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"Impact of Large Industrial Emission Sources on Mortality and Morbidity in Chile: A Small-Areas Study"

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Abstract

Chile suffers significant pollution from large industrial emitters associated with the mining, metal processing, paper production, and energy industries. The aim of this research was to determine whether the presence of large industrial facilities (i.e. coal- and oil-fired power plants, pulp and paper mills, mining facilities, and smelters) affects mortality and morbidity rates in Chile. For this, we conducted an ecological study that used Chilean communes as small-area observation units to assess mortality and morbidity. Public databases provided information on large pollution sources relevant to Chile. The large sources studied were oil- and coal-fired power plants, copper smelters, pulp and paper mills, and large mining facilities. Large sources were filtered by first year of production, type of process, and size. Mortality and morbidity data were acquired from public national databases, with morbidity being estimated from hospitalization records. Cause-specific rates were calculated for the main outcomes: cardiovascular, respiratory, cancer; and other more specific health outcomes. The impact of the large pollution sources was estimated using Bayesian models that included spatial correlation, overdispersion, and other covariates. Large and significant increases in health risks (around 20%–100%) were found for communes with power plants and smelters for total, cardiovascular, respiratory, all-cancer, and lung cancer mortality. Higher hospitalization rates for cardiovascular disease, respiratory disease, cancer, and pneumonia (20–100%) were also found for communes with power plants and smelters. The impacts were larger for men than women in terms of both mortality and hospitalizations. The impacts were also larger when the sources were

analyzed as continuous (production volume) rather than dichotomous (presence/absence) variables. In conclusion, significantly higher rates of total cardiovascular, respiratory, all-cancer and lung cancer mortality and cardiovascular, respiratory, cancer and pneumonia hospitalizations were observed in communes with power plants and smelters.

Keywords

cardiovascular; respiratory; cancer; power plants; copper smelter; mining facilities

Abbreviations

BYM: Besag, York, and Mollie

CAR: conditional autoregressive model

ICD-10: International Classification of Diseases, version 10

km^2: square kilometers

NO_X: nitrogen oxides

MW: megawatts

OECD: Organization for Economic Co-operation and Development

$PM_{2.5}$: particulate matter smaller than 2.5 micrometers

PM_{10}: particulate matter smaller than 10 micrometers

SO_2: sulfur dioxide

UNDP: United Nations Development Programme

HDI: Human Development Index

SES: Socioeconomic status

SMR: Standardized mortality/morbidity ratios

$USD: US dollars

US: United States

WinBUGS: Windows Bayesian inference Using Gibbs Sampling

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1 Introduction

Chile is a medium-sized country located in South America that has experienced substantial economic growth over the past several decades, resulting in a transition from a middle-income, developing nation to a high-income, OECD nation with a gross domestic product of $USD 14,581 by 2014 (World Bank, 2014). Its development strategy has focused on exploiting natural resources, especially copper mining, aquaculture, forestry, agriculture, and, more recently, a network of services in the major cities (Banco Central de Chile, 2015). This economic development has led to the installation of several large-scale industrial facilities across the country, including mines, smelters, pulp and paper mills, and a network of power plants, including coal- and oil-fired plants, to supply energy for industrial operations.

These large industrial facilities are known to emit large amounts of potentially toxic substances, into both the occupational environment (i.e. inside the facilities) and the general environment. These substances include known toxics such as criteria pollutants (*i.e.* particulate matter, nitrogen oxides, sulfur dioxide), metals, and carcinogens, as well as substances of unknown toxicity. These pollutants are released into the air, water, and solid waste and through dispersion processes can reach the population and pose a risk to human health.

Because these large industrial facilities present the risk of exposure to nearby populations, government and other organizations have developed public health agendas aimed at protecting the population. Efforts include air pollution regulations, emission permits, toxics release inventories, and occupational standards. However, there are several reasons to suspect that these regulations might not be entirely effective. First, facilities may emit several pollutants at the same time, potentially creating synergistic effects. Second, many of the pollutants released might be unknown or untested. For instance, a report to the US congress assessed that a large fraction of chemical substances has not been tested for toxicity (United States Government Accountability Office, 2005). Third, many of the pollutants have linear exposure-response functions (including most carcinogens and air pollutants such as $PM_{2.5}$ and ozone), meaning that there are no safe exposure levels, but risk levels considered "as low as practically acceptable" by the authorities. As environmental standards are usually set using cost-benefit criteria (Arrow et al., 1996), the population might be exposed to pollution that indeed poses health risks, albeit at levels deemed acceptable by authorities. Hence, there are likely risks associated with these known and unknown substances. Finally, there is always the chance that facilities fail to comply with the regulations, leading to exposure above limits or standards both for workers inside the facilities and for the general population.

Given the above, as well as concern on the part of communities residing near facilities, there have been efforts to better assess the overall public health impact of such large industrial facilities. Efforts to scientifically assess this impact have included ecological studies using small-areas, in which mortality and morbidity rates are compared for zones near the facilities versus more distant ones. Methods range from simple Poisson regressions to more modern Bayesian spatial models. To date, most research has been conducted in the United Kingdom (Dolk et al., 1999; Elliott et al., 1992; Elliott et al., 1996; Fielder et al., 2000; Sans et al., 1995; Wilkinson et al., 1999), Italy (Bilancia and Fedespina, 2009; Federico et al., 2010; Michelozzi et al., 1998; Parodi et al., 2004; Parodi et al., 2005), and more recently in Spain (Cambra et al., 2011; Cirera et al., 2013; Fernandez-Navarro et al., 2012; Garcia-Perez et al., 2013; Garcia-Perez et al., 2015; Garcia-Perez et al., 2010a; Garcia-Perez et al., 2010b; Garcia-Perez et al., 2012; Garcia-Perez et al., 2009; Lopez-Abente et al., 2006; Lopez-Abente et al., 2012a; Lopez-Abente et al., 2012b; Monge-Corella et al., 2008; Prieto et al., 2007; Ramis et al., 2011; Ramis et al., 2012; Ramis et al., 2009).

