

The absence of a methodological framework to sample and survey local prices is a current challenge to generate a meaningful database of prices at the municipal level. As part of this work, we compile several sources of price data,[9] which we transform to average municipal prices considering different tree species in each municipality and the reporting in diverse units of volume and mass. Appendix section D describes the process of constructing this price dataset in detail. Table 1 shows average firewood prices per cubic meter. The average real firewood price in 2018 Chilean pesos (clp) is 40,606 clp/m^3 (about 46 USD/m^3). The dataset with firewood prices comprises 46 municipalities (in eight regions) between the years 1990 and 2023, with between 1 and 31 observations by municipality (an imperfect panel with an average of 11 observations per locality). Appendix Figure A.1 panel (c) shows the geographic distribution of the municipalities for which prices are observed, ranging across all eight regions for which consumption is observed in the larger dataset.

The prices of substitute fuels come from the Chilean National Energy Commission (CNE), which reports yearly prices at the regional level for various hydrocarbon fuels and electricity in several units. As a reference price units we use kerosene price per litre, an LPG tank of 15 kg and the electricity tariff of an average household consuming 180 kWh per month.[10] We transform prices to Chilean pesos per megajoule (clp/MJ) to capture cross-price effects: 43.69 MJ/kg for kerosene, 46.28 MJ/kg for LPG and 3.6 MJ/kWh for electricity (from Claverton

[7] Available at `https://simef.infor.cl/reporte_lenia/`

[8] Available at https://www.ine.gob.cl

[9] The Forestry Institute (INFOR) and the National Consumer Service (SERNAC) are the main sources of information on firewood prices.

[10] The electricity tariff time series data come from the CNE's statistical yearbooks, which provide pricing information from 2015. We used the Energy Consumer Price Index (CPI) to estimate electricity tariffs dating back to 2000. The energy CPI comprises energy products (INE, 2018), with electricity carrying the highest weight in the index, accounting for over 45% of the total household energy budget in 2018 (Ministry of Energy Chile, 2019).

Energy). For the firewood conversion of 4,612.16 MJ/m^3, we use the average calorific content of the main species in the sample.[11]

Figure 2 shows the overall positive trend of the 122 price observations in comparison with other substitute fuels at the regional level for Chile's center-south. Energy prices, standardized to energy content, give a quick snapshot of the heating energy market in Chile. Firewood is the cheapest, followed by kerosene, which is 30% higher on average than firewood, and Natural Gas (LPG), approximately three times more expensive. Electricity has been the most expensive energy source of all in equivalent units, on average, eight times more expensive than firewood. Electricity in Chile is also more expensive than in other OECD and Latin American countries, although its price has been declining in part due to the expansion of capacity (including of solar energy) and the integration of once geographically separated markets (Gonzales et al., 2023).

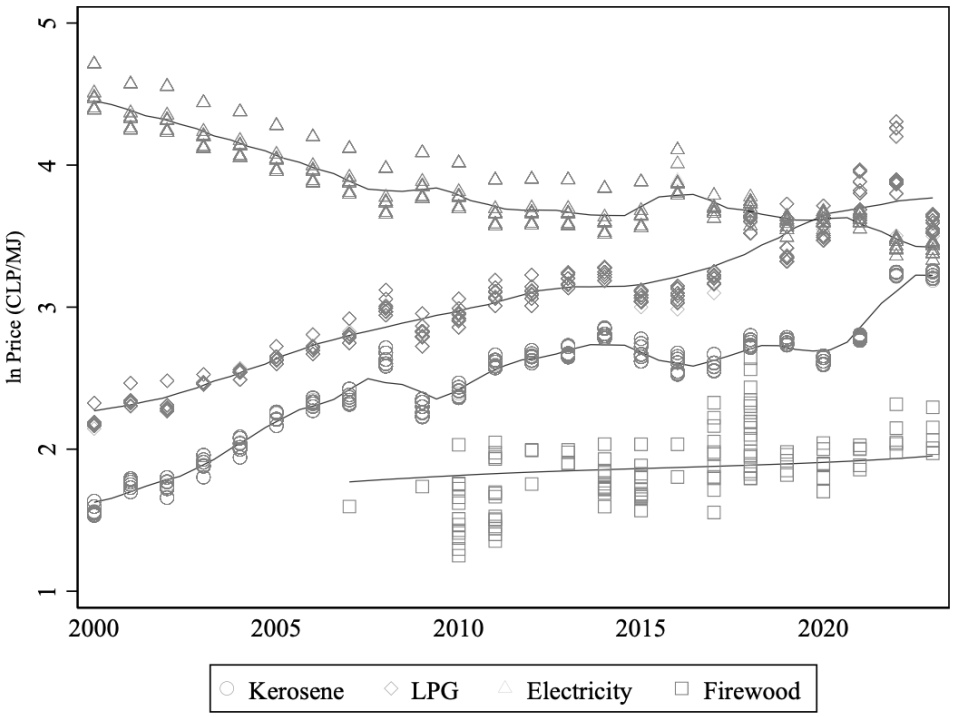


Figure 2: Heating Fuel Prices

Note: Firewood prices are at the municipality level (46 municipalities in eight regions). Kerosene, LPG and electricity are the average prices at the region level for 9 (out of 16) regions in Chile's center-south. Prices are in real terms as the logarithm of Chilean pesos per MJ.

C. Forest Cover

The estimations of municipality-level forest cover in square kilometers at the municipal level between 2010-2022 come from the Hansen et al. (2013) dataset (version 1.10).[12] The data derive from a combination of Landsat (4, 5, 7 and 8) satellite imagery characterizing global forest extent and change at a 30 square-meter grid. Hansen et al. (2013) defines tree cover as the fraction of canopy closure, taller than five meters, of high vegetation classified from a time series of Landsat images at 30 meters of resolution. Based on the definition and several image pre-processing, classification and validation techniques, the outcome is a percentage of

[11] Acacia (*Acacia Melanoxylon and Acacia Dealbata*), Oak (*Nothofagus obliqua*), Eucalyptus (*Eucalyptus globulus*) and Pine (*Pinus Radiata*).

[12] Accessed through the R package gfcanalysis

forest cover by the unit of analysis (30 m^2).[13] To obtain estimates of annual forest cover at the municipal level, FC_{mt}, for every year's set of raster images, we overlap the municipality polygons to count the square kilometres of forest cover within each municipal jurisdiction. The distribution of forest cover (FC_{mt} in $ln(km^2)$) is shown in Figure 4.[14]

D. Heating Degree Days (HDD)

The municipality time series of Heating Degree Days (HDD) were estimated based on the ERA5 satellite product[15] from the Copernicus Climate Change Service.[16] Figure 3 upper panel shows every municipality's time series of daily HDD in the last decade, depicting the yearly seasonality of heating requirements and the cross-sectional differences. The lower panel presents the annual HDD, showing the large cross-sectional differences but also a small decay over time, plus some (relatively smaller) differences in particularly warm or cold years, an essential control to understand the effect of prices on firewood consumption.

[13] Hansen et al. (2013) compare their estimates with the estimations of the Food and Agriculture Organization (FAO), finding the highest correlation in Latin America (up to 91%). They emphasize that, in the measures of forested and deforested area, deforestation is the conversion of natural forests to non-forest land uses. Clearing land of natural forests followed by natural recovery or managed forestry is not deforestation in their methodology.

[14] As Garcia and Heilmayr (2024) note, Hansen et al. (2013) data at the pixel level describe deforestation as a binary and nonrepeatable process that, without correction, could lead to measurement errors. They conclude, however, that two-way fixed effect specifications with spatially aggregated units of analysis (such as municipalities) recover true treatment effects. Moreover, in our present analysis we derive the forest cover variable from the basic data for multiple and spatially distant municipalities.

[15] ERA5 is a reanalysis product that combines model data with observations from across the world into a globally complete and consistent dataset. It offers daily surface temperature data at 2 meters, registered every two hours, with a grid resolution of 31 square kilometers (see Muñoz Sabater 2019 and Copernicus Climate Change Service 2022). To estimate a municipal average temperature, we took an average of all grid points within a municipality's boundaries to get a daily average at the municipal level. Based on daily values, we estimated HDDs using 18.3 °C as the benchmark temperature. Next, we sum up daily HDDs to generate the amount for a year.

[16] Accessed through the Google Earth Engine.

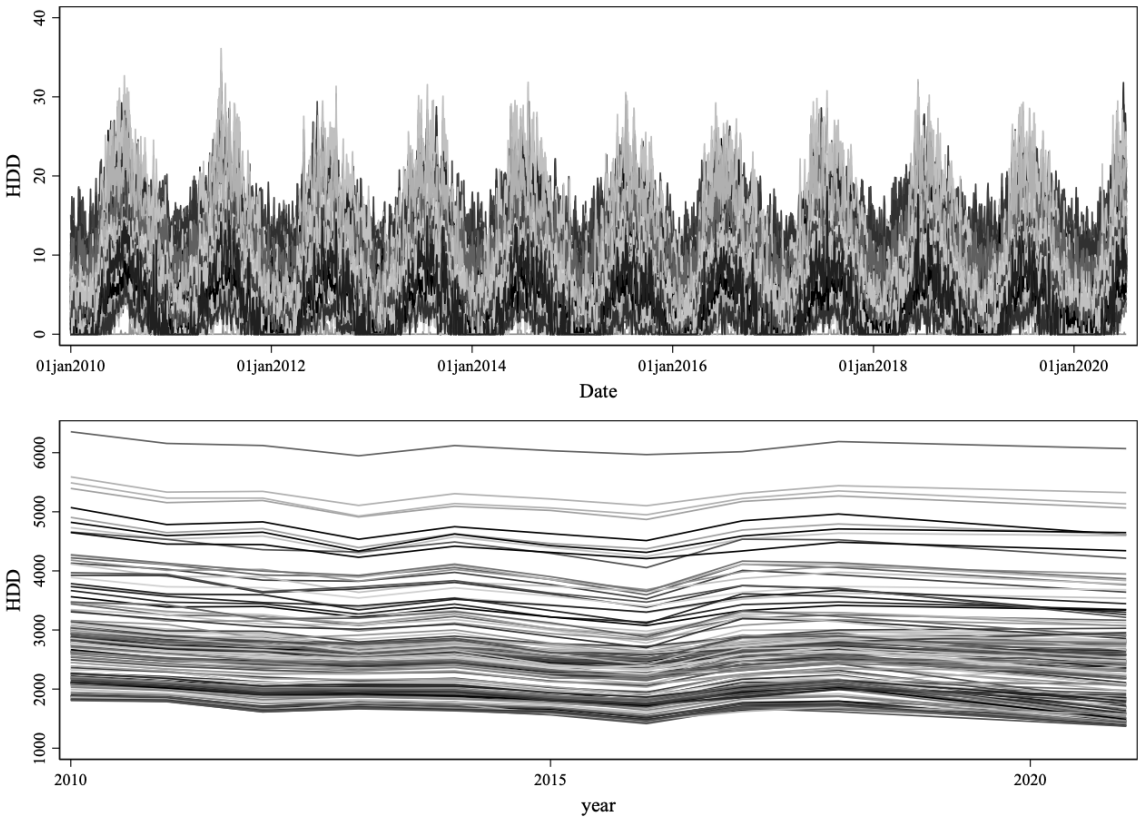


Figure 3: The Variability of Heating Degree Days across the Panel of Municipalities
Note: The upper panel shows the daily heating degree days for 160 municipalities between 2010-2022 estimated based on data from ERA5 Muñoz Sabater (2019) using 18.3 °C as the benchmark temperature. The lower panel shows the yearly aggregated HDD for the same munipalities.

