No Country for Old Men. Assessing Socio-Spatial Relationships Between Air Quality Perceptions and Exposures in Southern Chile

Àlex Boso1,6 · Aner Martínez2 · Marcelo Somos3 · Boris Álvarez4 · Constanza Avedaño5 · Álvaro Hofflinger4

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Abstract
An extensive body of research has been noted that many socially deprived communities tend to live in areas characterized by higher levels of outdoor air pollution. Whilst there is an expanding literature documenting this disproportionate distribution, most previous studies have taken place in the Global North, have focused with industrial or vehicle air pollution sources and have tend to ignore the complex interactions between exposures, public perceptions and social factors. In this paper, we investigate the social vulnerability to and risk perceptions of air pollution sourced from domestic heating in two Chilean cities with particularly high levels of PM$_{2.5}$ during winter months. To this end, we integrate primary survey data, with geographically detailed estimates of air pollution exposures and area-level characteristics obtained from the Chilean Census. We first examine the spatial distribution of PM$_{2.5}$ exposures and air quality perceptions, and subsequently explore relationships between socio-demographic characteristics, air pollution exposure, and health concerns. Our results revel evident spatial patterns of dispersion, with some neighborhoods being more polluted than others. Age and percentage of roofs in poor condition in the participant’s census tract are the best predictors of PM$_{2.5}$ exposure. We find no correlation between perceived and real levels of contamination. Our multivariate analysis indicates that personal perceptions of air quality are significantly associated with age, gender, family structure, and heating behaviors. Such detailed depictions provide insights into potential meaningful strategies to improve air quality and highlight the need to incorporate measures to better protect older adults.

Keywords Public perception · Air pollution · Chile · Environmental justice · PM$_{2.5}$

Àlex Boso
alex.boso@ufrontera.cl; alex.boso@ciemat.es

Extended author information available on the last page of the article
Introduction

Latin America is one of the most built-up regions in the world, with more than 80 per- cent of its population living in urban areas. The number of cities has increased sixfold in the last 50 years. Almost half of its urban population, about 242 million people, lives in cities with fewer than 500,000 inhabitants (United Nations, 2018). Some of these cities are noted for their dynamism, creativity and level of social innovation. However, they are also usually characterized for poorly planned growth, up to a certain point, disorganized, with large infrastructural deficiencies that cause high levels of social inequality and environmental degradation. In a few short decades, the result of a rapid and unequal process of economic development is that urban southern Chile has become one of the regions with the worst air quality on the planet (Jorquera et al., 2018; Boso et al., 2019, 2020).

Epidemiological studies suggest that prolonged exposure to air pollution is associated with higher rates of morbidity and mortality from respiratory and cardiovascular diseases (Cohen et al., 2017), and erodes emotional, psychological and social wellbeing (Barrington-Leigh & Behzadnejad, 2017; Lim et al., 2012; Pun et al., 2017). It can also affect social problems like the increase in school absenteeism (Liu & Salvo, 2018; Hofflinger & Boso, 2021) or the drop in a country’s GDP (Zhang et al., 2017). In southern Chile, air pollution stems from the widespread use of wood for domestic heating and cooking, as it is the cheapest fuel available (Reyes et al., 2019). The combination of a high percentage of low-income homes, inadequate thermal insulation and a large supply of old and inefficient wood-burning stoves forms a complex scenario of energy uncertainty that explains why more than two million people in the south of the country are exposed to annual unhealthy concentrations of PM$_{2.5}$ according to the WHO (Reyes et al., 2019; author, 2019; 2020). In this situation, the Government of Chile has implemented laws and pollution mitigation measures, including in particular Atmospheric Decontamination Plans (PDA). PDA are designed to curb wood-smoke air pollution, offering incentives to change stoves, aid for the improvement of fuel, a subsidy for thermal improvement and restrictions on the use of wood-burning stoves when pollution levels exceed certain limits as the main measures for atmospheric pollution control. However, the scale and multifactorial nature of the issue make improvements slow (Jorquera, 2021). Last winter, due to the intense emissions generated by residential wood-burning stoves and cookstoves as well as frequent atmospheric conditions due to a lack of wind, PM$_{2.5}$ concentrations higher than the standard national air quality (50 µg/m$^3$) were recorded in Temuco and Padre Las Casas for 27 and 66 days respectively according to the official numbers.