In Chile, major concerns include the potential impact of oil- and coal-fired power plants, due to their emissions of particulate matter ($PM_{2.5}$ and PM_{10}), sulfur dioxide (SO_2), nitrogen dioxides (NO_X), and metals such as mercury and arsenic; pulp and paper mills, due to their emissions of particulate matter, SO_2, sulfur compounds, and many organic carcinogenic such as dioxins and other halogenated (or chlorinated) compounds; and finally, large mining facilities and smelters, due to their emissions of particulate matter, SO_2, NO_X, and metals including arsenic and lead. Because of the nature and diversity of emitted pollutants, several health impacts are expected including cancer in several sites and cardiovascular and pulmonary diseases. The literature indicates that small-area ecological designs have only partially addressed the effects of large industrial facilities, with studies typically focused on mortality rather than morbidity (hospitalizations) and cancer rather than a wide scope of disease burden indicators such as cardiovascular or pulmonary outcomes (Bilancia and Fedespina, 2009; Cambra et al., 2011; Fernandez-Navarro et al., 2012; Garcia-Perez et al., 2015; Garcia-Perez et al., 2010a; Garcia-Perez et al., 2010b; Garcia-Perez et al., 2012;

Garcia-Perez et al., 2009; Liu et al., 2012; Lopez-Abente et al., 2012a; Lopez-Abente et al., 2012b; Monge-Corella et al., 2008; Parodi et al., 2004; Prieto et al., 2007; Ramis et al., 2011; Ramis et al., 2012; Ramis et al., 2009).

Previous studies in Chile have attempted to describe the spatial distribution of specific mortality outcomes using small-areas (Icaza G, 2006; Icaza G, 2013; Icaza et al., 2007), but no study to date has attempted to explore a specific hypothesis. Here we use a small-areas ecological study to determine whether the presence of large industrial facilities (i.e. coal- and oil-fired power plants, pulp and paper mills, mining facilities, and smelters) is associated with higher mortality and morbidity rates.

2 Materials and methods

2.1 Study site and design

Chile is a long and narrow midsized country located in southwestern South America (Figure 1). It has a total population of 17 million inhabitants and is divided administratively into 15 regions and 346 communes. Communes are the smallest units of local administration, with mayors elected by popular vote. Median commune population and surface area is 17,800 inhabitants and 633 km^2, respectively, although the range of figures varies widely (p25%-p75%: 9,158-51,043 inhabitants and 251-1658 km^2). Geographically, continental Chile extends from the parallels 17°29' in the north to 56°32' in the south, with a total length of 4200 km and an average width of about 200 km. Chile covers three climate zones, with the northern zone being arid, the central zone having a mild climate suitable for agriculture, and the southern zone being cold and humid, adequate for agriculture, livestock, and forestry. Regarding industrial facilities, large mining and metal processing facilities are located throughout the country, especially in the north. In the south, there are numerous forest plantations, with forest products processed to paper and other products in large pulp and paper mills. A network of power plants throughout the country provides energy to these large industrial operations, many of which are fueled by coal or oil.

To study the overall public health impact of these large industrial sources, an ecological study design was selected, using the commune as the small-area unit of observation. The ecological study design was selected because the health data were available at the commune level, which are the smallest units of local administration in Chile, and allows comparing zones with and without facilities as explained in the introduction. Because of their public health impact, we studied a set of ten specific health outcomes likely to be associated with the presence of large emission sources (see introduction), ranging from more general indicators such as total mortality and cancer, cardiovascular and respiratory diseases, as well as more specific outcomes, such as lung cancer and myocardial infarction for mortality, and leukemia and pneumonia for hospitalizations. The list of Outcomes studied are shown in Table 1. For each commune, data on mortality, hospitalizations, and population were aggregated for the 2000–2010 period, as Chilean population in some communes is very small, leading to observed cases per year of zero or close to zero, and therefore this aggregation was necessary in order to obtain robust and stable results.

Table 1. Health outcomes studied.

Type of outcome	Specific outcome (ICD codes)
Mortality	All deaths not due to external causes (A00–Q99) Cardiovascular (all I) Respiratory (all J) All cancers (all C) Lung cancer (trachea, bronchus, and lung, C33–C34) Myocardial infarction (I20–I24)
Hospitalization	Cardiovascular (all I) Respiratory (all J) All cancers (all C) Leukemia (C81–85; C88; C90–C96) Pneumonia (J12–J18)

Regarding exposure, we studied plants associated with industrial processes known to be most polluting and relevant for Chile, as explained in the introduction (*i.e.* coal- and oil-fired power plants, pulp and paper mills, mining facilities, and smelters). From them, we attempted to identify those facilities most likely to produce health impacts. For this, three selection filters were applied for all: i) first year of production, ii) type of process, and iii) facility size. Facilities were selected if they began production in year 2000, or earlier, with the rationale that this is a good trade-off between allowing time for chronic effects to take place (including latency factors) and acute impacts on the surrounding populations as all plants remain operating till year 2010. For type of process we identify the facilities most likely to impact nearby populations (*i.e.*, selecting the processes most likely to cause pollution), while for facility size (*i.e.* production capacity of the facility), we used a threshold based on a definition declared by the Chilean government, whenever possible, or by an international regulating agency in the absence of a Chilean definition.

Thus, for power plants, we selected facilities using coal, diesel oil, petcoke, or number 6 fuel oil, as these are known to emit large amounts of sulfur dioxide (SO_2), nitrogen dioxide (NO_X), particulate matter (PM), and heavy metals such as arsenic, mercury, and lead. We discarded facilities with a total capacity (sum of all sources inside a facility) below 50 MW as these are rather small internal engine facilities, as stated in the Power Plant Emission Standard Law (MMA - Ministerio del Medio Ambiente, 2009), representing only 0.08%, 0.04%, and 0.6% of PM, NO_X, and SO_2 emissions, respectively. A similar filter was used in a Spanish study (Garcia-Perez et al., 2009).