E. Socio-demographics

The socio-demographic data used in this study comes from a periodic Chilean socio-economic survey of individual households, CASEN - *Encuesta de Caracterización Socioeconómica Nacional*.[17] The survey is a random sample of households, taken every two to three years, stratified geographically, and representative at the national, regional, urban, rural and district (municipality) levels. We aggregate to the municipal level the individual responses in ten surveys between 2000 and 2022,[18] and interpolate all controls to have a continuous time series. The reader should note that the variable autonomous household income is the sum of wages and rents from asset ownership, representing disposable income. Imputed rent, which correlates with the size and the condition of a family's dwelling, is a separate control to account for possible wealth-effect differences between home owners and renters. Other controls at the municipality level are average age and education of the household head, average household size, the percentages of households owning their residences, the percentage of detached houses, and the percentage of apartments (relative to total dwellings). Finally, the municipalities' population comes from the demographic projections based on the census of the National Statistics Institute.

[17]The survey's primary objective is to assess the socioeconomic status of households: household composition, education, health, employment and income.

[18]The CASEN surveys are the years 2000, 2003, 2006, 2009, 2013, 2015, 2017, 2020 and 2022. Documentation and access to data sets are available at http://observatorio.ministeriodesarrollosocial.gob.cl/encuesta-casen

Table 1: Descriptive statistics

Variables	N	Mean	SD	Min	Max
Outcome					
Firewood Consumption (m^3/yr)	463	31,368	48,767	310.6	466,238
Firewood Per-Capita (m^3/yr)	463	1.115	0.857	0.0801	5.304
Prices					
Firewood per volume (clp/m^3)	122	40,606	21,986	17,851	116,003
Firewood per heat content(clp/MJ)	122	8.804	4.767	3.871	25.15
Kerosene (clp/MJ)	573	11.48	3.658	4.771	26.01
Natural Gas (clp/MJ)	573	23.61	10.77	8.537	74.10
Electricity (clp/MJ)	585	49.16	14.19	29.15	91.44
Forest cover instruments (km^2)					
Forest Cover (FC)	580	87,478	252,401	1,134	2.128e+06
DW Forest Cover (DW(FC))	580	57,286	11,938	30,397	92,682
Forest Potential (FC + DW(FC))	580	144,763	253,506	33,677	2.184e+06
Covariates					
Population count	582	46,217	65,431	1,465	308,175
Heating Degree Days	399	2,466	852.9	351.7	5,595
Autonomous Income (clp/month)	355	419,840	229,843	106,984	1.693e+06
Imputed Rent (clp/month)	355	109,556	63,847	24,716	281,928
Education (years)	355	8.241	1.693	4.402	12.55
Age (years)	355	53.15	3.215	43.76	64.74
Household members	355	3.321	0.456	2.463	4.275
% Owner	355	0.721	0.0757	0.492	1
% Detached House	355	0.945	0.0465	0.622	1
% Apartment	355	0.0176	0.0408	0	0.347

Notes: Prices are in Chilean pesos (clp) per megajoule (MJ), and income and rent are in Chilean Pesos. Prices are in real terms (base=2018).

IV. Forest cover as an instrument of firewood prices

Marginal costs of supplying firewood are correlated to the (purely exogenous) distance that separates markets from the forest source. This relation is likely to be all the more robust in the case of Chile, where suppliers are atomistic smallholders with low capital investments in their operations (Reyes et al., 2018). At a microeconomic level, accounting for a mix of fixed and variable transaction costs, Key et al. (2000) formalized the relationship between market prices and production decisions. One of the key findings in Key et al. (2000) is that, after assessing costs and expected selling prices, a producer faces a critical distance between point of origin and market destination, which determines market participation (See Appendix E for a graphical analysis of this decision process). In terms of empirical evidence, several studies have shown the relationship between proximity to forest stocks and prices (e.g., Foster and Rosenzweig 2003; Baland et al. 2010; Bošković et al. 2023).[19]

The instrument used in the econometric analysis, forest cover in km^2 by location, incorporates the distance in kilometres from which firewood is collected, a factor directly influencing the marginal costs of the product (i.e., the supply curve as discussed in Berry and Haile 2021). We call our instrument "forest cover potential," similar to the market potential of Harris (1954),

[19] Bošković et al. (2023) study the causal effect of travel time on the behavior of households that collect, buy and sell fuelwood, finding that that "higher travel times to the forest result in increased collection and sales, as well as a reduction in volumes purchased by households" (p. 21).

widely used in the economic geography literature. More specifically, for municipality m and period t we construct a time-lagged measure of forest cover potential ($FCP_{m,t-1}$) that incorporates local forest cover within the boundaries of a given municipality ($FC_{m,t-1}$) and a distance-weighted measure of forest cover beyond those boundaries ($DW(FC_{m,t-1})$). (See subsection A below.) Lagging the instrument reduces the possibility of simultaneous causality. Using local forest stocks exclusively ($FC_{m,t-1}$) would both ignore the influence on local prices of firewood supplies originating beyond municipal boundaries and create spillover effects (i.e., not meet the Stable Unit Treatment Value Assumption – SUTVA – as discussed by Angrist et al. 1996) where firewood prices do not solely depend on forest cover in the same locality. Inter-municipality trade would certainly lead to local forest stock changes influencing prices in neighbouring municipalities.[20]

While the case for relevance of the instrument is strong, several arguments could be raised regarding possible feedbacks from either prices or demand into the current stock of forests, thereby potentially weakening or invalidating altogether the instrument due to reverse causality or joint endogeneity. For example: self-collection could be price-induced and drive forest stocks; or city growth, related to demand, could be driving land conversions. We turn to addressing each of these arguments individually and conclude by arguing that, even if other possible feedback links exists, they would be irrelevant in the Chilean context.

Despite the importance of firewood in Chile's energy matrix, variations in forest area respond mostly to Chile's successful forestry industry and conservation policy and not to firewood incentives.[21] This is in contrast to the archetypal case of tropical forests and less developed countries, where prices drive forests stocks via widespread self-collection and deforestation pressures (e.g., Baland et al. 2010, 2018; Pattanayak et al. 2004). In Chile, property rights are well-defined, and forest poaching for firewood, although it exists in some national reserves, is negligible. Furthermore, there is little self-collection, which could directly connect demand to local forest stocks (Reyes et al., 2018; World Bank, 2020). Approximately 70% of firewood-using households are located in urban zones and what little self-collection that does take place is isolated to southern rural areas.[22] In the econometric specification, in addition to municipal fixed effects, the change in a municipality's rurality is accounted for by an index of population density, average income, housing prices, and family size. Controlling for these variables in combination with fixed-effects would reduce the likelihood of self-collection as a possible reverse-causality channel. Additionally, in the robustness checks section, we discuss the results of removing the local forest stocks from the forest cover instrument (similar to spatially lagging the cover) which, in addition to time-lags, would further dampen any existing self-collection feedback.

With respect to urban growth and forest stocks in Chile, although land-use change pressures towards urbanization were active until the 1990s, during the last three decades such pressures have dissipated. Hosonuma et al. (2012), using national indicators of forest status across 46 countries, find that, with economic development, Chile has entered the fourth stage of forest transition (i.e., post-transition). This stage is characterized by reforestation and natural tree

[20]The magnitude of the bias of violating SUTVA by using only local forest cover is unclear: it would be negligible, if firewood prices are randomly assigned, because spillovers would be unrelated to each municipality's forest cover. It would be positive if higher firewood prices correlate with areas where forest cover is low, which is likely the case, as seen by comparing Figure A.1 and A.2.

[21]Chilean forest product exports in 2024 were over US$5.67 billion, in the form of wood pulp, timber, plywood, MDF boards, and sawn timber (Cabrera and Grosse, 2016).

[22]The overwhelming bulk of firewood consumption derives from market exchanges, with self-collection accounting for a small percentage (Guta et al., 2024; Reyes et al., 2019). According to Reyes et al. (2018), the highest share of self-collection within a municipality, approximately 25%, is found in a heavily forested southern region (*Region de los Ríos*), but the country-wide proportion is much lower.

regeneration, where the main drivers affecting forest cover changes are local agriculture and the forest industry, not population pressures (or changes in firewood demand) or infrastructure.[23] With a population of only 20 million people, forest cover represents 21% of the country's total area, or approximately 16 million hectares of forest stock. Unlike deforestation pressures in some countries, especially in tropical areas, a growing Chilean forest cover has been displacing traditional agriculture. As noted by Cabrera and Grosse (2016), forest area, including native species forests and plantation forests, increased by 18.5% between 1997 and 2014.[24] A shock to firewood demand at any scale is unlikely to be reflected in the forest cover measure.

An argument for possible reverse causality would depend in major part on the scale of the firewood market relative to the size of the forest stock, the relatively small impact of other, non-firewood-market factors driving forest cover (e.g., forestry industry and conservation policy), and the development stage of the country. In the Chilean case, the comparatively small scale of the market relative to the stock, the dominant importance of non-firewood factors in forest variation, and that Chile is in the fourth or "post" stage of the forest transition model, all support the use of the instrument as exogenous to demand. Finally, even if there are other possible feedback mechanisms not considered here, the distribution of forest cover along Chile's unique, narrow, north-south geography assures that they would be overwhelmed by the main source of cross-sectional variability: distance to firewood sources driven by latitude.[25]

A. Constructing the instrument

We model the spatial spillovers using the product of a symmetric spatial matrix of dimension M (the number of municipalities), $\mathbf{W}_M$, where each element is a function of inter-municipal distances. The relative gains in total forest in any year t due to the distance-weighted additions from other municipalities is given by the vector $DW(FC_t)$:

$$DW(FC_t) = \mathbf{W}_M \times FC_t \tag{4}$$

where FC_t is the $M \times 1$ vector of municipal forest covers in year t. Adding the spatial component to the local forest cover produces the Forest Cover Potential in square kilometers for a municipality and year, FCP_t, as follows:

$$FCP_t = FC_t + DW(FC_t) \tag{5}$$

We account for the influence of forests in other municipalities on a locality's firewood prices, allowing that this effect diminishes with distance. This is modelled by setting each off-diagonal element, w_{mj}, of $\mathbf{W}_M$ to be the reciprocal of distances between municipalities. That is, $w_{mj} = 1/distance_{m,j}$, where $distance_{m,j}$ is the distance between centroids of municipalities m and j (and the diagonal set to zero). We assess the importance of alternative spatial dependencies in the robustness check section VI.

[23] Indeed, more recently, Reyes (2021) find that rates of native forest growth – i.e., not the species produced by the industry – significantly exceed rates of extraction, producing net increases in forest cover.

[24] All forest plantations (approximately 2.5 million hectares) are private, as well as 2/3 of native forests (Cabrera and Grosse, 2016).

[25] An additional consideration supporting the instrument's utility is that, as noted in the data section, the Hansen et al. (2013) forest cover dataset derived from satellite measurements dampens cover variation. It does not include repeated harvest/deforestation events in the same pixel location (Garcia and Heilmayr, 2024). And removals from within forested stands that do not lead to a non-forest state are not included in the characterization of forest changes, and longer-lived regrowing cover originating as non-forest during study period is not included in forest gain (Hansen et al., 2013).

The distribution of the natural logs of each component of the forest cover instrument, FCP_{mt}, is shown in Figure 4. Note that the distance-weighted measure (FCP) has the effect of tightening the distribution of the foster-cover instrument by increasing the total cover to a greater degree for those municipalities with lower local forest area (FC). The distribution of the relative gains in total forest due to the distance-weighted additions from other municipalities is given by $DW(FC)$. An interpretation of Figure 4 is that smaller municipalities with relatively low local own cover are, as a practical matter, often in neighborhoods of other municipalities where forests are available for firewood supply.

