Since January 2020 Elsevier has created a COVID-19 resource centre with free information in English and Mandarin on the novel coronavirus COVID-19. The COVID-19 resource centre is hosted on Elsevier Connect, the company's public news and information website.

Elsevier hereby grants permission to make all its COVID-19-related research that is available on the COVID-19 resource centre - including this research content - immediately available in PubMed Central and other publicly funded repositories, such as the WHO COVID database with rights for unrestricted research re-use and analyses in any form or by any means with acknowledgement of the original source. These permissions are granted for free by Elsevier for as long as the COVID-19 resource centre remains active.
Energy poverty influences urban outdoor air pollution levels during COVID-19 lockdown in south-central Chile

Aner Martinez-Soto a, Constanza C. Avendaño Vera a, Alex Boso b, Alvaro Hofflinger b, Matthew Shupler * , a

a Department of Civil Engineering, Faculty of Engineering and Science, Universidad de La Frontera, Temuco, Chile
b Núcleo en Ciencias Sociales y Humanidades, Butamallín Research Center for Global Change, Universidad de La Frontera, Temuco, Chile
c Department of Public Health, Policy and Systems, University of Liverpool, UK

ARTICLE INFO

Keywords:
COVID-19
Residential heating
Air pollution
PM2.5
PM10
Energy poverty
Biomass combustion
Low-cost sensors

ABSTRACT

The effect of COVID-19 lockdowns on ambient air pollution levels in urban south-central Chile, where outdoor air pollution primarily originates indoors from wood burning for heating, may differ from trends in cities where transportation and industrial emission sources dominate. This quasi-experimental study compared hourly fine (PM2.5) and coarse (PM10) particulate matter measurements from six air monitors (three beta attenuation monitors; three low-cost sensors) in commercial and low/middle-income residential areas of Temuco, Chile between 2019 and 2020. The potential impact of varying annual meteorological conditions on air quality was also assessed. During COVID-19 lockdown, average monthly ambient PM2.5 concentrations in a commercial and middle-income residential neighborhood of Temuco were up to 50% higher (from 12 to 18 μg/m3) and 59% higher (from 22 to 35 μg/m3) than 2019 levels, respectively. Conversely, PM2.5 levels decreased by up to 52% (from 43 to 21 μg/m3) in low-income areas. The fine fraction of PM10 in April 2020 was 48% higher than in April 2017–2019 (from 50% to 74%) in a commercial area. These changes did not appear to result from meteorological differences between years. During COVID-19 lockdown, higher outdoor PM2.5 pollution from wood heating existed in more affluent areas of Temuco, while PM2.5 concentrations declined among poorer households refraining from wood heating. To reduce air pollution and energy poverty in south-central Chile, affordability of clean heating fuels (e.g. electricity) should be a policy priority.

1. Introduction

Chile has undergone rapid economic growth over the last 30 years and was classified as a high-income country by the World Bank in 2013 (Pino et al., 2015). Despite rapid development, income inequality in Chile is the highest among Organization for Economic Co-operation and Development (OECD) member countries (Becerra et al., 2018). In the Araucanía region in south-central Chile, in which most of the population lives in the cities of Temuco and Padre Las Casas, the prevalence of income poverty (24%) is twice the national average (12%) (Ministerio de Desarrollo Social y Familia, 2015). The high poverty rate in Araucanía is partially due to a high indigenous population (32% of residents), as indigenous people in Chile are disproportionately affected by income poverty (18% experience poverty compared with 11% in Chile nationally) (Boso et al., 2018).

In Araucanía, many families also live in subsidized, low-quality housing with inadequate thermal insulation. Due to high heating fuel prices, many of the residents of these households experience ‘energy poverty’, as they are unable to afford thermally comfortable indoor conditions in winter (Pérez-Fargallo et al., 2020). In this region, households commonly burn wood in higher efficiency chimney stoves (leña) for cooking and heating (rural areas) (Shupler et al., 2020) or only heating (urban areas) (Reyes et al., 2019, 2015). Wood is the most popular energy source due to cultural preferences (Reeve et al., 2013) and affordability (wood is 4–5 times cheaper per unit of energy than cleaner sources (e.g. electricity or liquefied petroleum gas) (Martínez-Soto and Jentsch, 2019). The wood energy sector also plays a key role in livelihoods; over 60,000 people in south-central Chile are employed in supply chain and maintenance services related to wood-stove heating (Reyes et al., 2015).

In the cities of Temuco (capital of Araucanía) and Padre Las Casas in south-central Chile, approximately 80% of the 270,000 inhabitants rely...
on wood for heating (MMA, 2018). Poor quality housing construction in the cities allows household air pollution generated from wood burning to infiltrate the outdoor environment, significantly contributing to ambient air pollution (Chafe et al., 2015; Lai et al., 2019); this phenomenon of air pollution infiltration has been documented in high-income (Krebs et al., 2021) and low- and middle-income nations in Sub-Saharan Africa and Asia, where cooking with wood and other biomass is common (CDT, 2010; Huang et al., 2021). Like most cities in Chile, Temuco and Padre Las Casas are located in a valley between the Andes and coastal Cordillera mountains, leading to thermal inversion, limited rainfall, minimal air circulation and making them two of the highest polluted cities in North and South America (Martinez-Soto and Jentsch, 2019).

Burning firewood for heating contributes 82% and 94% of total annual emissions of coarse (PM$_{10}$) and fine (PM$_{2.5}$) particulate matter in Temuco, respectively (Boso et al., 2018). As an estimated 93% of the PM from firewood burning is PM$_{2.5}$ (Claudio Bravo-Linares et al., 2016), the average fine fraction of PM$_{10}$ (mass proportion of PM$_{2.5}$ in PM$_{10}$) is roughly double in Temuco (80–90%) than Santiago (30–60%) (Sanhueza et al., 2009), the capital of Chile, where most ambient air pollution originates from traffic (Tsapakis et al., 2002). Because of the high levels of PM$_{2.5}$ found in woodsmoke, ambient PM$_{2.5}$ concentrations in Temuco usually exceed the World Health Organization average annual PM$_{2.5}$ target level (25 μg/m$^3$) during more than one-third of days in a typical year (Díaz-Robles et al., 2008; Molina et al., 2017). Due to the ability of PM$_{2.5}$ to travel deeper into the lungs (C. A. Pope et al., 2015) and the chemical composition of woodsmoke, residents of Temuco are at higher risk for respiratory/cardiovascular mortality, relative to individuals living in other Chilean cities (Díaz-Robles et al., 2014).