For pulp and paper mills, we selected facilities that produce paper and/or non-corrugated cardboard, as these processes require extensive use of chemicals including chlorinated substances. Regarding size, as no Chilean regulation specifies a threshold, we used a filter based on the European Union Integrated Pollution Prevention and Control (IPPC) guidelines (European Union, 1996), which regulate pulp and paper mills with production above 10,000 tony^{-1} and 25,000 ton y^{-1}, respectively. Finally, for mines and smelters, we selected copper facilities, as these are the largest facilities in Chile and are known to produce air, water, and solid pollutants. We did not include other minerals as these might produce different sets of pollutants, and therefore impact different health outcomes. Regarding size, for mining facilities we included only those considered “large mining facilities” by the Chilean Mining Law (Ministry of Mining, 1967), with production of at least 75,000 tons y^{-1}. We did not use a size filter for smelters, as there are no regulations that provide size-based classifications.

2.2 Data on large industrial sources

All information regarding large industrial sources was collected from public databases and is completely reproducible. Data was collected from a main data source, which were considered the most complete and reliable, and then complemented with other secondary data sources when necessary. For each source type, we built a master database including the owner, type of facility, location, product, type of process, annual production, and first year of production for each facility. Table 2 provides a summary of the information sources and selection filters, while Table 3 shows a summary of the selection process.

Table 2. Large industrial facilities; data sources and filtering process.

Plant Type	Data sources (Reference)	Filters
Power plants	Main • Report “Installed capacity of national electric system, 2011” from the Chilean National Energy Commission (CNE - Comisión Nacional de Energía, 2011) Secondary • Report “General analysis of economic and social impact (GAESI) of a power plant emission standard” from the Chilean Ministry of Environment (MMA - Ministerio del Medio Ambiente, 2009) • Environmental Impact Statement (“Declaración de Impacto Ambiental, DIA”) from Chilean Environmental Evaluation Service site (SEA - Servicio de Evaluación Ambiental, 2014) • Webpages from the companies owning the facilities	Process Coal, diesel, petcoke, or fuel oil number 6 First year of production 2000 or earlier Installed capacity Over 50 MW.
Paper mills	Main • Web page of the largest company: the Paper and Cardboard Manufacturing Company (CMPC - Compañia Manufacturera de Papeles y Cartones, 2014) Secondary • Website of the Manufacturing Development Society's Forestry Directory (Sociedad de Fomento Fabril - SOFOFA, 2014). • Website of the Cellulose and Paper Technical Association of Chile (ATCP Chile - Asociación Técnica de la Celulosa y el Papel Chile, 2014) The Industrial Board of Cellulose, Wood, and Paper DirCemp - Directorio Industrial de la Celulosa, 2014)	Process Paper and/or non-corrugated cardboard First year of production 2000 or earlier Installed capacity Over 25,000 tons per year
Pulp mills	Main • Report “General analysis of social and economic impact of preliminary revisions to the emission standards for disturbing odors associated with the manufacturing of sulfated pulp, 2011” (MMA - Ministerio del Medio Ambiente, 2011) Secondary • Web pages of the companies that own the facilities • In the case of an inconsistency, the Environmental Evaluation Service was consulted (SEA - Servicio de Evaluación Ambiental, 2014)	Process Pulp (Cellulose) production First year of production 2000 or earlier Installed capacity Over 10,000 tons per year
Mining facilities	Main • Web page “List of the nation's mining facilities” from the Chilean General Secretary of the Presidency (Secretaría General de la Presidencia del Gobierno de Chile, 2013) Secondary • Web page of the Mining Counsel (Consejo Minero, 2014) • Web page of the National Mining Society (SONAMI - Sociedad Nacional de Minería, 2014) • Web pages of the companies that own the facilities	Process Copper Year Staring Operations 2000 or before Installed Capacity More than 75,000 tons a year.
Copper Smelters	Main Report “Final evaluation report on the benefits of emissions standards for copper smelters” (MMA - Ministerio del Medio Ambiente, 2012)	Process Copper First year of production 2000 or earlier

Table 3. Large-pollution-source selection process.

Source Type	Initial n	Filter: First year of production	Filter: production type	Filter: installed capacity
Power plants	Facilities (n=135) Communes (n=66)	Facilities (n=36) Communes (n=26)	Facilities (n=31) Communes (n=23)	Facilities (n=16) Communes (n=11)
Paper mills	Facilities (n=13) Communes (n=12)	Facilities (n=13) Communes (n=12)	Facilities (n=8) Communes (n=8)	Facilities (n=7) Communes (n=7)
Pulp mills	Facilities (n=8) Communes (n=8)	Facilities (n=6) Communes (n=6)	Facilities (n=6) Communes (n=6)	Facilities (n=6) Communes (n=6)
Mining facilities	Facilities (n=40) Communes (n=22)	Facilities (n=31) Communes (n=20)	Facilities (n=22) Communes (n=15)	Facilities (n=13) Communes (n=10)
Copper Smelters	Facilities (n=7) Communes (n=7)	Facilities (n=7) Communes (n=7)	Facilities (n=7) Communes (n=7)	Facilities (n=7) Communes (n=7)

2.3 Health data

Data on mortality and hospitalizations are routinely collected by the Ministry of Health's Department of Statistics and Health Information. A dataset with individual events were downloaded from a government web site (MINSAL - Ministerio de Salud, 2014), which is available to all researchers upon request. Data included anonymous information for each individual event taken from death certificates and hospital records, with outcomes coded according to the World Health Organization's International Classification of Diseases, Version 10. Each record contained date of event (death date for mortality, admission and discharge dates for hospitalizations), ICD-10 code for the outcome, and patient characteristics such as commune of residence, age, sex, place of death, and marital status. More information on the quality of death certificate data can be found elsewhere (Nunez and Icaza, 2006). Four communes were redistricted (*i.e*. split in two communes) during the study period (Alto Hospicio - Iquique; Hualpén - Talcahuano; Alto Bío Bío - Santa Bárbara; and Cholchol - Nueva Imperial). As data was aggregated for the 2000-2010 period, we decided to preserve the year 2000 commune definitions and borders. Three communes were excluded because they are islands (Antarctica, Isla de Pascua, and Juan Fernandez), resulting in a total of 339 communes used in the study.