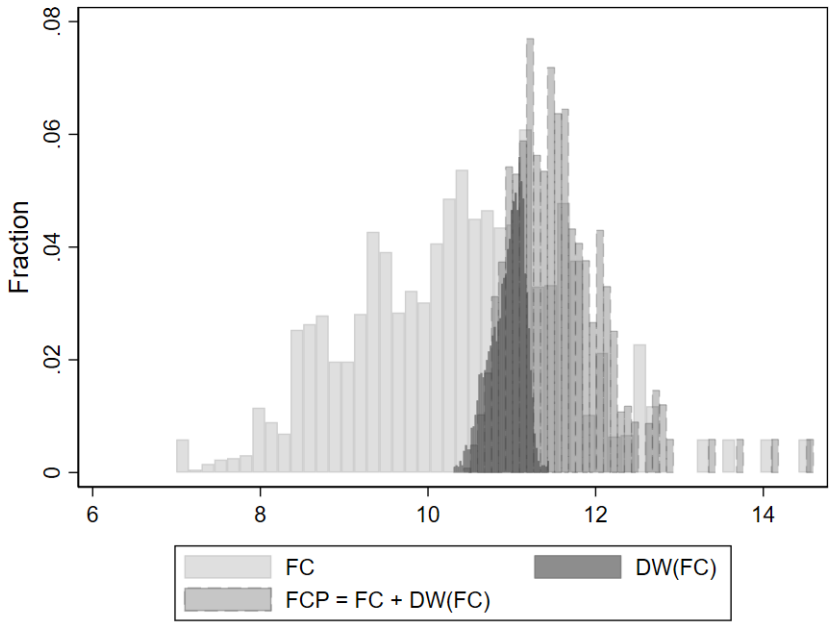


Figure 4: The distribution of municipality forest cover
Note: The histogram shows the distribution of the proportion of municipalities according to the values of the components of Equation 5, where forest cover in km^2 are shown in logarithms.

V. Results

The main focus of our attention is on the sensitivity of firewood consumption to changes in firewood prices. The measures of this sensitivity are the price elasticity estimates of total and per-capita demand aggregated at the municipal level. Of secondary interest are the results relating endogenous prices to the forest cover variable employed in the first stage of the instrumentation strategy. An additional concern regards the robustness of the identification and estimation of the demand elasticity to alternative definitions of the instrument based on the distance between potential firewood sources and each municipality. This section addresses these questions in turn.

A. The price elasticity of firewood demand

Table 2 presents the estimation results of the demand model (equation 1) following the TS2SLS approach. The table displays both stages of the estimation approach using both per-capita consumption and total consumption as the dependent variable of interest. Columns (1) and (3) show the first stage of model in which we regress the natural logarithm of firewood prices on forest cover potential (the identifying instrument) and other controls. The only difference between columns (1) and (3) is the inclusion of the variable Population (in logs) in the set of covariates. The columns (2) and (4) of Table 2 show the results of the demand estimation.

The coefficients of central interest, the price elasticity estimates, vary depending on the use of either per-capita consumption (-0.55) or total consumption (-0.71). In either case, firewood demand is inelastic, an important characteristic when evaluating the welfare effects of policy decisions that might lead to increased firewood prices. For example, a new law regulating solid bio-fuels in Chile requires wood humidity levels less than 25% (Ministry of Energy Chile, 2022). This restriction would require either longer curing periods or more intensive drying processes, both of which would add to production costs. If the policy were to increase firewood prices by 10% (Ministry of Energy Chile, 2023), although total firewood consumption would fall by 7.1%. In per capita terms, firewood expenditures would increase by almost 4.5% in a year.

Table 2: Two-Sample Two-Stage Instrumental Variable Model Results

	Per-Capita Consumption		Total Consumption	
	1^{st} Stage Price (1)	2^{nd} Stage Consumption (2)	1^{st} Stage Price (3)	2^{nd} Stage Consumption (4)
P. Firewood ($\widehat{p}$)		-0.546**		-0.707**
		(0.233)		(0.329)
FCP_{t-1}	-1.046***		-0.744***	
	(0.173)		(0.155)	
Income	-0.184	-0.288***	-0.275	-0.336***
	(0.210)	(0.0974)	(0.178)	(0.125)
Imp. Rent	0.292	0.422***	0.253	0.392***
	(0.197)	(0.123)	(0.166)	(0.133)
HH. members	1.091*	1.011**	0.262	0.837***
	(0.550)	(0.416)	(0.486)	(0.321)
% Owner	-0.523	-0.698***	0.00690	-0.372
	(0.502)	(0.262)	(0.439)	(0.239)
% House	-0.603	0.652	1.082	1.059*
	(0.741)	(0.543)	(0.689)	(0.614)
Price Kerosene	1.185***	0.170	0.974***	-0.812
	(0.213)	(0.965)	(0.183)	(1.001)
Price LPG	-0.404***	-0.782	-0.227**	-1.351*
	(0.123)	(0.682)	(0.108)	(0.687)
Price Electricity	0.991***	1.400***	0.807***	1.006*
	(0.314)	(0.494)	(0.275)	(0.531)
HDD	0.242	0.166**	0.175	0.169**
	(0.183)	(0.0829)	(0.155)	(0.0837)
	(0.741)	(0.543)	(0.689)	(0.614)
Dummy 2010	0.362*	1.351*	0.260	2.008***
	(0.193)	(0.733)	(0.163)	(0.749)
Dummy 2020	0.616***	2.332*	0.426**	3.586***
	(0.203)	(1.343)	(0.175)	(1.372)
Population			0.208***	0.290
			(0.0357)	(0.190)
Observations	120	448	119	448
Adj. R2	0.823	0.913	0.874	0.975
Municipality FE	Yes	Yes	Yes	Yes
First-stage F		36.46		23
N Instruments		1		1

Notes: The table reports the results of both stages of the 2S2SLS model for per-capita firewood consumption (model 1) and total firewood consumption (model 2). All variables are in logs except for variables in percentages. The standard errors are adjusted based on Inoue and Solon (2010). The First Stage uses the Forest Cover Potential (Equation 5) as an instrument of firewood prices. The second stage uses the predicted prices in the demand model. * $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$.

The two estimates of the income elasticity also strongly suggest that firewood is an inferior good, with households replacing firewood with other heating sources as their incomes increase. Our

results show that for a 1% increase in household income, firewood demand falls by approximately 0.3%, supporting the prediction that firewood demand will drop with Chile's economic growth. As an illustration, a 3% growth in average incomes for five years would lead to a 5.1% decrease in firewood consumption.

Another important result is the effect of the prices of potential substitute fuels. While kerosene and electricity appear to be substitutes, only the estimated coefficient associated with electricity is statistically different from zero for both the per-capita and total specifications. Electricity prices vary to a greater degree than kerosene and LPG prices, as Figure 2 shows. We note that the prices of substitute heating sources are at the regional level, suppressing variability between municipalities. Moreover, kerosene and LPG prices correlate with prices of oil and gasoline, the imports of which are regulated by a state agency (see the similar trajectory of both prices in Figure 2), leading to the loss of variability between regions. The influence of the prices of these two heating alternatives is likely absorbed by year fixed-effects. We show this relationship in Table A.1 columns (4) and (8) in the Appendix, where we estimate the model without year fixed-effects. The table shows that, after eliminating time fixed-effects, the main substitute is kerosene, the fuel used in small portable stoves.

In terms of cross-price elasticities, electricity is ranked second as a substitute fuel. The reader should note, however, that LPG is cheaper per MJ of energy content. The reader might consider that electricity and kerosene rank higher as substitutes than LPG because they require less capital costs compared to LPG stoves.[26]

B. The effect of forest cover on prices - First Stage relationship

In the first stage regression, two important elements stand out. First, forest cover potential (forest cover plus inverse distance weighted neighbouring forest cover) significantly affects firewood prices. Controlling for factors such as HDD, population, and municipality fixed effects, there is a strong negative correlation between prices and forests. The instrumental variable is relevant, with an F-statistic between 23 and 36, surpassing the conventional standard threshold of 10 (Murray, 2006). The second significant finding is the magnitude of the impact of forest cover on firewood prices. The estimated elasticity falls between -0.75 and -1, indicating that a 1% loss of forest cover leads to about a 1% increase in the marginal costs of firewood supply.

We examine the impact of the two components of forest cover potential (Equation 5) in Panel B of Table 3, specifically in columns 2-3 and 5-6, for the models using per-capita and total consumption in the second stage, respectively. The individual effects on Forest Cover Potential, $FCP_{m,t-1}$, from local ($FC_{m,t-1}$) and inverse distance-weighted forest cover ($DW(FC)_{t-1}$) (columns 2 and 5) shows that the coefficient of $DW(FC)_{m,t-1}$ captures all the variation in forest cover. This aligns with our assumption of a strong spillover effect, indicating a significant correlation between forested areas, as evident in Figure 5. Furthermore, including only local forest cover ($FC_{m,t-1}$) in the model (columns 3 and 6) results in a significant and negative effect, albeit weaker compared to $FCP_{m,t-1}$, consistent with the assumption of spatial spillover effects. These variations in the instrumental variable have qualitatively equivalent effects in the models for per-capita and total consumption. The sensitivity of the First Stage results to specific measure of neighbouring forest cover (i.e., the inverse weighting algorithm) is discussed in further detail in Section VI-A.

[26]The capital costs of heating appliances show a wide price variation. especially in the case of electric heaters versus LPG stoves. See for example DIPRES, 2021 pp.2

Table 3: TS2SLS Model - Stages and the Effect of Instruments

Panel A: Second Stage TS2SLS Model

	(1)	(2)	(3)	(4)	(5)	(6)
	Dep. Var: per-capita Consumption			*Dep. Var: Consumption*		
P. Firewood ($\widehat{p}$)	-0.546**	-0.713**	-0.456	-0.707**	-0.586*	-0.652*
	(0.233)	(0.297)	(0.335)	(0.329)	(0.309)	(0.388)

Panel B: First Stage TS2SLS Model

	Dep. Var: Price Firewood					
FCP_{t-1}	-1.046***			-0.744***		
	(0.173)			(0.155)		
FC_{t-1}		0.0303	-0.258***		-0.0332	-0.225***
		(0.0833)	(0.0825)		(0.0708)	(0.0649)
$DW(FC)_{t-1}$		-2.904***			-2.006***	
		(0.477)			(0.428)	

Panel C: Reduced Form Model (RF)

	Dep. Var: per-capita Consumption			*Dep. Var: Consumption*		
FCP_{t-1}	0.571***			0.526***		
	(0.179)			(0.164)		
FC_{t-1}		-0.0205	0.118*		0.0974	0.147**
		(0.0778)	(0.0653)		(0.0742)	(0.0598)
$DW(FC)_{t-1}$		2.066***			0.719	
		(0.655)			(0.639)	
Municicpality FE	✓	✓	✓	✓	✓	✓
Controls	✓	✓	✓	✓	✓	✓
F-stat IV	36.46	25.63	9.799	23.00	18.62	12.06
Obs 2^{nd} St & RF	448	448	448	448	448	448
Obs 1^{st} St	120	120	120	119	119	119
Adj-R^2 2^{nd} Stage	0.913	0.914	0.911	0.975	0.974	0.974
Adj-R^2 1^{st} Stage	0.823	0.842	0.771	0.874	0.888	0.859
Adj-R^2 RF	0.913	0.914	0.911	0.975	0.974	0.974

Notes: Panel A and B show the two stages of the TS2SLS model based on three different sets of instruments (Panel B). The instruments are as in Equation 5: $FCP_{m,t-1} = FC_{m,t-1} + DW(FC)_{m,t-1}$ with $DW(FC)_{m,t-1}$ estimated over all distances in the weighting matrix. Price and forest cover are in natural logs. The standard errors in panel A are adjusted based on Inoue and Solon (2010) correction. * $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$