An extensive literature in environmental justice research has evidenced a relationship between air pollution and certain social attributes that usually define the conditions of people’s lives. For example, several studies conducted mainly in countries in the Global North suggest that low socioeconomic status and racial minority populations are disproportionately exposed to certain air pollutants (Brainard et al., 2002;

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1 In this study, following Pellow’s conceptualization (Pellow, 2007) the term Global North is employed as a social rather than strictly geographic term meant to refer to more privileged communities, such as those in the “developed” or “first” world. In the same vein, the term Global South refers to politically and economically marginalized communities or nations such as those found in the “developing” world.
Buzzelli and Jerrett, 2004; Mitchell & Dorling, 2003; Pearce et al., 2006). From disciplines like geography or sociology, it has been observed that there can be different abilities to face environmental dangers in the same city, and that some social groups are more vulnerable than others because they are more exposed to air pollution or they perceive it inadequately (Walker, 2012). Until recently, while it is known that air pollution levels are extremely severe in Latin American cities, there has been little systematic research from the distributive approach of environmental justice (Romero et al., 2010; Romero-Lankao et al., 2013). Relating individual sociodemographic and attitudinal data to real pollution data carries with it methodological difficulties for social researchers in the Global South who usually face severe limits on resources and data collection. The frequent large-scale wood-smog pollution caused by PM$_{2.5}$ in urban southern Chile in a context of great social inequality stresses the need to study potential unequal exposure distributions.

Recently, the environmental justice literature has extended its concern to uncovering spatial patterns of inequality in the exposure to certain environmental dangers by studying the psycho-social processes that explain how people perceive risks and make decisions to protect their health (Jones and Rainey, 2006; Collins et al., 2015; Chakraborty et al., 2017). Risk perception is one of the main indicators that social researchers use to describe public concern for air quality (Bickerstaff, 2004). Risk perception usually plays a relevant role when guiding the behaviors of civic protection, mitigation and involvement for the control of urban atmospheric pollution (Oltra & Sala, 2018). Hence, understanding the conditions under which people tend to under- or overestimate environmental risks is usually considered a basic prerequisite to planning effective measures for the protection of health against environmental hazards (Brody et al., 2004; Johnson, 2012).

Historically, social sciences have endeavored to measure the perception of air pollution and the general public’s concern through surveys or, alternatively, qualitative interviews and focus groups. Over the last two decades, a corpus of literature has become established that has examined among other things the extent to which the public perception of air quality, given its subjective nature, corresponds to the real values, measured using objective indicators like PM$_{2.5}$, SO$_2$ or the AQI index, among others. After years of investigation, there is no consensus in the specialized literature about the conditions that determine the public’s ability to correctly perceive air quality and to understand the risks that air pollution poses (Reames & Bravo, 2019). Some studies have reported a correlation between real and perceived pollution. For example, Peng et al. (2019) found consistency between real and perceived levels of particulate matter and sulfur dioxide in China. In addition, they discovered that the relation between the two variables was mitigated by the transparency of local governments. Similarly, Coi et al. (2016) reported a greater risk perception in the participants most exposed to air pollution from a sample of 282 subjects in Italy. Similar findings have been described in studies conducted in different cities such as Chicago (Cutter, 1981) and Kansas City (Reames & Bravo, 2019) in the U.S., Sarnia, Ontario, Canada (Atari et al., 2009) or Shanghai, China (Dong et al., 2019). However, other studies have not observed a significant correlation between real and perceived pollution levels. For example, in their study of Houston and Portland, Semenza et al. (2008) found no relation between those participants
who had a worse perception of air quality and their levels of exposure. The same inconsistency was discovered by Brody et al. (2004) in some of the first studies comparing objective and subjective pollution. Similar results were reported by studies conducted in such varied contexts as Israel (Berezansky et al., 2010), South Korea (Kim et al., 2012) or London (Williams & Bird, 2003). In summary, the literature does not offer an unequivocal answer about whether the general public can correctly perceive air pollution.