2.4 Data on population characteristics

Population data was extracted from the 2002 national census figures along with the projections for each year of the analysis, available at the National Statistics Institute (INE - Instituto Nacional de Estadísticas, 2014). Other covariates included were the Human Development Index (HDI) obtained from the United Nations Development Program (UNDP) (United Nations Development Programme, 2014) and urbanization obtained from the 2002 census also.

2.5 Data Analysis

Standard rates. For each outcome, national rates were calculated for each year (2000–2010), sex, and age group using the health and population data. Seventeen 5-year age groups were constructed, ranging from 0–5 years to >80 years. Crude rates were calculated for each commune by sex. Expected numbers of cases were calculated using the indirect method. Thus, for each year, sex, age group, and commune, expected cases were calculated using national rates and commune population statistics. Total expected cases per commune were then calculated for the entire 2000–2010 period. Observed cases were also calculated for each commune for the whole period, and standardized mortality/morbidity ratios (SMR) (θ_i) were calculated as the ratio of observed (O_i) and expected (E_i) cases in each commune i, as shown in Equation 1.

$$\vartheta_i = \frac{O_i}{E_i} \qquad \text{Equation 1}$$

Models. The impact of the large pollution sources was estimated within a Bayesian framework using the model proposed by Besag, York, and Mollie (BYM) (Besag et al., 1991), which has been used extensively in spatial epidemiology (Cambra et al., 2011; Carlin, 2000; Haining et al., 2007; Law et al., 2006; MacNab, 2011). Details on the model specifications and implementation are detailed elsewhere (Lawson, 2003). Briefly, the excess risk in a commune is calculated using Equation 2:

$$\ln\left(E_i\theta_i\right) = \ln(E_i) + \alpha + X_i\beta + u_i + \varepsilon_i \qquad \text{Equation 2}$$

where α is the intercept, X_i is a vector of covariates or fixed effects, including the presence of large pollution sources and other covariates, u_i represents spatial autocorrelation, and ε_i is an overdispersion parameter that follows a normal distribution $N(0, \sigma_\varepsilon^2)$. Bayesian modeling requires specification of prior distributions for all parameters. We selected a non-informative normal distribution for the parameter β and a uniform prior for α. The parameter u_i allows for risk estimation in any commune to depend on neighboring communes. Thus, u_i follows a conditional autoregressive model (CAR) as proposed in the BYM model (Besag et al., 1991):

$$(u_i|, u_j \neq j, \sigma_u^2) \sim N(\bar{u}_i, \sigma_i^2) \qquad \text{Equation 3}$$

where, $\bar{u}_i = \frac{1}{\sum_j \omega_{ij}} \sum_j u_j \omega_{ij,}\ \sigma_i^2 = \frac{\sigma_u^2}{\sum_j \omega_{ij}}$, and $\omega_{ij} = 1$ if *i* and *j* are adjacent, or 0 if they are not. Thus, to fit the model presented in Equation 3, it is necessary to define a matrix of adjacency or neighborhoods among the communes. To this end, we classified two communes as neighbors if they shared any part of their borders. Due to the presence of islands in the south of Chile, some communes do not share any borders. In these cases, we defined the neighborhood using connectivity criteria, that is, selecting the surrounding communes to which people commute to access to health services. This was the case for Chiloé, the largest island in southern Chile. To complete the model specifications, we defined a gamma distribution for the parameters σ_ε^2 and σ_u^2, as suggested by Bernardinelli et al. (1995).

Predictors. All models included all large pollution sources as predictors (see Table 3). Large sources were included as dichotomous (presence or absence) or continuous (installed capacity) variables. In the latter case, the size filter was not applied. Pulp and paper mills were mixed into a single term. Models that treated facilities as continuous predictors excluded the mining facilities, as their processes and relative production magnitudes varied greatly.

Based on the results of preliminary analyses, we added other covariates and adjusted for potential confounders to ensure replicable and interpretable results. These included i) socio-economic status (SES), ii) urbanization level, iii) commune size, and iv) outlier indicators. An aggregate SES measure was calculated from the HDI. Originally, this measure is a unique index ranging from 0 to 1 (with 1 representing the highest SES), constructed from three components: health, education, and income. Because the health dimension is assessed by life expectancy at birth, which already takes mortality into account, it cannot be used as an explanatory variable. Therefore, we used the education and income components of the index as separate predictors (both ranging from 0 to 1). Urbanization was included as a continuous (percent) and categorical variable, and commune size was calculated as a three-level dummy variable based on number of inhabitants: small (<10,000), medium (10,000 to 50,000), or large (>50,000). These thresholds were selected as they best fit the data. Finally, we constructed outlier terms to identify and exclude abnormally high or low results, defined as communes for which the logarithm of the calculated rate was greater than three standard deviations from the mean.

Implementation. Models were implemented in WinBUGS © (Lunn et al., 2000). We ran Markov Chains with 350,000 iterations and burn-in periods of 50,000 iterations. For each parameter, samples from the posterior distribution were selected every 300 iterations, resulting in a total of 1000 samples for posterior inference. The main parameters of interest were the estimated βs for the vector of covariates and their 95% credibility intervals. Relative risks were estimated by exponentiation of the βs and intervals. Models were run for each of the outcomes, separately by sex, modeling sources as dichotomous or continuous variables. All models were implemented including all covariates simultaneously (i.e. large sources, SES parameters, urbanization, size, and outliers), unless noted.