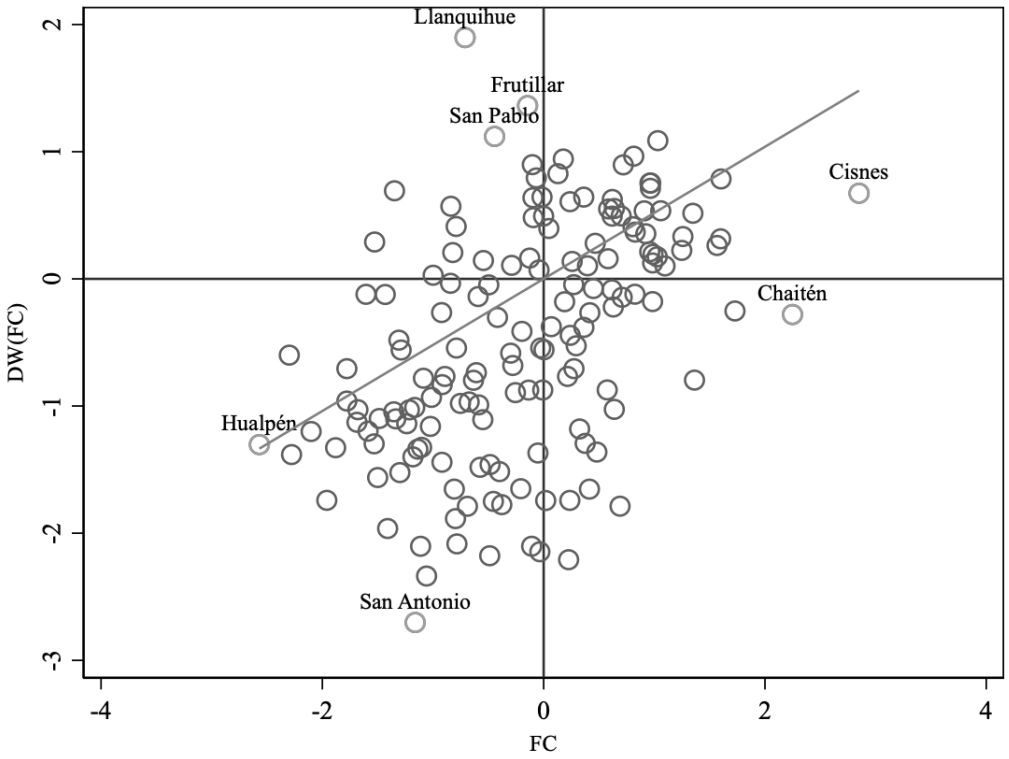


Figure 5: Relationship between local forest cover FC and distance-weight cover $DW(FC)$.
Notes: The scatter plot between the normalized values of $\ln FC$ and $\ln DW(FC)$ in 2020 shows the relationship between $DW(FC)$ and FC. The trend line, with slope 0.52 ($p - value < 0.01$) is similar to the Moran's I index (Anselin, 1995), except the variables are not normalized. In Appendix C Figure A.5, we illustrate the spatial autocorrelation in the system of forest cover and firewood consumption using Moran's I index.

C. The effect of forest cover on firewood consumption - the reduced form relationship

We estimate the direct effect of the instrument, lagged forest cover potential ($\ln FCP^d_{m,t-1}$) on firewood consumption as expressed in Equation 6 below. This reduced form includes the explanatory variables of the original demand model (Equation 1), except for firewood prices, which has been replaced by $\ln FCP^d_{m,t-1}$.

$$\ln Q^d_{mt} = \alpha + \rho \times \ln FCP^d_{m,t-1} + \theta' \mathbf{X}^d_{mt} + \gamma_t + \gamma_m + \epsilon_{mt} \tag{6}$$

We present the results of this model in Panel C of Table 3. The reduced form relationship provides important insights in the two-sample context, because it allows us to directly test the effect of the instrument on the outcome variable in the demand sample. We cannot directly test the relationship between the endogenous explanatory variable (prices) in the demand equation. It is only observed in a different sample. If prices have a negative effect on the demand for firewood, we should observe a proportional effect in the opposite direction in the reduced form (Angrist and Pischke, 2009). Note that in 3 the reduced form estimates are consistent with the instrumental variable approach in Panels A and B. In Table 3-C, columns (1)-(3) show the effect of the different components of forest cover potential on the demand for firewood (per capita). We find a positive and significant impact using the direct effect of total forest cover that corresponds to the estimated coefficients in Panels A and B. (For example, from column (1), $-0.546 \times -1.046 = 0.571$.)

VI. Robustness Checks

A. Sensitivity to the estimation of Forest Cover Potential

As shown in the previous Section V, the results confirm that forest cover has spatial spillover effects on local prices. This relationship is captured by adding to each municipality's local forest stock, the forest cover of surrounding municipalities inversely weighted by distance. Our preferred model, shown in Table 2 and columns (1) and (4) of Table 3, uses for a municipality's total forest cover potential a weight sum of all the forest cover in the country, measured by $DW(FC)$. We explore the degree to which prices are affected by distant forests by restricting the distance allowed to enter the $DW(FC_{mt})$ measure. We do so by changing the elements of the matrix $\mathbf{W}_M$ from the reciprocal of the distances between municipalities to the reciprocal of a value which we then vary between zero and the maximum distance possible. Specifically, $\{distance_{m,j}\} \in [0, distance_{max}]$, where $distance_{max}$ is the maximum distance allowed in the matrix between centroids of municipality m and j. Figure 6 shows, in the context of the per-capita demand model, the coefficients associated with the variables Forest Cover Potential ($\ln FCP_{m,t-1}$) and Price ($\ln P$) from the first and second steps of the TS2SLS regression. Each estimate corresponds to different measurements of $\ln FCP_{m,t-1}$ by varying $DW(FC)_{m,t-1}$ with increasing distance, from 100 km to 2,500 km. The lower panel in Figure 6 shows the F-stat associated with the instrument. The price sensitivity to forest cover (an elasticity estimated in the first stage) ranges from -0.6 to -1, as distance increases up to approximately 1,300 kilometres. Beyond this distance, the effect of additional forest does not influence the effect on prices. Moreover, the estimated coefficient of per-capita consumption does not vary significantly to changes in the instrument. The coefficient is consistently inelastic between -0.48 ($distance_{max} = 100$) and approximately -0.55 ($distance_{max} > 200$).

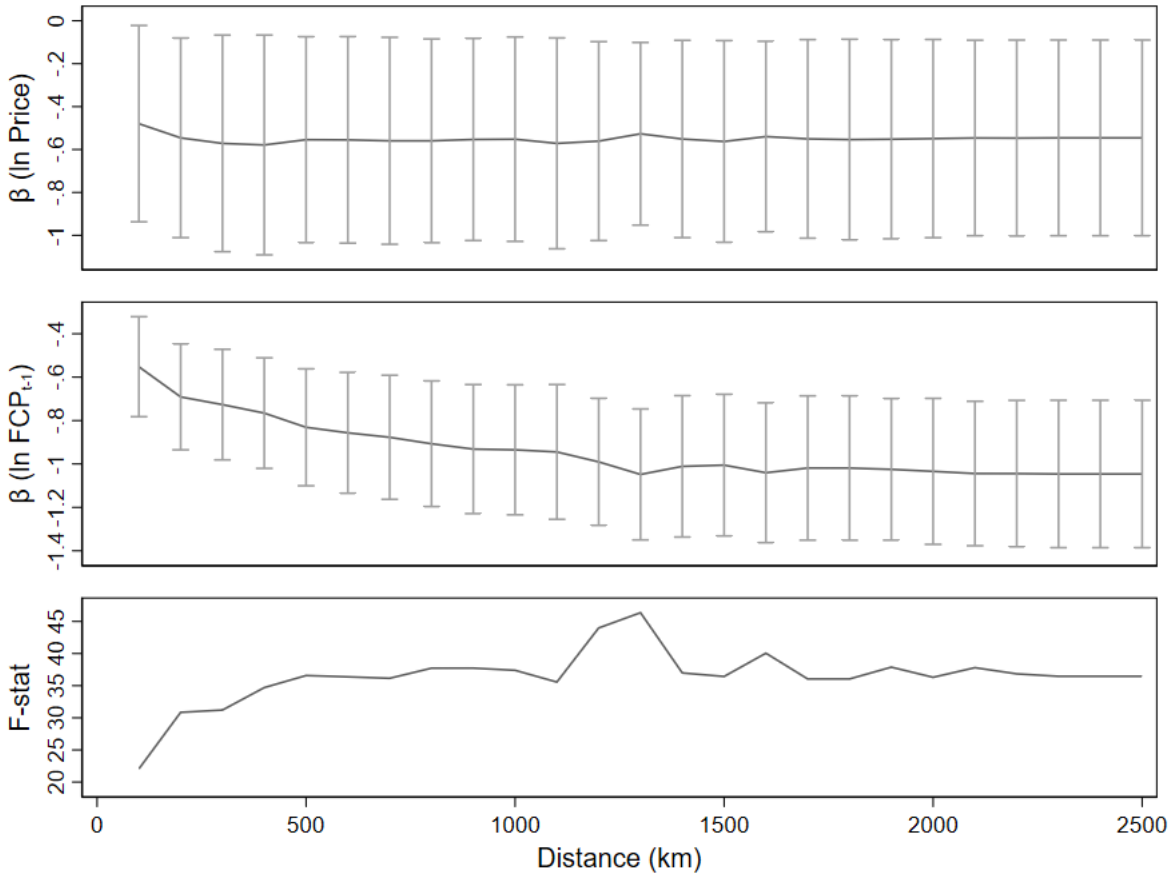


Figure 6: The Effect of distance restrictions in $\mathbf{W}_M$ on the instrument and 2S2SLS estimation of the per-capita consumption model

Notes: We restrict $\mathbf{W}_M$ to the distances in the x-axis, then use the instrument in our estimation. The top and middle panels show the estimated coefficients for Firewood Prices (second stage) and Forest Cover Potential (first stage), respectively. The bottom panel shows the F-statistic of the $H_0 : FCP_{mt} = 0$

B. Sensitivity of estimates to the exclusion of covariates

We evaluate the sensitivity of estimates to the exclusion of controls in the estimation for per-capita and total consumption. (Table A.1 in the Appendix shows the effect of covariates on the estimated price effect using the TS2SLS approach). This exercise demonstrates that the estimated value of the price elasticity of demand is dependent on the inclusion of other relevant explanatory variable, such as income (and other socio-demographic characteristics) and substitute prices. Only when controlling for these characteristics does the price elasticity of firewood demand gain statistical significance and the expected direction of its effect. Our results also show how the conditional relevance of the instrument interacts with covariates and affects its predictive power. More interestingly, the first stage instrumental variable's F-statistic changes when covariates are included and reaches its highest value when controlling for socio-demographic and substitute price covariates.[27]

[27]We also tested the same models of Table A.1 using provincial and regional fixed-effects in separate estimations. We find, consistent with our expectations, that the unobserved heterogeneity lies at the municipality level and that only when using municipality fixed-effects does one find statistically significant effect of prices, income, and other relevant variables. These results are available upon request.

C. *Spatially lagged forest cover potential*

Our instrument $FCP_{m,t-1}$ in Equation 5 has an own-location effect (or a direct effect) from forest cover within the boundaries of the municipality, and a spatial spillover effect (or indirect effect) from the forest cover of other municipalities. We test the effect of eliminating the direct effect of forest cover potential on municipal consumption. By doing so, we explore the extent of local geographical endogeneity, perhaps induced by significant changes in self-collection associated with a local demand shock. The question is whether we can identify signals of reverse causality that could bias the relationship between the instrument and consumption.