The frequent critical episodes that characterize winters in urban southern Chile jeopardize the health of the inhabitants. However, several questions remain unanswered about people’s air pollution exposures and concerns. How is air pollution spatially distributed in cities polluted by wood smoke? Which variables determine the different levels of individual exposure? To what extent can people perceive the quality of the air they breathe? Do they consider air pollution a real threat to their health or that of their main family and social ties? What factors determine the differences when perceiving and confronting the risks that air pollution poses? Answering these questions is not only relevant to fill the gap in the literature, but also to form the basis for the design and delivery of effective mitigation policies.

Data and Methods

Study Location

Temuco is the capital and largest city in the Region of La Araucanía. It has a population of 282,415 inhabitants on a surface of 464km². Padre Las Casas is a mid-sized commune with a population of 76,126 inhabitants on a surface of 465km². The two communes are located next to each other, divided by the Cautin River, forming a single large conurbation (See Fig. 1). In economic terms, according to the Social Development Report (MSDF 2018), La Araucanía is the region with the highest national poverty indices. However, Temuco concentrates the largest share of the wealth in the region, with an economy based mainly on the export of puffed or toasted cereals (36%) and fuel-wood (23%), in addition to solid commercial activity. On the other hand, Padre Las Casas has an Economic Complexity index five times smaller than Temuco, with an economy based mainly on the export of processed cereal grains (37%) and iron stovetops (35%).

The climate in these communes is oceanic, with high levels of humidity and precipitation almost the entire year. The temperatures are medium or high in summer with an annual mean of 10°C, whereas in winter the temperatures are low, with a mean of 3°C and several days of temperatures below 0°C. The climatic features of the area necessitate a high energy demand for heating, which is done mainly using wood-burning stoves. Due to the high pollution levels from particulate matter, Temuco and Padre Las Casas were declared zones saturated by PM_{10} in 2005 and PM_{2.5} in 2013 by the Chilean Ministry of the Environment (MMA in Spanish). Currently, Temuco and Padre Las Casas are among the most polluted cities in Chile and Latin America (IQAir, 2019).
Survey Data

Data Collection and Sample Structure

This study was based on a cross-sectional non-experimental design through the application of a one-time online survey. The data were collected in winter 2020, specifically between June and August. The questionnaire was answered by 639 participants residents of different macro-sectors in Temuco and Padre Las Casas. However, this study finally worked with a sub-sample of 586 people, including only those cases that reported their home address in order to perform a georeferencing analysis. To obtain the data, the online survey was applied using non-probability sampling by convenience. The study participants had to be over 18 years of age and resident in the communes of Temuco and Padre Las Casas. The ages of the participants went from 17 to 84 years (M = 38.41; SD = 16.22). Other sociodemographic characteristics of the sample are provided in Table 1.

The survey was disseminated online through several social networks like Facebook and Instagram. In addition, neighborhood associations in several areas of Temuco and Padre Las Casas were contacted to ask for their cooperation in disseminating the survey in their neighborhood. Additionally, to broaden the coverage of the survey in the population, application by telephone made it possible to reach participants who had no Internet connection or who did not handle digital media well. In all the application modalities, the participants were informed of the objectives of the study, as well as the ethical safeguards, including aspects such as voluntary participation and data confidentiality. Answering the survey took approximately 15 min.
Questionnaire Design

An online questionnaire was prepared, which consists of 2 sections. The first section includes sociodemographic questions such as age, gender, belonging to an indigenous people, socioeconomic level and education level. Questions were also included regarding the home such as main heating system, square meters or number of rooms. Additionally, the participants’ home address was asked about to generate a georeference of the surveys. In the second section, a series of questions were posed about the perception of pollution in Temuco and Padre Las Casas with a Likert-type response. These include perception of air quality in the city (1 = very bad; 5 = very good), perception of health risk (1 = not risky; 5 = very risky), level of concern for health (1 = not concerning; 5 = very concerning), among others.