3 Results

3.1 Characterization of the large pollution sources

Information of the large sources selected for further analysis is summarized in Table 3 and Figure 1. Details on the selected large industrial sources by commune are reported in Tables S1-S4. Sixteen power plants were selected, located in eleven communes, mainly in northern Chile, with a total installed capacity of 4,845 MW. Two communes had particularly large installed capacities: Mejillones with 1,626 MW and Tocopilla with 877 MW. Thirteen pulp and paper mills were selected, located in eleven communes in central and southern Chile. Two communes in southern Chile were the largest producers: Arauco and Nacimiento, with 787,696 and 580,000 tons y^{-1}, respectively. Fifteen mining facilities were selected, mainly located in central and northern Chile. The Antofagasta region in the north (covering 9 communes) was the largest-producing copper mining area, with 2,274,308 tons y^{-1}, including the two largest-producing communes: Antofagasta and Calama, with 1,023,389 and 953,377 tons y^{-1}, respectively. Seven copper smelters were selected in seven communes in central and northern Chile; with Calama and Machalí being the largest-producing communes, with 1,544,674 and 1,372,022 tons y^{-1}, respectively. Finally, two communes had more than one large source: Mejillones, with two power plants and a mining facility, and Puchuncaví, with a power plant and copper smelter.

3.2 Impact of large pollution sources on health outcomes

Summary statistics for the health outcomes are shown in Table 4. Rates varied widely among communes. The main causes of mortality were cardiovascular diseases and cancer, followed by respiratory diseases; while the main cause of hospitalization was respiratory diseases, followed by cardiovascular diseases and cancer. Overall, mortality and morbidity rates were slightly higher for men than women.

Table 4. Summary statistics for health outcomes by commune and sex

	Men (annual cases/1000 persons)				Women (annual cases/1000 persons)			
Outcome	**Mean**	**SD**	**Min.**	**Max.**	**Mean**	**SD**	**Min.**	**Max.**
Mortality								
Total	5.38	1.71	0.22	13.13	4.73	1.55	0	14.61
Cardiovascular	1.67	0.60	0	3.85	1.42	0.55	0	4.87
Respiratory	0.59	0.23	0	1.76	0.54	0.25	0	2.61
All cancer	1.33	0.45	0	2.89	1.18	0.39	0	2.68
Lung cancer	0.14	0.09	0	0.78	0.07	0.05	0	0.29
Myocardial infarction	0.61	0.24	0	1.41	0.38	0.18	0	1.34
Hospitalizations								
Cardiovascular	6.20	2.65	0.16	15.18	5.49	2.45	0	16.29
Respiratory	11.51	6.08	0	35.78	11.00	6.41	0	36.45
All cancer	3.00	1.49	0	11.64	3.28	1.60	0	11.25
Pneumonia	5.20	2.99	0	16.19	4.95	3.08	0	17.92
Leukemia	0.62	0.48	0	4.09	0.46	0.41	0	3.28

The results for the health impacts of large industrial sources modeled as dichotomous variables are shown in Table 5, while impacts modeled as continuous variables are shown in Table 6. Associations were generally positive for the dichotomous models. Overall, large and significant relative risks were found for communes with power plants and smelters. Higher risks were also observed for communes with pulp and paper mills and mining facilities, but these were not significant. For men, communes with power plants had increases on the order of 20% for total and cancer mortality and 20%–40% for cardiovascular-, respiratory-, and pneumonia-related hospitalizations. For women, communes with power plants also had significantly elevated total and cancer mortality, but at a lower magnitude (10%) than for men, as well as significantly elevated hospitalizations. Communes with smelters had significantly increased rates of respiratory hospitalizations for men, on the order of 30%.

Table 5. Model results for the impact of large industrial sources modeled as dichotomous variables

	RR (95% CI), Men*				RR (95% CI), Women*			
Outcome	**Power plants**	**Paper and pulp mills**	**Copper smelters**	**Copper mining facilities**	**Power plants**	**Paper and pulp mills**	**Copper smelters**	**Copper mining facilities**
Mortality								
Total	1.11 (0.99–1.24)	1.01 (0.92–1.11)	1.09 (0.96–1.23)	0.99 (0.89–1.11)	**1.09 (1.01–1.18)**	0.99 (0.932–1.07)	1.08 (0.98–1.20)	0.96 (0.88–1.04)
Cardiovascular	1.08 (0.96–1.21)	1.03 (0.94–1.14)	1.08 (0.94–1.25)	0.99 (0.87–1.11)	1.08 (0.98–1.19)	1.00 (0.916–1.10)	1.12 (0.98–1.27)	0.94 (0.84–1.05)
Respiratory	1.04 (0.91–1.21)	1.04 (0.92–1.18)	1.18 (0.98–1.42)	1.01 (0.85–1.18)	1.01 (0.90–1.15)	0.97 (0.867–1.10)	1.07 (0.89–1.29)	1.04 (0.90–1.21)
All cancers	**1.16 (1.03–1.30)**	0.94 (0.85–1.04)	1.08 (0.95–1.24)	0.97 (0.86–1.10)	**1.09 (1.01–1.19)**	0.97 (0.909–1.05)	0.98 (0.88–1.08)	0.99 (0.91–1.10)
Lung cancer**	**1.20 (1.03–1.42)**	0.98 (0.83–1.15)	1.02 (0.81–1.29)	0.92 (0.75–1.14)	1.04 (0.91–1.20)	0.85 (0.718–1.00)	1.17 (0.91–1.50)	1.00 (0.81–1.24)
Myocardial infarction	1.10 (0.95–1.26)	1.02 (0.90–1.16)	0.99 (0.82–1.19)	1.00 (0.85–1.18)	1.16 (0.97–1.37)	0.92 (0.796–1.07)	1.09 (0.86–1.38)	1.04 (0.85–1.27)
Hospitalizations								
Cardiovascular	**1.28 (1.01–1.62)**	0.96 (0.77–1.19)	**1.33 (1.00–1.78)**	0.77 (0.60–1.01)	**1.33 (1.06–1.66)**	0.94 (0.754–1.16)	1.15 (0.88–1.52)	0.94 (0.74–1.18)
Respiratory***	**1.46 (1.14–1.90)**	1.01 (0.824–1.24)	1.33 (0.95–1.76)	0.92 (0.69–1.20)	**1.44 (1.10–1.87)**	1.00 (0.802–1.24)	1.22 (0.85–1.76)	1.00 (0.76–1.34)
All cancer**	1.19 (0.98–1.44)	0.94 (0.80–1.010)	1.14 (0.92–1.44)	0.90 (0.71–1.10)	1.09 (0.88–1.32)	0.92 (0.773–1.07)	0.99 (0.77–1.30)	0.97 (0.78–1.20)
Pneumonia**	**1.33 (1.04–1.72)**	1.04 (0.84–1.28)	1.40 (0.98–1.96)	0.95 (0.72–1.26)	**1.40 (1.02–1.86)**	1.04 (0.816–1.31)	1.23 (0.85–1.77)	0.90 (0.74–1.10)
Leukemia**	0.87 (0.57–1.28)	0.98 (0.71–1.36)	1.44 (0.83–2.40)	0.67 (0.42–1.03)	0.97 (0.65–1.43)	1.03 (0.76–1.43)	0.72 (0.40–1.28)	1.18 (0.71–1.70)