We start by simply eliminating local cover, $FC_{m,t-1}$, from the instrument construction in Equation 5, introducing only the effect of the inverse-distance weighted measure of forest cover (outside municipal boundaries), $DW(FC)_{m,t-1}$. Additionally, we re-estimate the indirect effects, $DW(FC)_{m,t-1}$, with a buffer that restricts the weighting matrix $\mathbf{W}_M$ to a minimum distance from municipal boundaries. The results show a negative relationship between the restricted instrument, $DW(FC)_{m,t-1}$, and prices, yielding an estimated price elasticity of consumption consistent with the results of Table 3, models 2 and 5. These results, not reported here but available upon request, highlight the higher relative influence of $DW(FC)_{m,t-1}$, compared with the direct effect of local stocks, $(FC_{m,t-1})$. The effect on the elasticity estimate persists with a similar sign and magnitude when we increase the distance buffer to up to 100 km from the municipality boundaries. Beyond 100 km, the results lose statistical significance and sign, consistent with a decrease in the correlation between local consumption and distant forest stock levels.

VII. Discussion & Conclusions

This study is the first to apply a two-sample instrumental variables (IV) strategy to firewood markets, leveraging satellite-derived forest cover as an instrument for prices. Not only is the TS2SLS methodology policy relevant for Chile and other countries in which biomass fuel markets are significant, it is also applicable in other contexts. The two-sample approach is useful in informal markets where prices usually go unrecorded and demand relationships are therefore difficult to estimate, such as farmers' markets and grey market taxi and labor services. Our results demonstrate that spatial and temporal variation in satellite data can overcome the absence of direct observation of prices matched to biomass fuel quantities, providing an estimate of the price elasticities for this informally exchanged good. Specifically, we use a large-scale, geographically comprehensive dataset of firewood consumption, prices, and socio-demographic and climatic characteristics to characterize the demand for firewood in Chile.

The results support our hypothesis that firewood is an inferior good with respect to income and inelastic with respect to price, reflecting its status as a "necessity" product that makes it challenging to address through public policy. But importantly the results are significant for questions of public health. There is a direct relationship between the use of firewood and air pollution, especially $PM_{2.5}$ levels. As shown in Huneeus et al. (2020), 94% of the $PM_{2.5}$ emissions in Chile are due to residential heating and cooking with firewood (pp. 20), which is particularly the case in the center-south of the country, as shown in Figure A.3 in the Appendix. The exposure to dangerously high $PM_{2.5}$ concentrations elevate mortality risks, particularly among the elderly (Busch et al., 2024; Huneeus et al., 2020). Air pollution almost certainly increases hospitalization rates, as shown by, for example, Filippini et al. (2019), Tian et al. (2024), and Tomaskova et al. (2022). An indication of the costs of firewood use in Chile is the geographic pattern of hospital admissions due to respiratory disease. Chilean municipal-level data[28] on total hospital admissions for all respiratory causes shows a clear spatial correlation

[28] Available at https://deis.minsal.cl/#datosabiertos

between high firewood usage (producing high air pollution levels) and the level of hospital admissions of the elderly (80 years and older) and minors (between 1 and 9 years). (See Figures A.1 and A.4 for a visual representation of the data on admissions per 1000 residents for the elderly and minors from 2020.)

In Table 4, we estimate the effect of a 10% increase in firewood prices on the consumption levels observed in the municipal sample in 2020, using the demand elasticity estimated in Table 2 and the regional conversion factors of $PM_{2.5}$ estimated in Alamos et al. (2022).[29] The price increase yields a decrease in the amount of firewood consumed of 285,000 tons, resulting in an equivalent reduction of 4,500 tons of $PM_{2.5}$. In more concrete terms, the reduction in $PM_{2.5}$ pollution would be the equivalent of the yearly emissions of a small city of approximately 200,000 residents in the central valley of Chile (e.g. Los Angeles as estimated by Huneeus et al. 2020, p. 21). These results inform energy transition policies and environmental policy. To the degree that the relative prices of fossil-fuel-based products would rise as the government aims at a "net-zero" energy profile for the country, firewood demand is likely to be incentivized. In promoting an energy transition, the government will likely have to reduce the relative cost of electricity. Reconciling both of the objectives net zero and energy transition would require encouraging energy sources that are neither fossil fuels nor wood, such as solar or nuclear.

Income has had a notably weak effect on incentives to move away from firewood in Chile, as shown in Fercovic et al. (2024). While the price elasticity of demand is less than one, an increase in the price of firewood remains a reasonable mechanism to reduce its use and its associated pollution externalities and health effects. The price of wood remains much cheaper than alternative fuels. In terms of megajoules, on average firewood is between 3 and 8 times less expensive than kerosene and electricity.[30] If changes in firewood prices come from regulation that lessens moisture context of the product, the benefits would be twofold: reduced pollution from an energy source with improved combustion, and a reduction in use driven by higher consumer costs. We have presented the gains to pollution reduction only from the second effect, from reducing quantity demanded as prices rise. By including the first effect of lower moisture content, the total reductions in air pollution could be much larger.

Finally, the results presented here raise concerns about potential unintended consequences of health and environmental policies where there is a concrete risk of increasing energy poverty for a large proportion of the population with precarious living standards, as pointed out by Schueftan and González (2013); Reyes et al. (2019). Forest conservation policies also influence firewood markets and household welfare. To promote the expansion of protected areas is to promote indirectly higher energy prices in many communities. This is especially notable in regions where a significant share of the territory is already protected, as in Chile's southern regions and Patagonia. A significant amount of the firewood comes from forests of native species, which are the focus of forest conservation (Reyes et al., 2021); environmental NGOs and other institutions are lobbying to expand national parks (Guala et al., 2023; Louder and Bosak, 2019). In short, policy makers would face the further challenge of balancing ecological preservation and the social costs of restricting the availability of an important energy source.

[29]Both Alamos et al. (2022) and Huneeus et al. (2020) acknowledge the high uncertainty of the estimated emission factors due to challenges in quantifying firewood consumption, its humidity level, the efficiency of combustion of appliances, and conditions in its operation.

[30]The price differential in comparison with wood pellets is another matter. As a forest industry byproduct, wood pellets have only recently entered into competition as an alternative for home heating in some zones during the last decade. There is limited data on its use. In some southern towns, however, the penetration of wood pellets in the market is significant (for example, approximately 27% of homes in Coyhaique use the fuel exclusively or in combination with firewood and electricity (Reyes et al., 2021).

Table 4: The direct effect of a 10% increase in firewood prices on firewood consumption and $PM_{2.5}$ Emissions

	Population	Consumption (Q in Tons)	Δ Q [CI]	Δ $PM2.5$ in tons [CI]
Maule	1,131,939	383,962.0	-27,151.0 [-51,997 , -2,304.9]	-374.7 [-717.6 , -31.8]
Ñuble	511,551	275,459.9	-19,478.5 [-37,303.4 , -1,653.6]	-293.5 [-562.2 , -24.9]
Biobío	1,663,696	815,848.2	-57,690.8 [-110,484 , -4,897.5]	-869.4 [-1,665 , -73.8]
Araucanía	988,247	942,927.2	-66,676.9 [-127,693.4 , -5,660.4]	-1,186.8 [-2,272.9 , -100.8]
Los Lagos	891,440	945,862.8	-66,884.5 [-128,090.9 , -5,678]	-1,048.7 [-2,008.5 , -89.0]
Los Ríos	405,835	458,941.1	-32,452.9 [-62,150.9 , -2,755.0]	-514.7 [-985.7 , -43.7]
Aysén	107,297	217,138.3	-15,354.4 [-29,405.4 , -1,303.5]	-241.7 [-462.8 , -20.5]
Total	5,700,005	4,040,139.6	-285,689 [-547,125 , -24,252.9]	-4,529.6 [-8,674.7 , -384.5]

Notes: Regions organized from north (top) to south (bottom). The estimated reduction in emission levels from the regional-level change in firewood use is based on the aggregated municipality consumption in tons in 2020. The change in consumption comes from the coefficient on firewood prices from Table 2, $\beta = -0.707$ (0.33). To estimate emission levels, we use the regional conversion factors from Alamos et al. (2022), which estimates the aggregated emission factors (g/kg) at the regional level for each pollutant for firewood consumption in the residential sector, considering the distribution of technologies and humidity conditions of fuelwood for each region. The weighted conversion factor for grams of $PM_{2.5}$ per kilogram of firewood is 15.86 for the regions considered. We consider an average of 600 kg of firewood in a cubic meter based on INFOR, 2025.

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A. Online Appendix

A. The Geographic Distribution of the Data

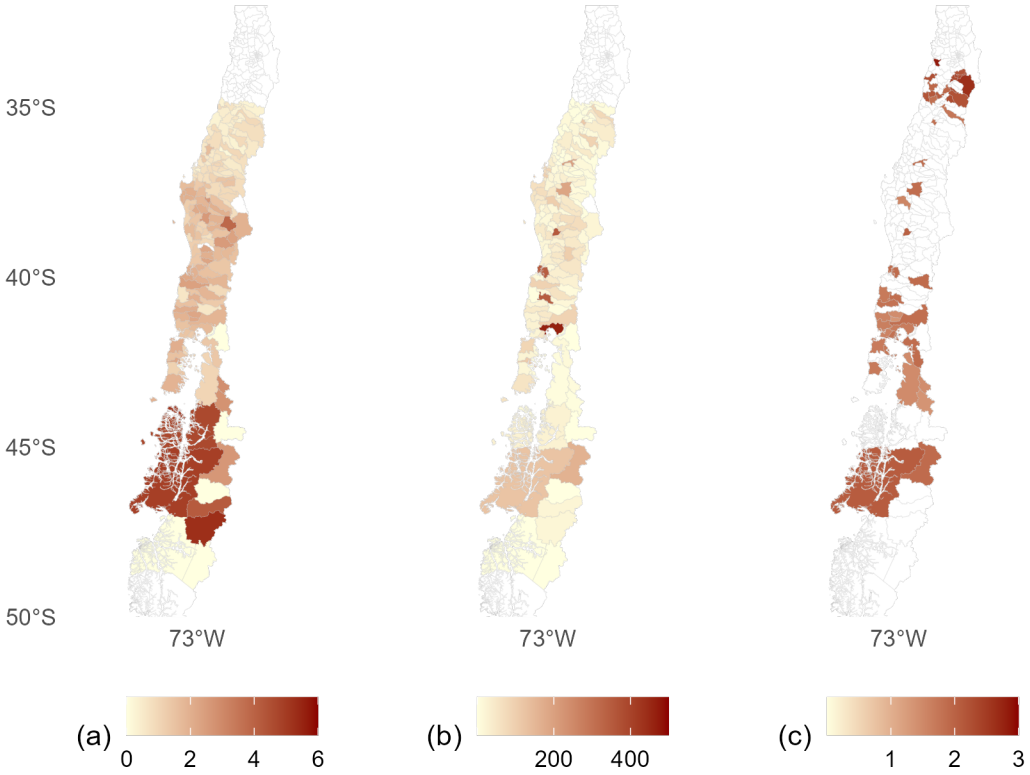


Figure A.1: Regional distribution of selected variables in 2020 at the municipal level. **Panel (a)** firewood consumption (m^3 per capita). **Panel (b)** Total firewood consumption (in 1000 m^3). **Panel (c)** Raw average of available firewood prices ($ln(CLP/MJ)$).