To generate the index of perception of air pollution health risk, the approach of Howe et al. (2019) was followed, based on the average 9 items of perception. These items investigate 3 fundamental aspects: i) the likelihood they believe air pollution could affect their health in the next 5 years, ii) how much they think a winter pollution episode could damage their health, and iii) what their level of concern is about the effects of air pollution on their health. The participant must respond how they perceive each of these 3 aspects in: themself, their family and their neighbors, thereby generating a matrix of 9 items. The response alternatives and scores generated go from 0 to 100; the higher the score, the higher the perceived risk. At the psychometric level, these items present a good internal consistency (α = 0.957), and they behave as a single factor.

Census of Population and Household

We used information from the 2017 population and household census (hereby referred to as “the census”) to construct two variables that serve as a proxy to
determine household income level. The census has different questions about the characteristics of the construction of the houses, for example, the materials used to construct the floors, the walls and the roof. We identified the houses with low-quality roofs as those that use some of the following materials: a) phonolite or asphalted felt planks, b) straw, thatch, bulrush or cane, c) unstable materials (tin, cardboard, plastics, etc.) or d) no solid roof cover. Thus, we estimated the percentage of houses with low-quality roofs in the 97 zones defined by the census present in urban areas of the municipalities of Temuco and Padre Las Casas. Additionally, the census asks if any member of the household is unemployed, a variable used to estimate the percentage of unemployment in each census tract of the two municipalities. It is important to note the constructed variables, houses with low-quality roofs and unemployment, are used as proxy variables for household income. Given that people are generally hesitant about giving information on their income level, in particular when the collection instrument is an online survey (as in this case), we decided to use the construction quality of the houses and unemployment as indicators that helped compensate for that limitation, since both are highly correlated with household income level.

**Air Pollution Data and Estimates of Exposure**

Two monitoring networks were used to capture data on the concentration of fine particulate matter (PM$_{2.5}$) in the air in Temuco. The first network belongs to the MMA and the second to the Aire-CEIS project at the Universidad de La Frontera (UFRO). The stations are located in different parts of the city and measure PM$_{10}$ and PM$_{2.5}$ concentrations hourly. The MMA Network is composed of three Met One BAM-1020 monitoring stations. The UFRO network is made up of 22 low-cost stations that use SPS30 sensors that have been calibrated to the MMA network stations using beta attenuation.

Based on the hourly data from all the stations, maps were made to identify the distribution of pollution in the city. For this, lines were developed with the same pollution levels that connected records from the stations with equal concentration of particulate matter, using the Delaunay triangulation as the theoretical basis (Van Kreveld, 1997). First, all the points from each monitoring station were connected to generate triangles, the vertices of which do not overlap. Second, lines with the same pollution levels were generated. Third, colors were assigned to each line generated, associating red with high concentration levels and blue with low concentrations of PM. In the final step, a degradation of the colors between the lines was produced to map all the spaces in the city.

For this study, two maps were created, considering for the first the averages of the PM$_{2.5}$ concentrations for August 2020 since it is one of the months with the highest PM concentrations. The second map was generated using the maximum PM$_{2.5}$ concentration on the day where one of the events of greatest PM$_{2.5}$ concentration occurred in the city (25.05.2020). Later, both results of the mapping were contrasted and the areas of the city were identified for both cases that have the highest PM$_{2.5}$ concentration levels.
**Statistical Analysis**

The analyses of this study were done with Stata v. 16.1. In the first instance, descriptive analyses of mean and standard deviation were performed for the different study variables.