*Model covariates: Urbanization (continuous) + Size of commune (categorical) + HDI income + HDI education+ (outliers)
** Model covariates: Urbanization (categorical) + Size of commune (categorical) + HDI income + HDI education+ (outliers)
*** Model covariates: Size of commune (categorical) +HDI income + HDI education + (outliers)
Bold: estimates whose 95% credibility intervals do not include 1

Table 6. Model results for the impact of large industrial sources modeled as continuous variables.

	RR (95% CI), Men*			RR (95% CI), Women*		
Outcome	**Power plants**	**Paper and pulp mills**	**Copper smelters**	**Power plants**	**Paper and pulp mills**	**Copper smelters**
Mortality						
Total	**1.42 (1.16–1.73)**	0.93(0.80–1.09)	**1.17 (1.03–1.33)**	**1.19 (1.02–1.37)**	0.96(0.84–1.08)	1.09(0.98–1.20)
Cardiovascular	**1.26 (1.01–1.60)**	0.98(0.83–1.15)	**1.15 (1.01–1.31)**	1.20(0.98–1.51)	0.96(0.81–1.12)	**1.16 (1.02–1.33)**
Respiratory	1.29(0.96–1.72)	0.95 (0.76–1.19)	**1.26 (1.06–1.52)**	1.03(0.78–1.39)	0.96(0.79–1.17)	1.09(0.93–1.28)
All cancers	**1.70 (1.36–2.13)**	0.87(0.75–1.04)	**1.16 (1.01–1.34)**	**1.25 (1.04–1.50)**	0.92(0.82–1.05)	1.03 (0.92–1.15)
Lung cancer	**1.94 (1.36–2.74)**	0.83(0.58–1.14)	1.03(0.81–1.29)	1.35(0.87–2.03)	0.64(0.43–0.93)	1.11(0.88–1.40)
Myocardial infarction	1.27(0.96–1.69)	1.04(0.83–1.30)	1.11(0.93–1.35)	1.16(0.82–1.64)	0.89(0.68–1.16)	1.07(0.87–1.34)
Hospitalizations						
Cardiovascular	**1.72 (1.12–2.67)**	0.93(0.63–1.35)	1.32(0.96–1.78)	**1.71 (1.16–2.59)**	0.90(0.65–1.30)	1.28(0.96–1.70)
Respiratory	**1.72 (1.05–2.80)**	1.14(0.75–1.69)	1.39(0.98–1.95)	**2.07 (1.33–3.19)**	1.18(0.78–1.82)	1.37 (0.98–1.90)
All cancer	**1.78 (1.23–2.59)**	0.97(0.70–1.32)	1.28(0.99–1.66)	**1.78 (1.23–2.59)**	1.09(0.77–1.54)	0.98(0.77–1.25)
Pneumonia	**1.71 (1.05–2.75**)	1.17(0.77–1.83)	**1.42 (1.02–2.04)**	**1.92 (1.16–3.22)**	1.27 (0.81–1.93)	1.35(0.93–1.97)
Leukemia	1.08(0.52–2.29)	1.17(0.60–2.23)	1.43 (0.80–2.43)	0.65(0.32–1.36)	0.88(0.45–1.71)	0.88(0.51–1.48)

*Model covariates: Urbanization (categorical) + Size of commune (categorical) + HDI income + HDI education + (outliers)

** For power plants, change in RR per 1000 MW of installed capacity. For paper and pulp mills, change in RR per 700,000 tons per year of production. For copper smelters, change in RR per 1,000,000 tons per year of production.

Bold: estimates whose 95% credibility intervals does not include 1

When modeling sources as continuous variables (Table 6), results yielded even more statistically significant associations, as well as associations of greater magnitude, than the previous ones modeled as dichotomous. The greatest impacts were again found for communes with power plants and smelters, while non-significant positive associations for pulp and paper mills were found. For men, communes with power plants showed the greatest associations, with increases in total, cardiovascular, all-cancer, and lung cancer mortality on the order of 30%–100% per 1000 MW of installed capacity. Hospitalizations were increased by about 70% for pneumonia, with more modest increases for cardiovascular disease, respiratory disease, and all cancers. The same pattern was observed for women. Communes with power plants showed increases of about 20%–30% per 1000 MW for total and all-cancer mortality, and about 70–100% per 1000 MW for hospitalizations due to cardiovascular disease, respiratory disease, all cancers, and pneumonia. In communes with smelters, men showed increased total, cardiovascular, respiratory, and all-cancer mortality, on the order of 10%–20% per million tons/y of production, and increased rates of hospitalizations for pneumonia, on the order of 40% per million tons/y of production.