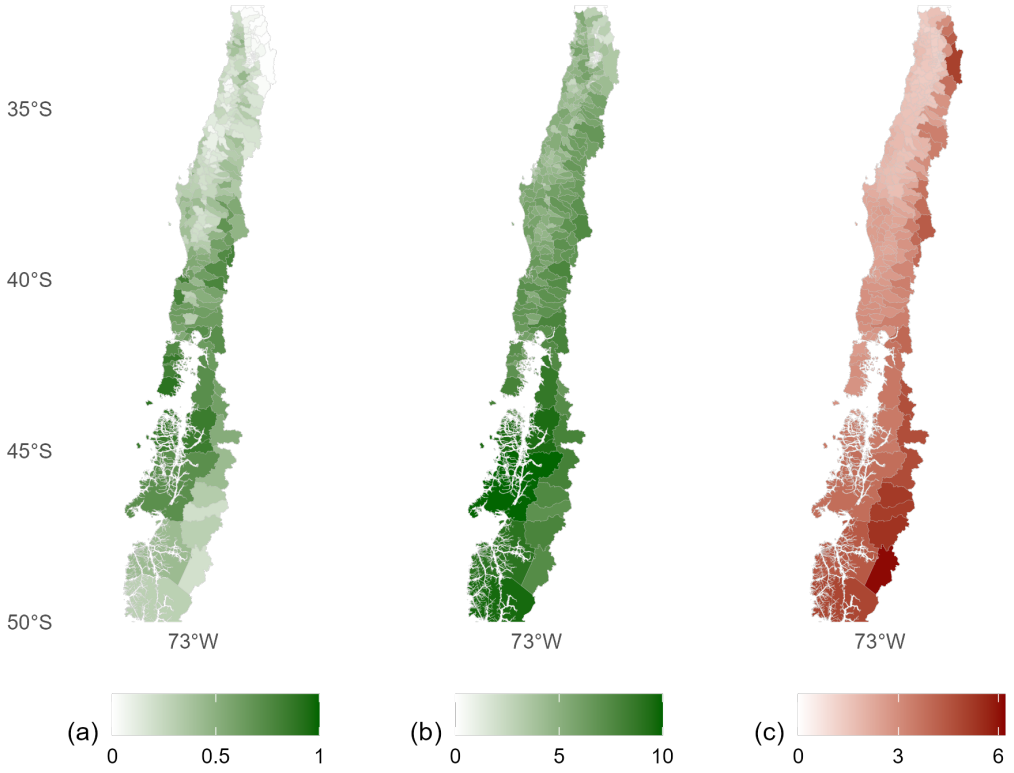


Figure A.2: Regional distribution of selected variables in 2020 at the municipal level. **Panel (a)** Forest Density (% of total area of municipality). **Panel (b)** Forest Cover (in $ln(km^2)$). **Panel (c)** Heating Degree Days (in 1000 °C).

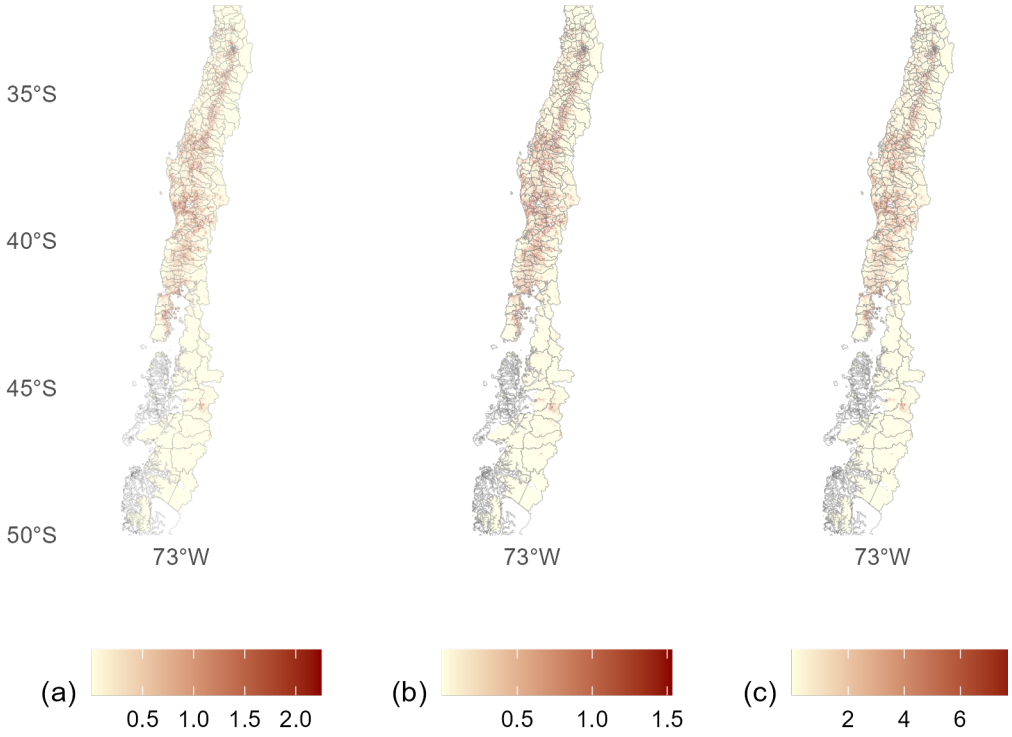


Figure A.3: Regional distribution of emission levels from residential firewood consumption (IPCC code category 1A4b) in tons in 2020, from the High-resolution inventory of atmospheric emissions of Chile (IMENA) developed by Alamos et al. (2022). **Panel (a)** $PM_{2.5}$ (tons). **Panel (b)** PM_{10} (tons). **Panel (c)** CO (tons).

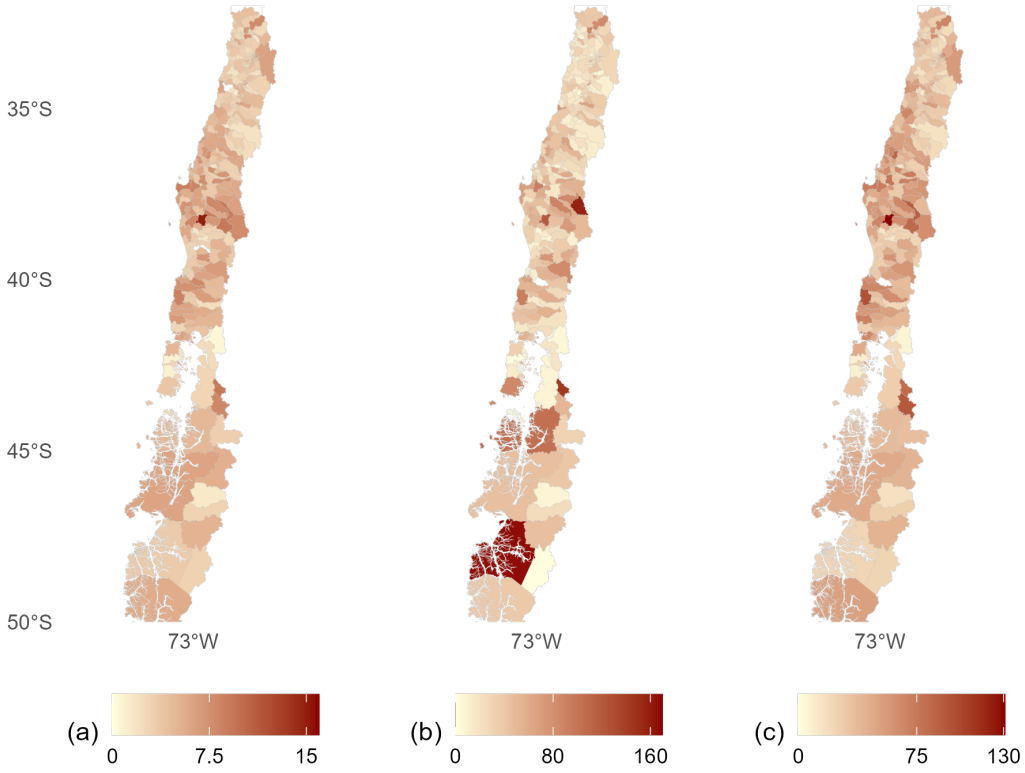


Figure A.4: Regional distribution of hospital admissions from diseases of the respiratory system (CIE10 categories J00-J99) in 2020, measured as admissions per thousand inhabitants of the same age category. **Panel (a)** All admissions. **Panel (b)** Ages 80 and older. **Panel (c)** Ages 1-9. Data from Chile's Health Ministry (DEIS, 2024)

B. *Other Regression results*

Table A.1: Second Stage TS2SLS Model - Effect of Covariates

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
	Dep. Var: per-capita Consumption				*Dep. Var: Consumption*			
P. Firewood	0.785**	-0.235	-0.546**	-0.380**	0.873*	-0.285	-0.707**	-0.375*
	(0.325)	(0.190)	(0.233)	(0.169)	(0.471)	(0.270)	(0.329)	(0.225)
Income		-0.226***	-0.288***	-0.307***		-0.217**	-0.336***	-0.268**
		(0.0722)	(0.0974)	(0.0957)		(0.0903)	(0.125)	(0.111)
Imp. Rent		0.383***	0.422***	0.450***		0.337***	0.392***	0.385***
		(0.0929)	(0.123)	(0.125)		(0.112)	(0.133)	(0.121)
HH. members		0.648*	1.011**	0.754**		0.597**	0.837***	0.581**
		(0.383)	(0.416)	(0.326)		(0.233)	(0.321)	(0.237)
% Owner		-0.583**	-0.698***	-0.589***		-0.372**	-0.372	-0.323*
		(0.233)	(0.262)	(0.221)		(0.182)	(0.239)	(0.193)
% House		0.666	0.652	0.731		0.557	1.059*	0.759
		(0.483)	(0.543)	(0.482)		(0.496)	(0.614)	(0.470)
P. Kerosene			0.170	1.527***			-0.812	1.180***
			(0.965)	(0.446)			(1.001)	(0.433)
P. LPG			-0.782	-0.0143			-1.351*	0.0660
			(0.682)	(0.189)			(0.687)	(0.165)
P. Electricity			1.400***	1.164***			1.006*	0.718*
			(0.494)	(0.407)			(0.531)	(0.395)
HDD	-0.144	0.0241	0.166**	0.161**	0.0140	0.0369	0.169**	0.132*
	(0.109)	(0.0504)	(0.0829)	(0.0749)	(0.0823)	(0.0472)	(0.0837)	(0.0676)
Dummy 2010	-0.102	0.303***	1.351*		0.0624	0.354***	2.008***	
	(0.157)	(0.0964)	(0.733)		(0.129)	(0.0912)	(0.749)	
Dummy 2020	-0.159	0.458**	2.332*		0.0773	0.565***	3.586***	
	(0.268)	(0.181)	(1.343)		(0.272)	(0.162)	(1.372)	
Population					-0.662***	0.239	0.290	0.312**
					(0.199)	(0.146)	(0.190)	(0.153)
Municipality FE	✓	✓	✓	✓	✓	✓	✓	✓
Obs 2nd Stage	463	460	448	448	463	460	448	448
Obs 1st Stage	121	120	120	120	119	119	119	119
Adj-R2	0.829	0.911	0.913	0.912	0.961	0.974	0.975	0.973
F-stat IV	27.21	17.75	36.46	40.12	13.20	10.44	23.00	23.74

Notes: All variables are in logs, except for the percentages. The standard errors are adjusted based on Inoue and Solon (2010) correction. The First Stage uses one year lagged Forest Cover Potential ($FCP_{m,t-1}$). * $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$

