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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.

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

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 μm; PM_{10}, particulate matter smaller than 10 μm; 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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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, 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, 2005), and more recently in Spain (Cambra et al., 2011; Cirera et al., 2013; Fernandez-Navarro et al., 2012; Garcia-Perez et al., 2013, 2015, 2010a, b, 2012, 2009; Lopez-Abente et al., 2006, 2010a, b, 2012, 2009; Monge-Corella et al., 2008; Prieto et al., 2007; Ramis et al., 2011, 2012, 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, 2010a,b, 2012, 2009; Liu et al., 2012; Lopez-Abente et al., 2012a,b; Monge-Corella et al., 2008; Parodi et al., 2004; Prieto et al., 2007; Ramis et al., 2011, 2012, 2009).

Previous studies in Chile have attempted to describe the spatial distribution of specific mortality outcomes using small-areas (Icaza et al., 2006, 2013, 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 (Fig. 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%: 9158–51,043 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.

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