4 Discussion

This study reveals that communes with power plants experience elevated mortality and hospitalization rates. Communes with smelters also suffer higher mortality and morbidity, albeit at lower rates and with less consistency among outcomes. Several findings are consistent with the hypothesis that these large sources of pollution have a major health impact for the population. First, increases in morbidity and mortality were generally large, on the order of 10%–100%. Second, results for mortality and morbidity by health outcome were consistent. Third, the health impacts were typically greater among males than females, attributable to increased occupational exposure to the pollutants. Fourth, impacts were greater and more consistent when exposure was modeled as a continuous variable (*i.e.* facility size), which is expected as the continuous variable serves a better surrogate for exposure than the dichotomous one. Finally, the health impacts observed could be explained, at least in part, by air pollutants (PM, NO_X, and SO_2). Communes with power plants or smelters are likely to have high air pollution levels, and high air pollution has been shown to produce the type of impacts observed (WHO, 2005). As an example, according to the WHO air quality guidelines, increases of $PM_{2.5}$ of 10 μg m^{-3} have been associated with increases in total and cardiopulmonary long-term mortality of 4% and 6%, respectively.

Several ecological studies have analyzed the impact of industrial sources; however, few have analyzed the sources and health outcomes targeted by this study (Table S5). For mortality, studies performed in the Basque region of Spain (Cambra et al., 2011) have reported that power plants and smelters impact cancer mortality and total mortality, respectively. These studies also reported that smelters affect respiratory and myocardial infarction mortality in women; in our study, we found a positive but statistically insignificant associations for these relationships. For Spain as a whole, Garcia-Perez et al. reported that the presence of a power plant impacted lung cancer at a magnitude similar to that found in this study. Similar findings were obtained by Parodi et al. and Bilancia et a. in Italy (Bilancia and Fedespina, 2009; Parodi et al., 2004). However, Fernandez-Navarro et al., Ramis et al. and Garcia-Perez et al. found that mining facilities also impacted rates of lung cancer, which we were not able confirm here (Fernandez-Navarro et al., 2012; Garcia-Perez et al., 2015; Garcia-Perez et al., 2009; Ramis et al., 2012). Regarding hospitalizations, only one study, performed in New York, has analyzed the impact of power plants at the small-area (Liu et al., 2012). As the current study, the authors found an impact on respiratory disease hospitalizations. Finally, several studies have found impacts on cancer mortality for paper or pulp mills, however in general these impacts are on specific cancer locations (Lopez-Abente et al., 2012a; Lopez-Abente et al., 2012b; Ramis et al., 2012). Overall, the impacts that we found for power plants and smelters are consistent with the literature though greater in magnitude than previously described, possibly due to more stringent regulations in other countries.

There are limitations to this study. First, it is an ecological study which makes it difficult to establish causality; however, the advantage of this design is that it can capture associations across different aggregated populations. Second, because the time-aggregation used (2000-2010) a trade-off in aggregating exposure data (before 2000) was chosen. This can introduce a possible exposure misclassification as there could be less than needed latency time for long-term impacts, and also underestimate exposures after year 2000 for short-term impacts. This bias should be minor as i) chronic impacts will likely dominate over acute impacts for most outcomes, ii) latency factors are likely to be covered as most plants started well before year 2000, iii) acute impacts should be dominated by plants operating before 2000, as only large power- and cellulose-plants were installed recently, and mostly after year 2005. Another misclassification problem is the exposure aggregation at the commune level. We did not consider impacts of plants in surrounding communes as we consider the observing unit being rather large spatially and absorb most of the impacts. In any case, if a misclassification bias take place, both for temporal and spatial aggregation, it will likely bias the results to the null, so our observations would represent conservative estimates.

Third, the study analyzed an earlier time period, prior to the introduction of several recent regulations in Chile; therefore, the impacts found might not reflect the current situation. This provides an opportunity to explore the public health impact of major regulations introduced after the year 2000 as an ongoing effort. A fourth limitation is related to the set of outcomes studied. As this is the first study of its kind in Chile, we chose fairly broad disease markers. This limitation may explain why some pollution sources did not appear to have an impact. More specific outcomes (such as specific cancer locations) and populations (such as children or the elderly) should be addressed in future studies. The fact that we did not find impacts for some sources may also be attributable to sample size, as the impact may be smaller than the credibility intervals provided by the study.

Regarding data quality, in Chile mortality data is generally considered to be a more reliable than hospitalizations. Hospitalization data is also complicated by the problem of multiple records for one incident event. However, in this study, mortality and hospitalization results were highly consistent. Potential confounders include covariates associated both with exposure and outcomes. One such confounder is SES as is likely that communes with industrial plants have lower SES and it is known that populations with low SES have poorer health (Brulle and Pellow, 2006; James et al., 2012; Norton et al., 2007), which has been shown in Chile (Frenz and Gonzalez, 2010; Gattini et al., 2002). However, SES can be both as confounder, *i.e.* have an independent effect, or can be causally linked with industrial plants, *i.e.* SES impacts health through exposure to industrial plants. Considering the later possibility imply that our results are conservative estimates. Residual confounding is always a possibility, but it is unlikely that could explain the large impacts observed in this study. Another potential confound is smoking, which was not measured. However, for smoking to act as a confounder, communes with large sources of pollution must have a higher smoking prevalence than communes without these facilities, which is also unlikely.