In response to the high ambient PM$_{2.5}$ concentrations found in Temuco and Padre Las Casas, the Chilean government introduced an Atmospheric Decontamination Plan (ADP) in 2015 to mitigate outdoor air pollution (Boso et al., 2019, 2018). The ADP consisted of 1) providing subsidies to families to insulate their households and upgrade their heating devices to more efficient wood heaters, pellet stoves or kerosene stoves and 2) creating a Critical Episode Management (CEM) system that identified ‘critical episodes’ with high PM$_{2.5}$ concentrations (average 24-h PM$_{2.5}$ concentrations $\geq$80 μg/m$^3$) during which the use of wood boilers and wood-burning stoves is restricted. Households that are not compliant with the wood-burning restriction during the emergency period face financial punishment (Boso et al., 2018). Although nearly 8000 wood stoves were replaced between 2011 and 2017 and 8500 households were retrofitted between 2015 and 2017 under the program (Reyes et al., 2019), there has not been a significant reduction in PM$_{2.5}$ concentrations since implementation of the ADP (Mardones and Cornejo, 2020).

1.1. The effect of COVID-19 lockdowns on ambient air pollution

In urban areas with emissions primarily originating from transportation and industry, lockdowns enforced in 2020 to control spread of the Coronavirus Disease 2019 (COVID-19) (Hasnain et al., 2020; Thu et al., 2020) simultaneously reduced ambient air pollution levels (Collivignarelli et al.; Gayen et al., 2021). For example, in Delhi, India, the average concentration of PM$_{10}$ and PM$_{2.5}$ decreased by 57% and 33%, respectively, compared to the previous three years (Mahato et al., 2020). In Zaragoza, Spain and Rome, Italy average PM$_{2.5}$ concentrations decreased by 58% and 24%, respectively, during March 2020 compared to February of the same year (Chauhan and Singh, 2020).

In south-central Chile, where ambient air pollution originates primarily from residential wood burning, the effect of COVID-19 lockdown on urban air quality may be different. As COVID-19 containment measures may have altered wood heating patterns during winter months of 2020 due to more time spent at home and loss of employment or reductions in income, household and ambient air pollution levels may not have declined as in other cities (Querol et al., 2021). This study therefore assesses the effect of COVID-19 lockdown on ambient PM$_{2.5}$ and PM$_{10}$ concentrations in Temuco and Padre Las Casas from March-September 2020. As exposure to PM$_{2.5}$ from wood burning is associated with several cardiovascular and respiratory diseases (Pena et al., 2017; D. Pope et al., 2015; Siddharthan et al., 2018), and increased ambient PM$_{2.5}$ and PM$_{10}$ levels have been associated with higher COVID-19 transmission (Coccia, 2020; Ogen, 2020; Zhu et al., 2020) and mortality (Setti et al., 2020; Wu et al., 2020), an understanding of the spatial variation in urban ambient air pollution levels in south-central Chile during COVID-19 lockdown can inform future policy measures aimed at protecting public health and the environment.

2. Methods

2.1. COVID-19 lockdown in Chile

On March 16, 2020, the Chilean government announced the closure of all shopping malls, daycares, schools, and universities. Two days later, borders were closed to international travel, and a national emergency was declared; a night-time curfew was instated on March 22, 2020 (Tariq et al., 2021). COVID-19 lockdown measures were categorized based on the number of infected persons in a localized area: (1) Quarantine (2) Transition (3) Preparation (4) Initial opening (Cuadrado et al., 2020). The strictest “quarantine” phase, in which movement was restricted and only essential businesses remained open, occurred from March 28 to April 29, 2020. A “transition” period followed from April 30 to July 23, 2020 in Temuco, which allowed unrestricted movement Monday-Friday for nonessential purposes. A “preparation” phase included free movement every day of the week and allowed gatherings of up to 25 people in closed spaces and up to 50 people in open spaces. In the “initial opening” period, which occurred from July 24 to October 2, 2020 in Temuco, face-to-face classes with up to 25 students in schools were additionally allowed.

2.2. Air pollution measurements

A quasi-experimental study was conducted by comparing hourly PM$_{2.5}$ and PM$_{10}$ concentrations from March 1st to September 30th for 2019 and the same period in 2020 (during COVID-19 lockdown) using six air monitoring stations located throughout Temuco and Padre Last Casas. Three stations contained reference grade Met One beta attenuation monitors (BAM-1020, Met One Instruments, Oregon, USA) (Gobeli et al., 2008), which are part of a larger 29 monitor network through cities in Chile maintained by the Chilean Ministry of the Environment (MMA). The other three stations consisted of low-cost Sensirion SPS30 sensors (Bruce-Keller et al., 2018; Maag et al., 2018).

The limit of detection of the beta attenuation monitors is 4.0 μg/m$^3$ and all measurements from the beta attenuation monitors used in this study are publicly available (http://sinca.mma.gob.cl/) via the National Air Quality Information System (SINCA) (SINCA, 2015). Quality control procedures were followed around operation of the reference monitors, including flow rate control, automatic leak detection and data validation to check for missing, duplicate or abnormal data (SINCA, 2015).

The SPS30 sensors are part of a larger network of 30 sensors throughout Temuco, developed by the Center for Software Engineering Studies at Universidad de La Frontera (UFRO) (“Plataforma AIRE CIEUFRO,” n.d.) with support from the municipality of Temuco, that provide real-time air quality data to residents via a mobile and web application called “AIRE Temuco” (http://aire.cieufro.cl/#/dashboard). The sensors were used as part of the Temuco air monitoring network because they are cheaper, less bulky and have lower power requirements (Rai et al., 2017; Wang et al., 2015), enabling a much larger number of measurements to be collected in the city on a modest budget. As the performance of low-cost sensors is generally not well-characterized (e.g. the relationship between reflected light and particle size is altered by the particle composition and size distribution).
(Thomas and Gebhart, 1994) and their long-term reliability is uncertain, it is important that the performance of the monitors is evaluated to ensure data accuracy (Castell et al., 2017; Jovasević-Stojanović et al., 2015).