On the other hand, 3 linear regression models were built with 3 dependent variables: i) level of air pollution exposure (PM$_{2.5}$), measured as a continuous variable in units of micrograms per cubic meter (µg/m$^3$); ii) perception of air quality, measured as a categorical variable (five-point Likert scale); and iii) index of perception of air pollution health risk, measured as a continuous variable with values from 0 to 100. To validate the results of the air quality perception model (categorical dependent variable), a logistic regression model was estimated ($0 = $very bad or poor and $1 = $fair, good or very good air quality). The results of the logistic model are equal to the regression model in terms of statistical significance and sign of the coefficients. For this reason, it has been decided to keep the results of the linear regression, as it facilitates interpretation and comparison with the other models.

Three groups of variables for each model were used as independent variables. The first variables were on characteristics of the household: presence of children under 3 years, use of wood-burning stoves and exposure to PM$_{2.5}$ (except in the first model where this variable is the dependent variable). The second, variables of sociodemographic characteristics of the participant: age, gender and education level. The third, variables of characteristics of the participant’s neighborhood obtained with the census data: percentage of unemployed people and percentage dwellings with low-quality roofs in the sector. The latter were used as proxy variables for socioeconomic level. For each of these models, the linearity assumptions, multicollinearity and independence of errors were reviewed to give greater validity to the results.

**Results**

**Spatial Distribution of Air Pollution Exposure**

The results on the average particulate matter concentration levels in August in Temuco and Padre las Casas show a heterogenous distribution. Figure 2 shows 4 sectors in Temuco where the contamination is pronounced. These sectors are Amanecer (Z1), Santa Rosa (Z2), Las Encinas (Z3) and Fundo el Carmen (Z4). By contrast, in Padre las Casas the area farthest from the Cautin River (Z5) is the one with the highest concentration of particulate matter. All these areas with a high concentration of particulate matter are mainly residential areas, which is consistent with results from previous pollution studies that link the use of firewood as the main heating source in the residential sector.

Additionally, it is observed in Fig. 2 that the concentration of particulate matter in Temuco (Z1) is up to 10% higher than the maximum concentrations of PM$_{2.5}$ in Padre las Casas. This may be due to the Z1 sector being purely residential; however, in Padre las Casas, although the land use is mainly for residential purposes, there is also a significant part of the city that has commercial uses.
Spatial Distribution of Survey Responses

In addition to evaluating the spatial distribution of PM$_{2.5}$, we explored the spatial patterns of air quality perception and health risk perception in Temuco and Padre las Casas. The answers of the 586 participants of the survey were georeferenced through the home address reported. Then, these data were interpolated to obtain a general overview of the perception of air quality in the combined urban area.

In Fig. 3, the spatial distribution of air quality perception in the communes of Temuco and Padre las Casas can be seen. Generally, it is noted that the perception is very bad in most city sectors, with an average of 4.49 (SD=0.835). Nevertheless, there are some specific sectors that report an air quality perception as moderately good or very good, especially in the west of Temuco and northwest of Padre las Casas. In general, no clear spatial correlation was observed between the real and perceived pollution levels. In some of the most contaminated areas of the conurbation, such as the southwest area of Temuco or the southern area of Padre las Casas, positive perceptions of air quality were recorded.

In Fig. 4, the spatial distribution of the health risk perception due to air pollution in the communes of Temuco and Padre Las Casas can be observed. In this case, it is possible to note that the perception of risk is moderately high in most sectors with a mean of 72.82 (SD=22.47). However, moderately low or very low risk scores were observed in various sectors of the conurbation, with no clear spatial pattern being established. This indicates to us that the determinants of risk perception depend on factors not associated with characteristics of a certain neighborhood or area of the city.
Determinants of Air Pollution Exposure and Risk Perception

Table 2 shows the results of the three regression models built for the variables exposure to pollution, air quality perception and air pollution health risk perception. The column VIF (variance inflation factor) indicates that there is no multicollinearity between the independent variables used in the models.