C. Spatial Relationship

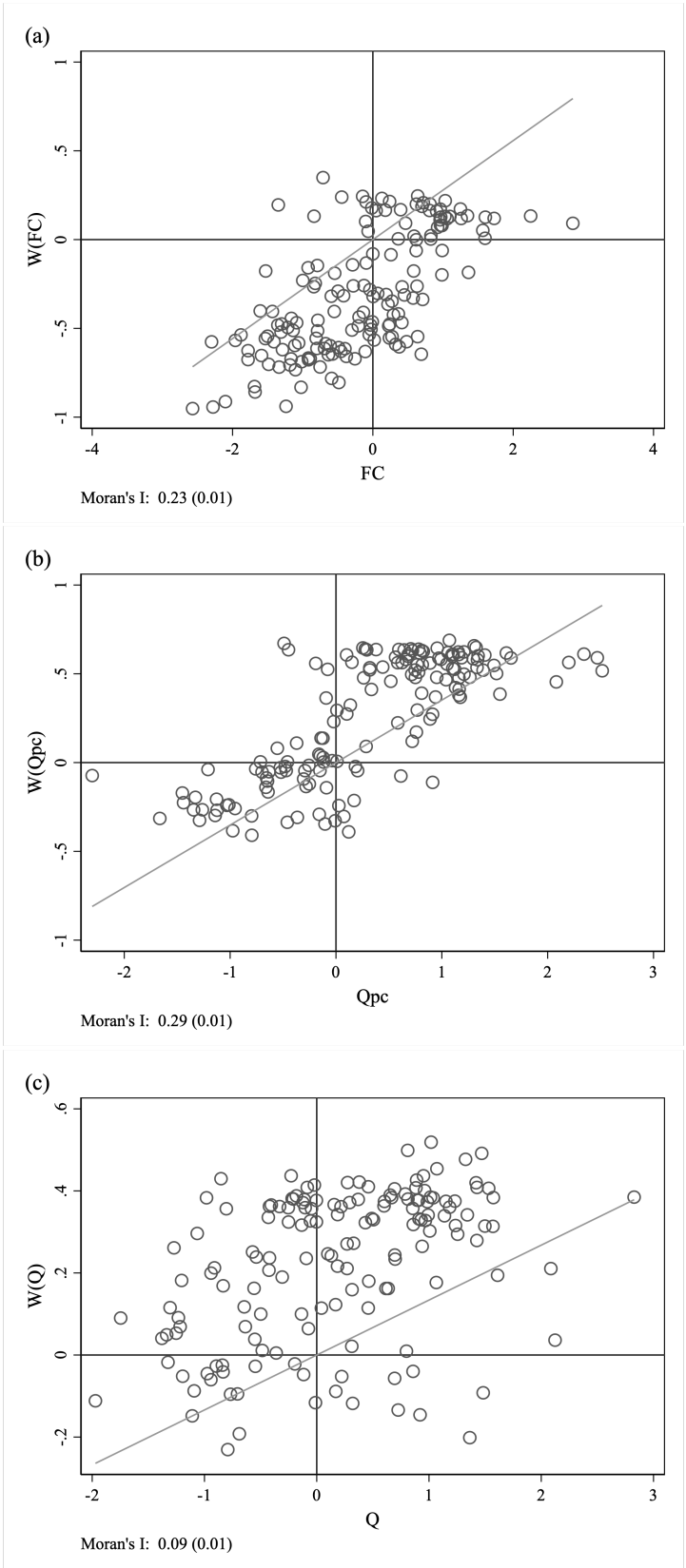


Figure A.5: Moran's Index using the standardized values of the logarithms of forest cover (FC) in panel (a), per-capita firewood consumption (Qpc) in panel (b), and total consumption (Q) in panel (c)

Note: The Moran's I statistic is estimated using the 154 municipalities in the sample in 2020, using the inverse distance matrix in equation 4 with power decay parameter 1 and all distances between the centroids of the municipalities in the sample. The average distance between centroids is 325.3 kms (range: 6-1,472 kms)

D. Price Data

This section describes the methodology for obtaining firewood prices at the municipality level. We start by describing the main sources of information used to build the dataset, which has an online system to publish the available data.

Forest Institute (INFOR): publishes a quarterly price report for forest products. Firewood prices are included for a selection of Provinces. Table A.2 shows the location of the producers surveyed by INFOR a year. We assigned the provincial price to the municipality capital of the province when 50% or more of the surveyed producers were located in the municipality. As shown in Table A.2, within provinces, the majority of sampled producers are located in one or two municipalities. Even in the cases where producers are located in two municipalities, the majority are sampled from just one. We decided to remove five observations where the sampling was balanced between two municipalities.

National Consumer Advocacy Agency (SERNAC): Since 2010, publishes a monthly average firewood price report by species and units for the cities of Temuco, Talca, and Osorno. The report includes details about the producers, including the humidity level of its product (whether they sell certified dry firewood or not), the species and the units.

Other than the previous sources, we also accessed several studies that collected municipality price data.

- *Ministerio del Medio Ambiente de Chile (2012).* Comparative study about the supply of firewood in the cities of Rancagua, Curico, Talca and Osorno. They surveyed firewood producers in terms of units, product quality and prices (Ministry of Environment Chile, 2012).
- *Servicio Nacional del Consumidor, SERNAC (2018).* This study surveys 43 firewood producers in 16 municipalities in the *O'Higgins* (sixth) Region. It includes a general description of the regional firewood market, with an account of municipality price averages and characteristics of the production in 2018 (SERNAC, 2018).
- *Corporacion Nacional Forestal, CONAF (2012).* Study about the firewood market in the Province of *Llanquihue*, using information from the records of public bids for government service offices. The study reports information about firewood prices and demand in eight municipalities in the province in 2012.
- *Corporacion Nacional Forestal, CONAF (2012b).* Study about the firewood market in the Province of *Palena*, using information from the records of public bids for government service offices. The study reports information about firewood prices and demand in four municipalities in the province in 2012.

D.1. Annual average Prices by Municipality

The annual average firewood prices are estimated based on two levels of aggregation: the firewood species offered in each region and the different units of reporting. In other words, we look into each geography's time series and observe how well the species are represented over time and whether the units can be expressed in price per cubic meter (or kilograms). Next, we describe this process.

Units. The reported units vary from *pesos* per kilogram, bags of different weights, and different measurements of cubic meters (stereo, meter *ruma*, and other fractions of cubic meter). We transform the units in either *pesos* per kilogram or *pesos* per cubic meter.

The following units were transformed to *pesos* per kilogram; $/bag in units of 2, 2.5, 5, 12, 15, 20, 25 and 40 kilograms. Nevertheless, bags of 5 kg or less have a disproportionately high price (more than 60% higher than the next alternative (12 kg) in comparable units), so they were left out of the sample. For the rest of the sample, we obtained the price per kilogram by dividing the price per bag by the quantity in kilograms.

To obtain prices per cubic meter, we transformed the following units observed in the sample: $/1.1m3, $/1.1ml, $/vara, 1.1 $/ton, $/store. We transformed units based on the following equivalence:

- 1 cubic meter (m3) = 1 stere = 1 ml = 4 varas = 1.6 mr

Species: We first grouped species into five categories: Sweet Acacia, eucalyptus, pine and native species:

- Sweet Acacia: *Vachellia farnesiana* and *Acacio Melanoxylon*
- Eucalyptus: *Eucalyptus Nitens* and *Eucalyptus Globulus* (Eucalyptus)
- Pine: *Pseudotsuga menziesii* (Douglas fir) and *Pinus radiata*
- Native species: *Nothofagus obliqua* (hualle), Nothofagus dombeyi (Coihue), *Nothofagus pumilio* (Lenga), *Nothofagus antarctica* (Ñirre), *Eucryphia cordifolia* (Ulmo), *Weinmannia trichosperma* (tineo), *Tepualia stipularis* (Tepu), *Amomyrtus luma* (Luma), *Drimys winteri* (Canelo), *Lomatia hirsuta* (Radal), *Luma apiculata* (Arrayan), *Podocarpus salignus* (Mañio)
- Fruit Trees: Species catalogued directly as "fruit trees" in the database.
- Other: Species catalogued directly as "other species" trees in the database.

After aggregating units to prices per cubic meter or kilogram for each of the broad five species categories, we aggregated the data to yearly averages by unit and species. Then, we compare the time series of each species in a given geography. Figure A.6 exemplifies this for the municipalities of Temuco (Cautin), Aysen, Osorno and Valdivia.

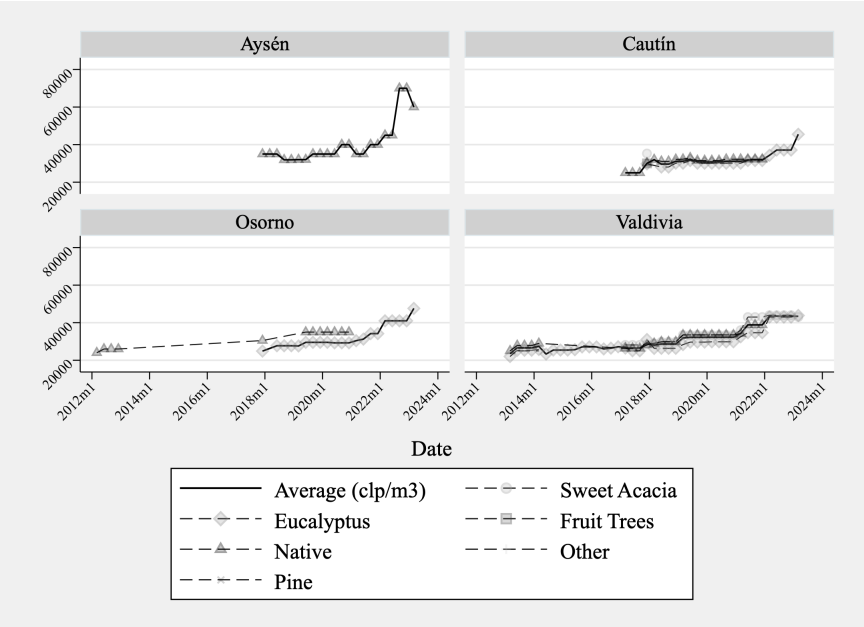


Figure A.6: Firewood price by species, selected municipalities.
Note:

Annual Average. After obtaining average prices by species, we proceed to calculate the annual average in kilograms or cubic meters. To do so, we consider how representative species are within municipalities across the sampled years.

Figure A.6 exemplifies the three cases we observe in the sample. First, municipalities for which only one species is reported (like Aysén in Fig. A.6). Second, municipalities where most observations are from a single species. Osorno in Fig A.6, 80% of the observations are eucalyptus, and only 20% are sampled as native species. In this case, and in all cases where 70% or more of the observations in a municipality are from one species, we use only that species' values to represent the municipality. Finally, a third case is municipalities (like Temuco or Valdivia in Figure A.6), where firewood prices are reported for several species (none of them with more than 70% of the total observations), in this cases we estimate the averages of the species that have at least 10% of observations in the municipality's sample. For example, for the municipality of Temuco, we averaged Eucalyptus (49%) and Natives (45%), while we excluded sweet acacia and fruit trees, each with less than 4% of observations; in the case of Valdivia, we averaged eucalyptus (47%), natives (27%) and sweet acacia (22%) and we excluded others (1%).

The final step of our methodology was to select the source that better represents the municipality prices. For municipalities like San Antonio or Valdivia, as shown in Figure A.7, the available information comes from one source, but for Temuco and Osorno, price data comes from more than one source. For those cities, we use the source best represented along the time series. For both these cases, it is INFOR.