2.3. Calibration of sensirion SPS30 sensors

Measurements from the three SPS30 sensors, the most accurate sensors in the “AIRE Temuco” network, were calibrated to a Grimm laser aerosol spectrometer 11-E (Grimm Technologies, Ainring, Germany) over an 8-h period on December 24, 2019 (midway through the study period) in an airtight chamber. The efficiency of the laser aerosol spectrometer meets the European standards (EN12341 and EN14907) for PM₁₀ and PM₂.₅, respectively. The coefficient of determination (R²) between the SPS 30 sensors and the Grimm laser aerosol spectrometer during the 8-h calibration period was 0.92 for PM₂.₅ and 0.96 for PM₁₀ (see Figs. S3 and S4 for calibration curves). Field collocation of similar sensors and beta attenuation monitors in Santiago, Chile also showed relatively high correlation among 24-h average PM₂.₅ concentrations (R² = 0.63–0.87) (Tagle et al., 2020).

2.4. Accounting for changes in ambient air pollution due to meteorology

2.4.1. Heating degree days

As colder winter temperatures generally lead to higher rates of wood burning for heating, a heating degree day (HDD) approach (Dickson, 1961; Liddell et al., 2016) was used to assess the impact of ambient temperature changes on PM₂.₅ and PM₁₀ measurements between study years. HDD, a proxy of energy demand, compares the mean outdoor temperature recorded for a location to an outdoor temperature of 15° Celsius (C) at which a heating system would be activated (based on calculations of thermal building performance from the International Organization for Standardization (ISO 15927–6) (British Standard Institution, 2008). For example, HDD of 12 corresponds to an outdoor temperature of 3 °C as it is 12° below 15 °C. An outdoor temperature of 15 °C was used in HDD calculations, as opposed to an indoor comfort temperature, due to the potential for meteorological factors (e.g. humidity) and subjective differences in perceived comfort to cause variations in the indoor thermal comfort temperature (Papakostas and Kyriakis, 2005; Roshan et al., 2017; Vasco et al., 2017).

The HDD was calculated historically from 2009 to 2020, with average temperatures obtained from the Chilean Meteorological Directorate - Climate Services (“Dirección Meteorológica de Chile – Servicios Climáticos, Dirección General De Aeronáutica Civil (DGAC), (https://climatologia.meteochile.gob.cl/),” n.d.). All temperatures used in the HDD calculation were converted to Kelvin and HDD are reported in units of Kelvin days (Kd) (equation 1) (“Dirección Meteorológica de Chile – Servicios Climáticos, Dirección General De Aeronáutica Civil (DGAC). (https://climatologia.meteochile.gob.cl/),” n.d.).

\[
\text{HDD}_{\text{Kd}} = \sum_{i=1}^{153} (T_b - T_{da})
\]

(1)

where:

\( \text{HDD}_{\text{Kd}} \): sum of heating degree days for April–August period (Kelvin days (Kd)).

\( T_b \): base temperature [°C], \( T_b = 15 \) °C.

\( T_{da} \): daily average temperature [°C] \( T_{da} > 15 \) °C is not included in the HDD calculation.

2.4.2. Comparing PM₂.₅ ground measurements in Temuco to modeled concentrations

We compared historical (2016–2020) average annual PM₂.₅ concentrations obtained from the reference-grade monitors used in this study to modeled average annual PM₂.₅ estimates (provided at 1 km×1 km spatial resolution globally) obtained from satellite-derived aerosol optical depth measurements (Shaddick et al., 2018) during the same time period.

Satellite-based observations provide a measure of light extinction in the atmospheric column during the daytime (van Donkelaar et al., 2006) and therefore will likely underestimate outdoor PM₂.₅ concentrations in Temuco as the PM₂.₅ from woodsmoke is mostly emitted at night when household heating is more prevalent. Additionally, thermal inversions, which are common in Temuco during the winter given the topography of the region, are not handled well with satellite-based measurements. Therefore, the modeled average annual outdoor PM₂.₅ estimates from Shaddick et al. provide reasonable counterfactual measures for assessing expected PM₂.₅ concentrations in the absence of COVID-19 lockdown, due solely to changes in meteorological conditions from 2019 to 2020. This analysis follows the methodological framework used by a study assessing changes in ambient pollution during COVID-19 lockdown in Italy (Putaud et al., 2021); this study compared ground measurements in northern Italy in 2020 to forecasts made from the Copernicus Atmosphere Monitoring Service (CAMS), which did not account for the impact of COVID-19 lockdown on ambient air pollution levels.

2.5. Statistical analysis

As the distribution of PM measurements was right skewed, all data were log transformed; geometric means (referred to as ‘mean’ from this point forward) are reported. Measurements from the SPS30 sensors, obtained every 10-min, were aggregated into hourly and monthly means. The fine fraction of PM₁₀ (mass percent of PM₁₀ that is PM₂.₅) was calculated by dividing the mean PM₂.₅ concentration recorded at a monitoring station by the mean PM₁₀ concentration from the same station, over a given time period. Analysis and generation of figures were conducted in SPSS Statistics for Windows version 25.0 (IBM Corp, 2017) and R version 3.5.1 (R Core Team, 2017).

3. Results

The six monitors used in this study (Fig. 1) are located in low-income residential (Pedro Valdivia, Pueblo Nuevo, Padre Las Casas), middle-income residential (Las Encinas) and commercial (Centro, Niêol) areas (Table 1).

3.1. Relationship between heating degree days and ambient air pollution

At the two longest-running monitoring stations in Temuco (Las Encinas and Padre Las Casas) (Table 1), differences in number of heating degree days (HDD) were highly correlated (r = 0.78–0.85) with average PM₂.₅ concentrations obtained from the reference-grade monitors used in this study to modeled average annual PM₂.₅ estimates (provided at 1 km×1 km spatial resolution globally) obtained from satellite-derived aerosol optical depth measurements (Shaddick et al., 2018) during the same time period.
monthly PM$_{2.5}$ concentrations during July from 2009 to 2020 (Las Encinas) and 2013–2020 (Padre Las Casas) (Fig. 2).