Several approaches might be used in future studies. First, researchers could analyze health impacts in even smaller areas such as census tracts, which could improve the precision of the exposure variables. To this end, it may be advisable for the government (DEIS) to collect health information at this level. Another way to improve the precision of the exposure variables is to gather more precise information regarding facility emissions. In Chile, since 2005 emissions are declared by facilities using the Ministry of Environment's Registry of Emissions and Contaminant Transfers (Ministerio del Medio Ambiente Chile - MMA, 2014). However, this system could not be used for this study, as no data was available before 2005, and at the time of the study the information regarding air and water discharges was incomplete. Furthermore, the registries included addresses but not company names, which could lead to errors in identifying the industrial facilities. Third, the analysis of health impacts could be improved by increasing the number of outcomes and stratifying the sample into specific age groups such as children and the elderly. As explained above, some pollution sources might have specific health impacts (such as asthma, COPD, other leukemia and blood disorders, specific cancers locations, specific cardiovascular outcomes, malformations, and so on) not covered in this study. Finally, the current study can be used as a baseline to study the health impacts of current and future regulations for large industrial sources of pollution.

This is the first study of its kind in Chile, and to our knowledge, Latin America. Despite its limitations, if the large health impacts identified here are even partially valid, current regulation and operation of these facilities should be reviewed to protect the surrounding populations and workers. Public health efforts should include reviewing emission standards, emission permits, environmental standards, and occupational regulations. We noted that several efforts have been ongoing since 2000 regarding this issue. Finally, as an organized society, we may do well to evaluate whether these facilities should be built farther from human populations and whether we might update them to cleaner production systems or replace them, for instance, for renewable energy sources.

In conclusion, communes with large industrial sources of pollution, especially power plants and smelters, showed large health impacts as measured by mortality and morbidity. The main health outcomes affected were total mortality as well as mortality and morbidity related to cardiovascular disease, pulmonary disease, and cancer.

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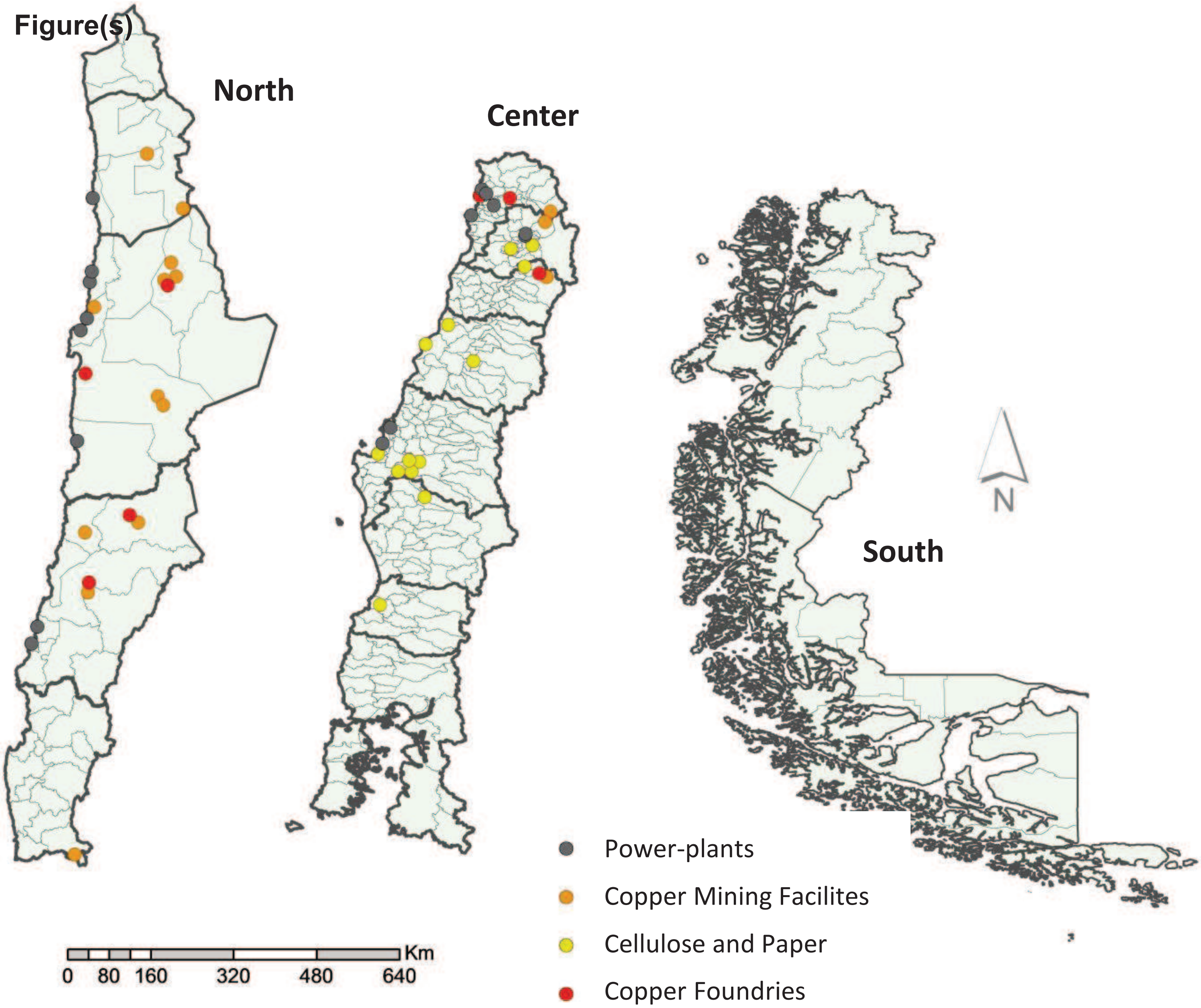
Figure(s)



North
Center
South
N
Power-plants
Copper Mining Facilites
Cellulose and Paper
Copper Foundries
Km
0
80
160
320
480
640