The first model (Exposure) uses the level of exposure of the homes to PM$_{2.5}$ as a dependent variable. The results show that as the age of the participants increases, so too does the level of exposure of their homes ($p < 0.05$). On the other hand, as the level of education of the respondents increases, the level of exposure to PM$_{2.5}$ in their homes decreases ($p < 0.05$). In addition, when the percentage of houses with poor-quality roofs increases in the respondents’ residential neighborhoods (census zones), the level of exposure to PM$_{2.5}$ in their homes also increases.

The second model (Air Quality) uses the participants’ perception of air quality in the city as a dependent variable. The coefficients of the model show that homes with children under 3 years have a worse perception of the air quality than homes without children ($p < 0.05$). On the other hand, as the age of the participants increases, the perception of the air quality is more positive, which also happens in homes that use wood-burning stoves ($p < 0.05$).

The third model (Health Index) uses the index of risk to health from air pollution as a dependent variable. In this case it is observed that homes that use firewood as
Fig. 4 Health risk perception in Temuco and Padre Las Casas

Table 2 Regression Models

|                          | (1) Exposure | (2) Air Quality | (3) Health index | VIFa |
|--------------------------|-------------|-----------------|-----------------|------|
| Individual and household characteristics |             |                 |                 |      |
| Children < 3 years (dummy) | 0.06        | -0.19**         | 0.23            | 1.02 |
| Use of wood-burning stoves (dummy) | 0.06        | 0.26**          | -4.89*          | 1.12 |
| Exposure (pollution)      | -0.00       | 0.16            |                 | 1.13 |
| Age                      | 0.05*       | 0.01***         | -0.05           | 1.21 |
| Gender (woman)            | 0.59        | -0.06           | 4.58*           | 1.01 |
| Education                |             |                 |                 |      |
| High school (baseline elementary school) | -5.51**     | 0.37            | -3.05           | 1.37 |
| College                  | -3.92*      | 0.27            | -4.25           | 1.37 |
| Neighborhood characteristics |           |                 |                 |      |
| % unemployment           | 0.01        | 0.04            | 0.58            | 1.98 |
| % low-quality roofs      | 0.59***     | 0.01            | 0.13            | 2.14 |
| Observations             | 528         | 469             | 524             |      |

*** p < 0.001, ** p < 0.01, * p < 0.05

a Small VIF values indicate low correlation among the independent variables; ideally, VIF should be below 5 (Belsley, 1991)
fuel to cook or heat perceive air pollution as less dangerous than users of other types of heating technology \( (p < 0.05) \). By contrast, women perceive higher air pollution health risk levels \( (p < 0.05) \).

**Discussion**

From the pioneer studies of Bullard (1983), environmental justice research has consistently shown how Afro-American and Latin communities in the United States tend to be disproportionately exposed to air pollution from industrial sources or surrounding traffic (Brown, 1995; Miranda et al., 2011; Mohai et al., 2009; Ringquist, 2005; Walker, 2012). Other studies mainly conducted in the Global North have consistently shown that the poorest families are usually those most exposed to bad air quality (Jerrett et al., 2001; Brainard et al., 2002; Mitchell & Dorling, 2003; Buzzelli and Jerret, 2004; Pearce et al., 2006). However, previous studies have thus far been less successful when they have tried to evaluate socio-spatial distribution patterns of exposure to air pollution and risk perceptions in countries in the Global South, despite some noteworthy approaches (Romero et al., 2010; Romero-Lankao et al., 2013; Chakraborty & Basu, 2021). This article sought to improve the current state of knowledge regarding the major factors shaping exposure to and local perceptions of air pollution in the special context of urban southern Chile. Two main results should be highlighted.

First, despite wood-burning stoves, the main source of pollution, being dispersed throughout the city, the concentrations of \( \text{PM}_{2.5} \) are not distributed homogenously. Our interpolation of the data provided by two systems of monitoring stations located in different morphological and geographic zones of the two cities studied contributes one of the first representations of the urban canopy in southern Chile. The present study shows \( \text{PM}_{2.5} \) spatial dispersion patterns, with some sectors more polluted than others. When the contamination data are related spatially to individual and contextual sociodemographic variables, environmental inequality patterns are noted. Our statistical results indicate that the respondent’s age, education level and percentage of roofs in poor condition in the census tract partially explain the variations observed in exposure to \( \text{PM}_{2.5} \). Our interpretation of the results is that in southern Chile the environmental injustice communities emanate from the connection between environmental risks and structural sociopolitical factors. The case of older adults and the air pollution discovered in this article is paradigmatic.