The total number of HDD in April–August from 2009 to 2020 ranged from approximately 850 Kd (2015) to 1100 Kd (2010), with an overall average of nearly 1000 Kd (Fig. 3). As the number of HDD in 2019 and 2020 were similar (approximately 950 Kd; signaling slightly warmer winters than the overall average), air pollution measurements in this study were compared between 2019 and 2020 to reduce confounding of winter temperature fluctuations on ambient PM concentrations.

In 2019, average monthly PM$_{2.5}$ concentrations during the winter months of June–August in low-income residential areas, including Padre Las Casas (36–47 μg/m$^3$), Pedro Valdivia (40–42 μg/m$^3$) and Pueblo Nuevo (42–53 μg/m$^3$) were approximately twice as high as concentrations in commercial areas of Temuco (Nielol (12–15 μg/m$^3$) and Centro (26–29 μg/m$^3$)) (Table 2). Apart from the monitoring station in Nielol, average monthly PM$_{2.5}$ concentrations recorded at all monitoring stations exceeded the Chilean standard of 20 μg/m$^3$ during each of the three winter months in 2019.

### 3.2. Effect of COVID-19 lockdown on fine particulate matter levels

During COVID-19 lockdown in April–July 2020 (‘quarantine’ and ‘transition’ periods), PM$_{2.5}$ levels in commercial areas (Centro, Nielol) and a middle-income neighborhood (Las Encinas) of Temuco were an average of 19–42% higher than corresponding months in 2019 (Table 2). In a single month, average PM$_{2.5}$ concentrations during the ‘transition’ period were up to 50% (July 2020 in Nielol) and 59% (May 2020 in Las Encinas) higher than the same month in 2019 (Table 2). Conversely, during the first month of the ‘initial re-opening’ phase (August 2020), average PM$_{2.5}$ concentrations in the two commercial areas were 3–4% below August 2019 levels.

In Padre Las Casas, the highest night-time PM$_{2.5}$ levels before and during COVID-19 lockdown were observed and remained relatively unchanged (Table 2), with average outdoor concentrations exceeding 100 μg/m$^3$ from 8 to 10 p.m. during May–August of 2019 and 2020 (Fig. 5). In contrast, average PM$_{2.5}$ concentrations during the ‘transition’ phase (May–July 2020) of COVID-19 lockdown were substantially lower than 2019 levels in the low-income neighborhoods of Pedro Valdivia (~48%) and Pueblo Nuevo (~32%). The relative decline in PM$_{2.5}$ levels between 2019 and 2020 in these two low-income communities in Temuco was greater during morning (7–11 a.m.) and nighttime (5 p.m.–12 a.m.) hours, when air pollution from heating is typically highest (Fig. 4). Similarly, in the residential area of Las Encinas, increases in PM$_{2.5}$ concentrations during lockdown (above baseline 2019 levels) were most visible at night during home heating hours (Fig. 5). Conversely, the increase in PM$_{2.5}$ concentrations in 2020 relative to 2019 in commercial areas (Centro, Nielol) of Temuco was more evenly distributed across all hours of the day (Figs. 4 and 5).

### 3.3. Effect of COVID-19 lockdown on coarse particulate matter levels

Apart from the city center (Centro), average PM$_{10}$ concentrations...
Table 2
Average monthly PM$_{2.5}$ and PM$_{10}$ concentrations during winter months in 2019 and 2020.

| Month          | Nielol (commercial) | Padre Las Casas (mixed commercial and low-income residential) | Las Encinas (middle-income residential) |
|----------------|---------------------|---------------------------------------------------------------|------------------------------------------|
|                | Average PM$_{2.5}$  | Average PM$_{10}$                                           |                                          |
|                | (µg/m$^3$)          | (µg/m$^3$)                                                  |                                          |
| April (quarantine) | 3 22 16             | 9 18 18                                                     | 9 6 17                                     |
| May (transition)| 8 24 17             | 21 23 22                                                   | 21 15 22                                   |
| June (transition)| 15 29 27           | 37 46 16                                                   | 22 16 16                                   |
| July (transition)| 14 25 22           | 36 43 33                                                   | 23 18 17                                   |
| August (opening) | 11 27 32            | 47 55 32                                                   | 20 25 31                                   |
| Sept. (opening) | 15 19 22            | 47 55 32                                                   | 23 25 31                                   |
| Mean: overall  | 11 24 21            | 31 39 23                                                   | 21 25 28                                   |
| Mean: lockdown months$^a$ | 13 25 22         | 34 39 23                                                   | 20 25 25                                   |
| Mean: opening months$^b$ | 14 23 21          | 34 39 23                                                   | 20 25 25                                   |
| Mean: lockdown months$^c$ | 12 25 22          | 34 39 23                                                   | 20 25 25                                   |
| Mean: overall  | 11 24 21            | 31 39 23                                                   | 21 25 28                                   |
| Mean: lockdown months$^c$ | 11 24 21          | 31 39 23                                                   | 21 25 28                                   |

a. Lockdown months: April (quarantine) and May–July (transition).
b. Opening months: August–September (initial opening).
c. Lockdown months: May–July (transition).
registered to all monitors were significantly lower during winter months of COVID-19 lockdown than in winter 2019 (Table 2; Fig. 6). The largest relative decline in average monthly PM$_{10}$ concentrations between 2019 and 2020 occurred in the commercial area of Nielol; the average PM$_{10}$ concentration during the month of strict quarantine in Nielol (17 μg/m$^3$) was 29% lower than April 2019 (24 μg/m$^3$). A 7–12% lower average PM$_{10}$ concentration in Nielol in 2020 compared to 2019 was maintained when restrictions were eased during the ‘transition’ phase in May and June (Table 2). The decline in PM$_{10}$ concentrations in April 2020 relative to April 2019 in Nielol was visible at all hours of the day (Fig. 7). In contrast, in the residential areas of Pedro Valdivia and Pueblo Nuevo, lower PM$_{10}$ levels in 2020 compared with 2019 were most apparent during typical wood heating hours at night and early morning (Fig. 6).

Because the size of particulate matter produced from residential wood burning is mostly PM$_{2.5}$, monthly average PM$_{10}$ concentrations decreased by a lesser extent (no more than 16%) in primarily residential neighborhoods compared with Nielol (Table 2).