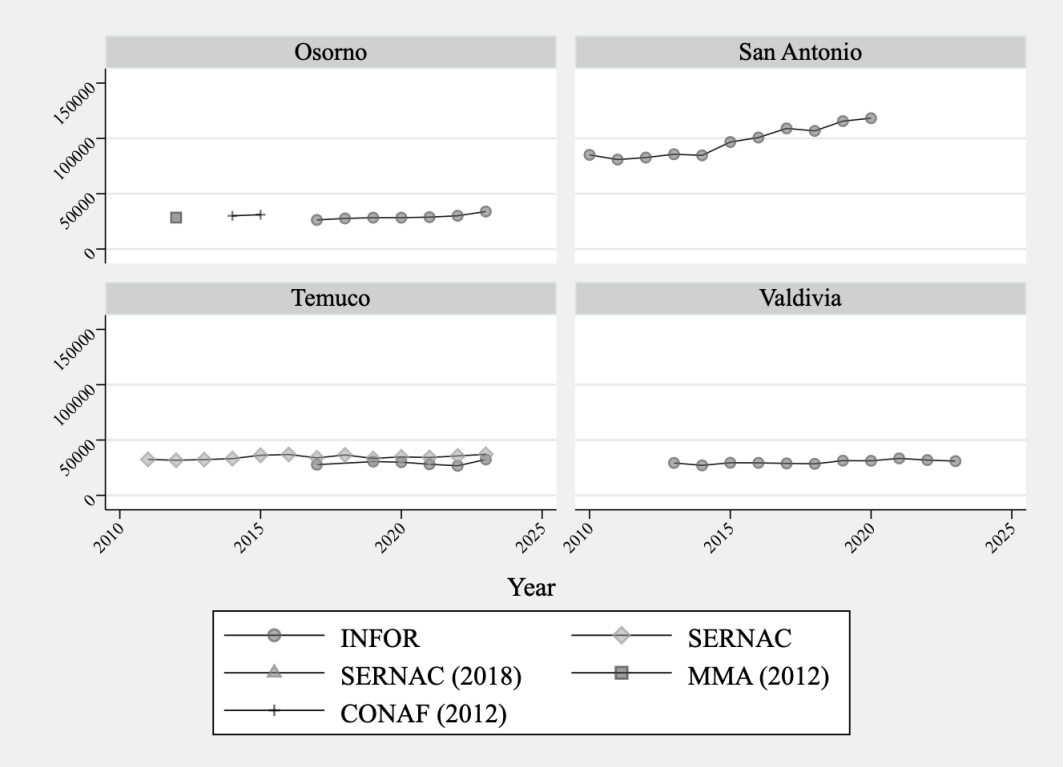


Figure A.7: Firewood price by source, selected municipalities.
Note:

The final dataset of prices, the imperfect panel of municipalities, is shown in figures A.8 and A.9 for prices in clp/kg and clp/m3, respectively.

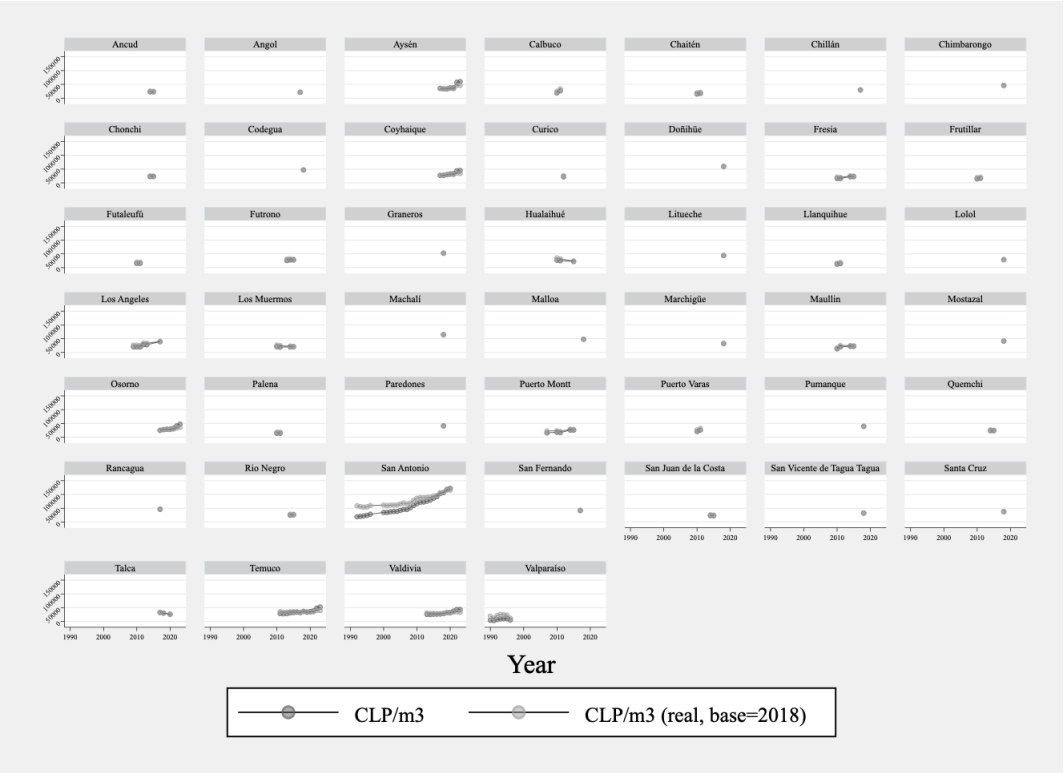


Figure A.8: Firewood price in CLP/m3
Note:

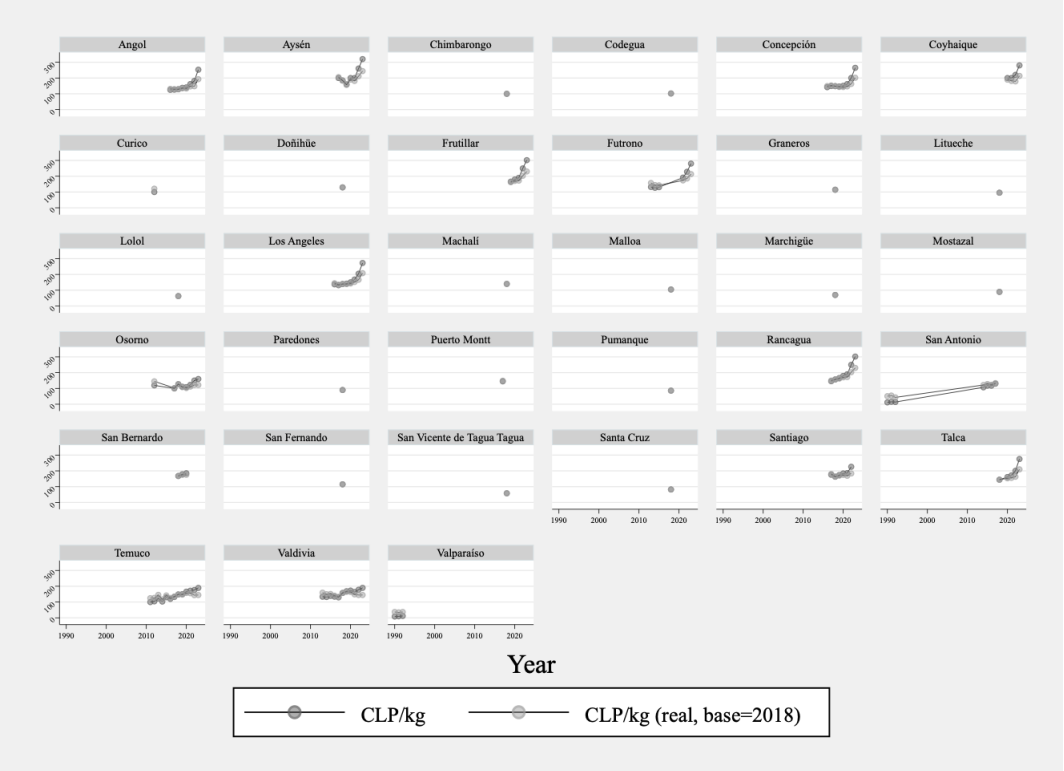


Figure A.9: Firewood price in CLP/kg
Note:

Table A.2: Forest Institute (INFOR) sampling of producers

Province / Year	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022
Arauco													
Aysén								Aysén (1)	Aysén (1)		Aysén (1)	Aysén (1)	Aysén (1)
Bio Bio	Los Ángeles (1)	Los Ángeles (1)	Los Ángeles (1)	Los Ángeles (1)									
Cautín								Temuco (24), Pitrufquén (2), Cholchol (1)	**Temuco (1), Villarrica (1)**		Temuco (1)	Temuco (1)	Temuco (1)
Concepción										Concepción (2), Coronel (1)			
Coyhaique								Coyhaique (2)	Coyhaique (2)		Coyhaique (2)	Coyhaique (1)	Coyhaique (1)
Diguillín										Chillan (1)			
Llanquihue								Puerto Montt (1)		Frutillar (1)			
Malleco								Angol (7)					
Osorno			Osorno (1)					Osorno (5)	Osorno (4)		Osorno (4)	Osorno (4)	Osorno (2)
Ranco				Futrono (2), La Union (1)	Futrono (2), La Union (1)	Futrono (2), La Union (1)	**Futrono (1), La Union (1)**	Futrono (1), La Union (2)	**Futrono (1), La Union (1)**		**Futrono (1), La Union (1)**	Futrono (1)	Futrono (1)
San Antonio	San Antonio (2)	San Antonio (2)	San Antonio (2)	San Antonio (2)	San Antonio (2)	San Antonio (2)	San Antonio (2)		San Antonio (1)		San Antonio (1)	San Antonio (1)	San Antonio (1)
Talca									Talca (1)	**Constitucion (1), Maule(1)**	Talca (1)		
Valdivia				Valdivia (4), Los Lagos (1)	Valdivia (4), Los Lagos (1)	Valdivia (3), Los Lagos (1)		Valdivia (9), Los Lagos (1), Panguipulli (1)	Valdivia (3), Los Lagos (1), Panguipulli (1)	Valdivia (1)	Valdivia (3), Los Lagos (1), Panguipulli (1)	Valdivia (3), Los Lagos (1), Panguipulli (1)	Valdivia (3), Los Lagos (1), Panguipulli (1)

Notes: This table shows the number of producers (in parenthesis) sampled by INFOR in each municipality within a Province. INFOR publishes the averages by Province. We use this information to give the price information to the sampled municipality when all or most producers are sampled from one municipality. We excluded the municipalities in bold because the sampling its balanced from two or more municipalities.

E. Firewood producer/seller's Economic Model

Figure A.10, based on the theoretical model of market participation of Key et al. (2000), shows two indirect utilities as a function of market price, p_2^m, in some municipality, m, where to initiate

sales the price must exceed the opportunity cost of entering that market, t^p (including firewood production costs and lost sales obtainable in closer markets). The utility to a potential, price-taking seller is increasing in the obtainable price in the municipality. Starting at a without distance-related costs, above $p_1^m - t^p$, a producer would sell along V_0^s (a to d). The inclusion of transportation costs and the opportunity costs of the seller's travel time is expected to lower utility at any market price. The distance-related costs are represented by the vertical line between a and b. A higher b represents a farther municipality. The utility relationship with price in municipality m is represented by a shift to V_1^s, which requires a higher market price p_2^m to enter this market. The key takeaway from Figure A.10 is that proportional transaction costs, such as transportation costs, generate a spatial pattern of firewood producer participation. That is, there is a critical distance (and forest cover) where sellers enter a specific municipal market.

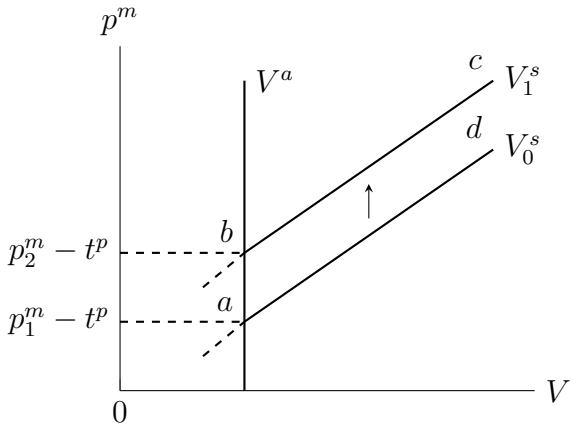


Figure A.10: The relationship between a municipality's firewood price and a potential seller's utility (based on Key et al. 2000)

Utility is increasing in the decision price for sellers. Starting at a without distance-related transaction costs, above $p_1^m - t^p$, utility increases along V_0^s (a to d). Including distance-related costs would lower utility at any market price, represented by a shift to V_1^s, which requires a higher price in the distant municipality to enter the market.