One of strengths of the protests that exploded at the end of October of 2019 in Chile is the criticism of the private administrators of pension funds. The Chilean pension system is based on a person’s individual savings during their working life in a highly versatile and precarious market. Thus, only a minority of the population can pay in sufficiently to obtain a pension that ensures the material bases of subsistence in their old age with dignity. The mass use of poor-quality firewood for heating, the large supply of old devices and stoves, the bad quality of construction, or inadequate thermal insulation are a reflection of the energy uncertainty that characterizes many homes inhabited by older adults, with few studies conducted in the south of the country (Reyes et al., 2019; Boso et al. 2020a; Pérez-Fargallo et al., 2020). In...
this light, the unequal distribution of poor air quality described in this study can be interpreted as the environmental dimension of the situation of extreme social injustice to which a number of older Chilean adults are subjected.

Second, the maps of air quality perception in Temuco and Padre Las Casas show that, generally, their residents think the air in their city is heavily polluted. This result is consistent with previous studies, which indicated that the population of southern Chile has a basic knowledge of air quality thanks to the dissemination of information through formal and informal communication channels (Vallejos-Romero & Oñate-Nancucheo, 2013; Boso et al. 2018, 2019). However, there is less consensus about the health risk that air pollution poses among the participants. In this sense, our study has managed to identify how certain social groups who are clearly exposed to high levels of toxic air tend to dampen their risk perceptions. Interestingly, we have found no correlation between the perceived and real pollution levels. In a city that generally has bad air quality, the individual variables seem to be more determinant in predicting the participants’ perception rather than their real exposure to PM$_{2.5}$. Our multivariate analysis indicated that personal perceptions of air quality and air pollution health risk are significantly associated with gender, age, family structure and heating behaviors.

Two practical lessons can be inferred from this study. Traditionally, the Decontamination Plans in southern Chile have treated poor air quality as an environmental problem that affects the entire population the same (Vallejos-Romero and Oñate-Nancucheo, 2013; Reyes et al., 2019; author 2020). Most air pollution control measures seek to reduce average exposure over the city, considering only the general values shared by the official monitoring stations, rather than targeting exposure reduction and mitigation programs in those neighborhoods experiencing the strongest impact. This approach may neglect important spatial patterns, generating new situations of inequality. Our findings shed light on the variability associated with air pollution risk perception and exposures in Temuco and Padre las Casas. Focusing on neighborhoods and segmenting the public in risk communication campaigns are key to approaching the situations of environmental injustice uncovered in this study. In the same sense, the combination of PDA with structural social intervention policies aimed at improving residential conditions, pensions and, indeed, the quality of life of older adults, is necessary to obtain an effective reduction in their vulnerability levels. Our interpretation is similar to other previous studies that call for the need to design geographically-based decontamination plans to confront the challenges of environmental injustice.

The present study also illustrates the value of low-cost sensor developments in monitoring air quality. Through the new stations of the Aire project, we were able to utilize data from 22 PM$_{2.5}$ sensors. Had we relied on the official air monitoring network, we would have been limited to four PM$_{2.5}$ stations in our study area, greatly limiting our ability to interpolate air pollution data with respect to the complex topography of Temuco and Padre las Casas. Our study shows that the democratization of information, which the revolution of new low-cost technologies for environmental monitoring supposes, can create new opportunities for researchers and the environmental justice communities in the Global South. In appraising our results alongside the large body of literature from countries like the USA or Canada, it is observed that despite
differences in the specific groups and contextual circumstances, disproportionate air pollution exposure is concentrated in socially vulnerable communities. We believe that environmental justice principles appeal for a reduction of general air pollution levels starting from the most disadvantaged groups. The development of low-cost sensors can help environmental justice researchers and promoters to better identify these groups and design equitable and inclusive urban policies.