3.4. Effect of COVID-19 lockdown on fine fraction of PM$_{10}$

In a commercial (Nielol) and middle-income residential area (Las Encinas), large increases in the fine fraction of PM$_{10}$ occurred during the
The fine fraction of PM$_{10}$ obtained at these two monitoring stations at night in April 2020 was more than 40% higher than in April 2017–2019 (Table 3). During the daytime in April 2020, the increase in the fine fraction of PM$_{10}$ above April 2017–2019 levels (32%) in Nielol was double that of Las Encinas (16%). During the transition period from May–July 2020, the fine fraction of PM$_{10}$ during night hours in Las Encinas reached 100%, which was 33–40% greater than the recorded proportion in 2017–2019. In Nielol, the relative increase between the 2017–2019 and 2020 fine fraction of PM$_{10}$ was conversely reduced by over 75% (48%–11%) between the quarantine phase (April 2020) and the first month of the transition phase (May 2020) (Table 3). The percent increase in the fine fraction of PM$_{10}$ in Las Encinas between 2020 and 2017–2019 levels was halved (35%–17%) during the first month initial re-opening of Temuco in August 2020.

In low-income neighborhoods of Pedro Valdivia and Pueblo Nuevo,
Table 3  
Average and standard deviation (SD) of fine fraction of PM\(\text{10}\) concentrations located at Nielol (combination of commercial and middle-income residential) between 2019 and 2020 (Table 5). This increase was approximately a third as much as the 10.33% increase in average annual PM\(\text{2.5}\) levels measured by the beta-attenuation monitor at Las Encinas (middle-income neighborhood). The detected rise in the average outdoor annual PM\(\text{2.5}\) concentration located at Nielol (combination of commercial and middle-income residential) between 2019 and 2020 (7.43%) was twice as high as the increase in PM\(\text{2.5}\) levels estimated by Shaddick et al. et al. yet lower than the increase detected at Las Encinas monitoring station. Contrastingly, in the low-income neighborhood of Padre Las Casas, the average annual PM\(\text{2.5}\) concentration decreased by 2.66% (Table 5).

3.5. Comparing ground PM\(\text{2.5}\) measurements in this study to another data source

Two satellite-derived average annual PM\(\text{2.5}\) measurements from Shaddick et al. located near the study setting in Temuco showed an increase of 3.94% and 3.34% in average annual PM\(\text{2.5}\) concentrations between 2019 and 2020 (Table 5). This increase was approximately a third as much as the 10.33% increase in average annual PM\(\text{2.5}\) levels measured by the beta-attenuation monitor at Las Encinas (middle-income neighborhood). The detected rise in the average outdoor annual PM\(\text{2.5}\) concentration located at Nielol (combination of commercial and middle-income residential) between 2019 and 2020 (7.43%) was twice as high as the increase in PM\(\text{2.5}\) levels estimated by Shaddick et al. et al. yet lower than the increase detected at Las Encinas monitoring station. Contrastingly, in the low-income neighborhood of Padre Las Casas, the average annual PM\(\text{2.5}\) concentration decreased by 2.66% (Table 5).

4. Discussion

4.1. Socioeconomic heterogeneity in ambient particulate matter concentrations

This quasi-experimental study presents a juxtaposition of elevated ambient PM\(\text{2.5}\) levels in commercial and middle-income neighborhoods and a decline in low-income areas of Temuco. In three low-income residential areas, average PM\(\text{2.5}\) concentrations decreased by an average of 32% (Pueblo Nuevo) and 48% (Pedro Valdivia) or did not increase (Padre las Casas) during COVID-19 lockdown despite more time confined at home and similar winter temperatures as 2019 (Fig. 3). The changes in outdoor PM\(\text{2.5}\) concentrations between 2019 and 2020 are likely not entirely due to differences in meteorological conditions, as annual increases in PM\(\text{2.5}\) concentrations reported at Nielol (7.4%) and Las Encinas (10.3%) during winter months in 2020 are a factor of two and three times higher, respectively, than would be expected in the absence of COVID-19 lockdown (3.4–3.9%; Table 5).

Similarly, annual average PM\(\text{2.5}\) concentrations declined by 2.7% in Padre Las Casas between 2019 and 2020 despite the 3.4–3.9% increase in average annual outdoor levels estimated from satellite measurements (Shaddick et al., 2018); the satellite-based measurements, which are obtained during the daytime (van Donkelaar et al., 2006), do not accurately account for woodsmoke emissions that are mainly emitted at night when household heating is more common. Therefore, the discrepancy between ground and satellite-based PM\(\text{2.5}\) measurements in Padre Las Casas is likely due to a decline in the rate of wood-burning for heating during COVID-19 lockdown as the city of Padre Las Casas has a larger indigenous population and higher poverty rates than Temuco (Barton and Ramírez, 2019).

Likewise, the areas of Pueblo Nuevo and Pedro Valdivia experienced steep declines in outdoor PM\(\text{2.5}\) concentrations during lockdown. Both of these areas contain a high proportion of social housing, with families living in small residential condominiums and apartment buildings typically not larger than 30 square meters (Garin Contreras et al., 2009; Vergara, 2019). With over half (53%) of Chileans indicating household income declines or financial debt (60%) due to the COVID-19 pandemic, and a third (33%) reporting unemployment (Umaña-Hermosilla et al., 2020), the lower monthly ambient PM\(\text{2.5}\) levels found in this study
highlight the disproportionate, negative downstream effects of the COVID-19 lockdown on energy insecure households in urban south-central Chile, who likely did not have the income to pay for wood heating (Reyes et al., 2015). These households may have become more vulnerable to respiratory and cardiovascular stress due to living in unsafe, cold indoor temperatures for prolonged periods (Howden-Chapman and Chapman, 2012; Schueftan et al., 2016).

Additionally, as human mobility in Chile was reduced during COVID-19 lockdown to a lesser extent in lower socioeconomic municipalities (20–40% reduction) compared with more affluent areas (60–80% reduction) (Gozzi et al., 2020; Mena et al., 2021), the inability of families working in the informal sector to quarantine due to the need for daily wages may have partially contributed to lower home heating demands in low-income neighborhoods and therefore driven down PM$_{2.5}$ levels (Jay et al., 2020).