Our study has several limitations. Our survey has a certain over-representation of young participants. Although initially the survey was planned to be done in person, the Covid-19 pandemic forced the research team to redesign the data collection to safeguard the health of the participants and interviewers. As a result, the project was adapted to the telephone and online formats, which made it difficult to reach on a mass scale sectors of older adults or those with no Internet connection. Aware of the limitations of the context, additional efforts were made to disseminate the survey in groups of seniors through different channels such as neighborhood meetings, WhatsApp groups or other applications and through telephone calls. However, future studies could improve our results with more robust samples and fieldwork.

Conclusion

This study had two objectives: i) to evaluate the spatial distribution of the estimated exposures of PM$_{2.5}$ and the residents’ perception of air quality; ii) to identify which variables (individual, household or neighborhood) are associated with real and perceived pollution levels. Our study managed to clearly identify low-educated older adults, who live in neighborhoods with poor living conditions, as an environmental injustice community. They not only suffer through higher exposures to unhealthy levels of PM$_{2.5}$, but also tend to have greater difficulties subjectively evaluating the severity of the environmental risk they are facing. The results are not only relevant for the methodological challenge involved in spatially relating real pollution, perception of air quality and sociodemographic variables on different levels. Our findings call attention to the situation of older adults in urban southern Chile. The limitations of the Chilean pension and health systems means retirees must face serious situations of economic deprivation and lack of access to health care, in addition to living in poor environmental settings and having difficulties to use alternative fuels. On the other hand, a collective attenuation of risk perceptions among older communities, specially men, who are disproportionately exposed to high levels of PM$_{2.5}$ may reinforce the distributional injustice this group is coping with.

To summarize, our study demonstrates the complexities of the interaction between socio-demographics, living and environmental conditions and psychological factors, and the research challenges of and new opportunities for an environmental justice agenda in Latin America.

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Data Availability Data and additional materials are available on request.

Code Availability Not applicable.

Declarations

Ethics Approval The authors obtained written consent from all participants, in accordance with Universidad de la Frontera’s Research Ethics Committee.

Consent to Participate Not applicable.

Consent for Publication Not applicable.

Conflicts of Interest The authors declare that they have no competing interests.

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Authors and Affiliations

Àlex Boso1,6 · Aner Martínez2 · Marcelo Somos3 · Boris Álvarez4 · Constanza Avedaño5 · Álvaro Hofflinger4

Aner Martínez
aner.martinez@ufrontera.cl

Marcelo Somos
marcelo.somos@ufrontera.cl

Boris Álvarez
b.alvarez01@ufromail.com

Constanza Avedaño
avendano01@ufromail.cl

Álvaro Hofflinger
alvaro.hofflinger@ufrontera.cl

1 Department of Social Science, Faculty of Social Science, Education and Humanities & Butamallín Research Centre for Global Change, Universidad de La Frontera, Avenida Francisco Salazar 01145, Temuco, Chile

2 Department of Civil Engineering, Faculty of Engineering and Science, Universidad de La Frontera, Avenida Francisco Salazar 01145, 4780000 Temuco, Chile

3 Butamallín Research Centre for Global Change & Department of Forest Sciences, Faculty of Agriculture and Forest Sciences, Universidad de La Frontera, Avenida Francisco Salazar 01145, 4780000 Temuco, Chile

4 Núcleo en Ciencias Sociales Y Humanidades & Butamallín Research Centre for Global Change, Universidad de La Frontera, Avenida Francisco Salazar 01145, Temuco, Chile

5 Department of Civil Engineering, Faculty of Engineering and Science, Universidad de La Frontera, Avenida Francisco Salazar 01145, Temuco, Chile

6 Department of Environment, Socio-Technical Research, CIEMAT, Avenida Complutense 40, 28040 Madrid, Spain