While household-level energy consumption patterns were not examined in this study, high rates of energy poverty have been documented in Temuco prior to the pandemic (Becerra et al., 2018). Over two-thirds (68%) of low-income households in southern Chile are estimated to keep their living room temperatures below the thermal comfort standard of 21°C established by WHO (Boso et al., 2018) during the winter months (Reyes et al., 2019), accepting higher levels of thermal discomfort to reduce costs (Becerra et al., 2018; Boso, A., Hofflinger, A., Garrido, J., & Álvarez, 2020). A similar pattern in household energy consumption during COVID-19 lockdown was found in Nairobi, Kenya, a city has also has a high population proportion working in the informal sector, with many households cooking less frequently or switching from paid cooking fuels (e.g. liquefied petroleum gas) to gathering wood for free to offset significant income loss during lockdown (Shupler et al., 2021). In both Temuco and Nairobi, families in Temuco typically

![Fig. 8. Mean hourly fine fraction (mass percent of PM$_{10}$ that is PM$_{2.5}$) in 2019 and 2020 obtained from SPS30 sensors.](image)

![Fig. 9. Mean hourly fine fraction (mass percent of PM$_{10}$ that is PM$_{2.5}$) in 2019 and 2020 obtained from beta attenuation monitors.](image)
Table 4

| Month      | Centro (commercial) | Pedro Nuno (low-income residential) | Pueblo Nuevo (low-income residential) |
|------------|---------------------|-------------------------------------|--------------------------------------|
| Day (9 a.m.-8 p.m.) | Night (8 p.m.-9 a.m.) | Day (9 a.m.-8 p.m.) | Night (8 p.m.-9 a.m.) | Day (9 a.m.-8 p.m.) | Night (8 p.m.-9 a.m.) |
| 2019       | 2020                | 2019                                | 2020                                | 2019                                | 2020                                |
| Transition |                     |                                     |                                     |                                     |                                     |
| May        | 42 (13)             | 50 (19)                             | 64 (28)                             | 60 (39)                             | 61 (23)                             |
| June       | 44 (17)             | 46 (15)                             | 61 (23)                             | 60 (19)                             | 62 (14)                             |
| July       | 46 (13)             | 46 (15)                             | 59 (15)                             | 69 (26)                             | 60 (19)                             |
| Initial    | 49 (16)             | 54 (19)                             | 54 (19)                             | 60 (26)                             | 60 (26)                             |

Average and standard deviation (SD) of fine fraction of PM$_{2.5}$ (%) registered to SP3S30 sensors during day and night hours during winter months (May–August) of 2019 and 2020.

4.2. Health impacts of elevated ambient fine particulate matter levels

With over 90% of PM emissions from residential wood burning consisting of PM$_{2.5}$ (Díaz-Robles et al., 2014), the increase in average monthly outdoor PM$_{2.5}$ concentrations in largely commercial areas (Nielol and Centro) by up to 50% yet decline in average monthly outdoor PM$_{10}$ concentrations by up to 29% between 2019 and 2020 in Temuco (Table 2) was evidently driven by an increase in household wood burning during COVID-19 lockdown. A rise in average ambient PM$_{2.5}$ levels in commercial areas in the study setting during COVID-19 lockdown is an anomalous result when compared with trends observed in other high-income countries, where urban ambient PM$_{2.5}$ concentrations typically plummeted (by 24–159%) due to lower industrial emissions (Chauhan and Singh, 2020; Mahato et al., 2020).

The increase in outdoor PM$_{2.5}$ concentrations in commercial areas may be due to the presence of some residential buildings. However, the relative increase in the fine fraction of PM between 2019 and 2020 in Nielol and Centro was less than that of Las Encinas (a primarily residential area) (Tables 3 and 4), suggesting that the increase in PM$_{2.5}$ emissions from wood burning was more drastic in the residential area. The spike in average PM$_{2.5}$ levels in commercial areas may also be partially due to localized (e.g. wind direction) and synoptic (e.g. thermal inversions) meteorological patterns, that transported particles generated from wood-burning in nearby residential areas with minimal vertical mixing (Yáñez et al., 2017). As Temuco is situated in a narrow valley, dilution of the air is poor during thermal inversions, causing elevated ambient air pollution levels (Rutillant and Garreau, 1995; Toro A et al., 2019).

Higher PM$_{2.5}$ concentrations during COVID-19 lockdown in regions of Temuco is problematic from a health perspective, especially with possible increased length of exposure to household air pollution while confined at home (Chen et al., 2021). Research conducted in low and middle-income countries (LMICs) where there is high prevalence of cooking with wood and other polluting fuels demonstrates that elevated PM$_{2.5}$ levels found in household air pollution places the population at increased risk for infectious, cardiovascular and respiratory diseases and mortality (Apte et al., 2015). As Chile had some of the highest rates of COVID-19 cases globally during April–August 2020 (Undurraga et al., 2021), it is possible that increased PM$_{2.5}$ levels in Temuco may have exacerbated COVID-19 transmission (Fattorini and Regoli, 2020; Zhu et al., 2020). Older individuals (≥65 years), who have the greatest health risk from exposure to wood smoke (Díaz-Robles et al., 2015), and are more likely to suffer from severe symptoms of COVID-19, can be particularly vulnerable (Undurraga et al., 2021).

While most of the 2.3 million deaths due to household air pollution exposure in 2019 occurred among three billion individuals living in LMICs that cook with wood and other polluting fuels (Murray et al., 2020; State of Global Air, 2020), this study suggests that household air pollution may have posed an increased health burden during COVID-19 lockdown in certain high-income countries where wood burning is prevalent. Recent studies conducted in Spain (Querol et al., 2021) and across Europe (Evangelou et al., 2020) found that residential wood combustion was likely a more significant source of ambient emissions of PM$_{2.5}$ and black carbon, a component of PM$_{2.5}$ generated from wood combustion (Bond et al., 2013; Shpigel et al., 2020), during COVID-19 lockdown compared with years prior to the pandemic.

4.3. Efforts to reduce ambient air pollution in Temuco

As part of the Atmospheric Decontamination Plan (ADP), temporary bans on residential wood-burning during ‘critical episode’ periods has reduced short-term PM$_{2.5}$ and PM$_{10}$ concentrations by up to 17.5% and 9.2%, respectively (Mardones and Cornejo, 2020). However, the ADP spending over 10% (Reyes et al., 2019) and 20% (Ahmed et al., 2015), respectively, of monthly household income on energy.
has had limited effectiveness in reducing long-term PM$_{2.5}$ concentrations (Schuftsan and González, 2015). Replacement of all existing wood stoves with more efficient burning stoves may therefore not significantly achieve meaningful ambient PM$_{2.5}$ concentration reductions in Temuco, especially with rising per capita energy consumption expected due to increasing household income (Jorquera et al., 2018).

The marked increase in PM$_{2.5}$ levels during COVID-19 lockdown in Temuco underscores an imperative need for more robust policies that can accelerate the transition away from wood burning for heating in the city. Providing households with affordable access to cleaner forms of energy (e.g. liquefied petroleum gas or electricity) for cooking and heating, which emit significantly lower PM$_{2.5}$ emissions (Shupler et al., 2020), would be a more effective policy component of ADPs (C Brav-o-Linares et al., 2016). Increased use of clean fuels would not only improve health outcomes from reductions in household and ambient PM$_{2.5}$ concentrations, but also reduce localized rates of deforestation (Reyes et al., 2015; Schuftsan and Gonzalez, 2013) and potentially free up time for individuals to shift to other income-generating activities, due to lower time spent on stove maintenance, chimney cleaning and storing, chopping and drying wood (Boso, A., Hofflinger, A., Garrido, J., & Alvarez, 2020).

### 4.4. Strengths and limitations

This study leveraged publicly available data from low-cost sensors and regulatory-grade beta attenuation monitors strategically placed throughout commercial and low- and middle-income residential neighborhoods of Temuco and Padre Las Casas. Combining the monitoring networks enabled an examination of the differential impacts of COVID-19 lockdown on urban ambient air quality across neighborhoods with potentially distinct changes in energy consumption patterns, which may be attributed to variation in neighborhood-level socioeconomic status. While the accuracy of the low-cost sensors used in this study can be affected by meteorological factors such as temperature and humidity, the sensors showed high agreement with the reference standard during calibration (Figs. S3 and S4). Further, measurements were aggregated at monthly levels, thereby lowering the risk of measurement error impacting study findings (Malings et al., 2020). A heating degree day analysis revealed that PM$_{2.5}$ concentration fluctuations during COVID-19 lockdown in 2020 relative to 2019 were likely not attributed solely to changes in ambient temperatures (Fig. 2).

Household-level energy consumption patterns in Temuco and Padre Las Casas during COVID-19 lockdown were not assessed. However, given existing documented negative impacts of lockdowns on energy insecurity (Shupler et al., 2021) and the history of energy poverty and inadequate maintenance of thermal comfort in the region prior to the pandemic (Becerra et al., 2018; Boso et al., 2018), energy poverty was likely an influential factor in the dichotomy of ambient air pollution trends observed in Temuco in 2020. Data on household-level energy consumption behaviors in Temuco during lockdown can further uncover policies needed to ensure low-income families are thermally protected during Chilean winters.

The spatial variation in the PM$_{2.5}$ concentration patterns pre- and post-pandemic highlights the utility of having a dense sensor network across numerous residential and commercial districts in Temuco and Padre Las Casas, which can help identify priority areas for intervention where energy poverty rates may be highest (e.g. Fuel Poverty Potential Risk Index) (Pérez-Fargallo et al., 2018). Promoting use of the existing monitoring network in Temuco as a public health tool, and potentially expanding the network in an economically viable manner using low-cost sensors (if properly tested and calibrated), can empower residents to make informed decisions regarding the scheduling of outdoor activities using neighborhood-level, real-time air quality data (Kumar et al., 2015; Snyder et al., 2013).

### 5. Conclusion and policy implications

Differences in the main sources of ambient pollution emissions between Temuco and Padre Las Casas and other urban areas in high-income countries led to vastly diverse impacts on urban air quality due to COVID-19 lockdown. Similar to findings in certain regions of Europe (Evangelou et al., 2020; Querol et al., 2021), higher average outdoor PM$_{2.5}$ concentrations in commercial and more affluent residential areas of Temuco during COVID-19 lockdown relative to 2019 due to higher rates of wood burning while confined indoors may have increased the risk of adverse cardiovascular and respiratory outcomes. Conversely, substantial reductions in ambient PM$_{2.5}$ levels in low-income neighborhoods between 2019 and 2020 suggests lower-than-usual maintenance of thermal comfort during lockdown due to energy poverty, which can similarly lead to higher risk of adverse cardiovascular and respiratory events.

The results of this study underscore the need to reduce indoor air pollution in south-central Chile, which can best be achieved by transitioning to cleaner sources of household energy (e.g. electricity, liquefied petroleum gas). As these cleaner fuels may not be easily accessible in the short-term, residential insulation programs may serve as near-term remedies for increasing residents’ thermal comfort to potentially enhance their quality of life and reduce the economic burden of energy consumption (Margones and Cornejo, 2020). Nonetheless, as building design solutions have not been shown to significantly reduce outdoor PM$_{2.5}$ emissions, clean sources of household energy need to be made increasingly affordable (e.g. via clean fuel subsidies and improved energy infrastructure) to avoid a double burden of unsafe ambient air pollution levels and cold indoor residential temperatures during winter. More aggressive governmental intervention to minimize use of wood burning is urgently needed in south-central Chile to provide health, environmental and economic co-benefits.

### CRediT authorship contribution statement

Aner Martinez-Soto: Writing – original draft, Conceptualization. Constanza C. Avendaño Vera: Investigation, Formal analysis, Writing – review & editing. Alex Boso: Writing – review & editing. Alvaro Hofflinger: Writing – review & editing. Matthew Shupler: Methodology, Formal analysis, Writing – original draft, Writing – review & editing, Visualization.
Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

The authors would like to thank the AIRE Temuco team for their technical assistance with air monitor specifications and calibration methodology. The authors received no external sources of funding to conduct this work. Matthew Shupler is funded by a grant from the Na...
A. Martinez-Soto et al.

Energy Policy 158 (2021) 112571

Querol, X., Massagüé, J., Alastuey, A., Moreno, T., Gangoiti, M., Mantilla, E., Duquev, J. J., Escudero, M., Monfort, E., Pérez García-Fandiño, C., Petetin, H., Jordà, O., Vázquez, V., de la Rosa, J., Campos, A., Muñoz, M., More, S., Hervias, M., Javato, R., Cornide, M.J., 2021. Lessons from the COVID-19 air pollution decrease in Spain: now what? Sci. Total Environ. 779, 146380. https://doi.org/10.1016/j.scitotenv.2021.146380.

R Core Team, 2017. R: A Language and Environment for Statistical Computing. R Foundation for Statistical Computing, Vienna, Austria.

Rai, A.C., Kumar, P., Pillai, F., Skouoldius, A.N., Di Sabatino, S., Ratti, C., Yasar, A., Ricketby, D., 2017. End-user perspective of low-cost sensors for outdoor air pollution monitoring. Sci. Total Environ. 691-695. https://doi.org/10.1016/j.scitotenv.2017.06.266, 607-608.

Reeve, Scott, H., Bolluri, 2013. This is not a burning issue for me: how citizens justify their use of wood heaters in a city with a severe air pollution problem. Energy. Energy Pol. 53, 204-211.

Reyes, R., Nelson, H., Navarro, F., Retes, C., 2015. The firewood dilemma: human health in a broader context of well-being in Chile. Energy Sustain. Dev. 28, 75-87.

Reyes, R., Schueftan, A., Ruiz, C., González, A., 2019. Controlling air pollution in a context of high energy poverty levels in southern Chile: clean air but colder houses? Energy Pol. 124, 301-311.

Roshan, GbR., Ghangherme, A.A., Attia, S., 2017. Determining new threshold temperatures for cooling and heating degree day index of different climatic zones of Iran. Renew. Energy 101, 156-167. https://doi.org/10.1016/j.renene.2016.08.053.

Rutllant, J., Garreard, R., 1995. Meteorological air pollution potential for Santiago, Chile: towards an objective episode forecasting. Environ. Monit. Assess. 34, 223-244. https://doi.org/10.1007/BF00057496.

Sanhueza, P.A., Torreblanca, M.A., Diaz-Robles, L.A., Schiappacasse, L.N., Silva, M.P., Reyes, R., Nelson, H., Navarro, F., Retes, C., 2015. The firewood dilemma: human health in a broader context of well-being in Chile. Energy Sustain. Dev. 28, 75-87.

Schueftan, A., Ruiz, C., González, A., 2019. Controlling air pollution in a context of high energy poverty levels in southern Chile: clean air but colder houses? Energy Pol. 124, 301-311.

Shaddick, G., Thomas, M.L., Amini, H., Broday, D., Cohen, A., Frostad, J., Green, A., Ruttllant, J., Garreaud, R., 1995. Meteorological air pollution potential for Santiago, Chile: towards an objective episode forecasting. Environ. Monit. Assess. 34, 223-244. https://doi.org/10.1007/BF00057496.

Setti, L., Passarini, F., Gennaro, G. De, Al, E., 2020. Searching for SARS-COV-2 on Sanhueza, P.A., Torreblanca, M.A., Diaz-Robles, L.A., Schiappacasse, L.N., Silva, M.P., Reyes, R., Nelson, H., Navarro, F., Retes, C., 2015. The firewood dilemma: human health in a broader context of well-being in Chile. Energy Sustain. Dev. 28, 75-87.

Silva, M.P., Reyes, R., Nelson, H., Navarro, F., Retes, C., 2015. The firewood dilemma: human health in a broader context of well-being in Chile. Energy Sustain. Dev. 28, 75-87.

Tariq, A., Undurraga, E.A., Laborde, C.C., Vogt-Geisse, K., Luo, R., Rothenberg, R., Chowell, G., 2021. Transmission dynamics and control of covid-19 in Chile, march–october, 2020. PLoS Neglected Trop. Dis. 15, 1–20. https://doi.org/10.1371/journal.pntd.0009070.

Tomas, A., Gehbhart, J., 1994. Correlations between gravimetry and light scattering photometry for atmospheric aerosols. Atmos. Environ. Conf. Visibility Fine Particles 28, 925–928. https://doi.org/10.1016/1047-3289(94)90251-8.

Thu, T.P.B., Ngoe, P.N.H., Hai, N.M., Tuan, L.A., 2020. Effect of the social distancing measures on the spread of COVID-19 in 10 highly infected countries. Sci. Total Environ. 742, 140430. https://doi.org/10.1016/j.scitotenv.2020.140430.

Vergara, L., Muñoz-Mejías, M., Pino-Sepúlveda, R., Ortega-Aguilera, R., García-Herrera, C., 2017. Thermal simulation of a social dwelling in Chile: effect of the thermal zone and the temperature-dependant thermophysical properties of light envelope materials. Appl. Therm. Eng. 122, 777-784. https://doi.org/10.1016/j.applthermaleng.2016.10.030.

Vergara, L., 2019. Mediacinacion social y transformaciones residenciales recientes en ciudades de La Araucania. Cult. Hombre-Soc. 29, 36-60. https://doi.org/10.7770/0719-2789.2019.cohs.04a03.

Wang, Y., Li, J., Jing, H., Zhang, Q., Jiang, J., Biswas, P., 2015. Laboratory evaluation and calibration of three low-cost particle sensors for particulate matter measurement. Aerosol. Sci. Technol. 49, 1063–1077. https://doi.org/10.1080/02786826.2015.1100710.

Wu, X., Netherly, R.C., Sabath, B.M., Al, E., 2020. Exposure to air pollution and COVID-19 mortality in the United States: a nationwide cross-sectional study. Medecin Prev. V´arez, M.A., Baetzig, R., Cornejo, J., Zamudio, F., Guajardo, J., Fica, R., 2017. Urban airborne matter in central and southern Chile: effects of meteorological conditions on fine and coarse particulate matter. Atmos. Environ. 161, 221–234. https://doi.org/10.1016/j.atmosenv.2017.05.007.

Zhao, Y., Xie, J., Huang, P., Cao, L., 2020. Association between short-term exposure to air pollution and COVID-19 infection: evidence from China. Sci. Total Environ. 727, 138704. https://doi.org/10.1016/j.scitotenv.2020.138704.