High resolution inventory of atmospheric emissions from transport, industrial, energy, mining and residential ~~sectors~~activities of Chile

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Abstract. This study presents the first high-resolution national inventory of anthropogenic emissions for Chile (INEMA). Emissions for vehicular, industrial, energy, mining and residential sectors are estimated for the period 2015-2017 and spatially distributed onto a high-resolution grid (1 x 1 km approximately). The pollutants included are CO_2, NOx, SO_2, CO, VOCs, NH_3, and particulate matter (PM_{10} and $PM_{2.5}$) for all sectors. CH_4 and Black Carbon are included for transport and residential sources, while Arsenic, Benzene, Mercury, Lead, Toluene, and Polychlorinated dibenzo-p-dioxins and Furan (PCDD / F) are estimated for energy, mining and industrial sources. New activity data and emissions factors are compiled to estimate emissions, which are subsequently spatially distributed using census data and Chile´s road network information.

The estimated ~~total~~ annual average total national emissions of PM_{10} and $PM_{2.5}$ during the study period are 191 and 173 kilotonnes (~~Kt)~~ ,kt/annum), respectively. The residential sector is responsible for over 90% of these emissions. This sector also emits 81% and 87% of total CO and VOC, respectively. ~~Additionally~~On the other hand, the energy and industry sectors contribute significantly to NH_3, SO_2, CO_2 emissions while the transport sector dominates NOx and CO_2 emissions, and the ~~Mining~~mining sector dominates SO_2 emissions. In general, emissions of anthropogenic air pollutants and CO_2 in northern Chile are dominated by mining activities as well as thermoelectric power plants while in central Chile the dominant sources are transport and residential emissions. The latter also mostly dominates emissions in southern Chile which has a much colder climate. Preliminary analysis revealed the dominant role of the emission factors in the final emission uncertainty. Neverthel ess, uncertainty in activity data also contributes~~,~~ as suggested by the difference in CO_2 emissions between INEMA and EDGAR. A comparison between these two inventories also revealed considerable differences for all pollutants in terms of magnitude and sectoral contribution, especially for the residential sector. EDGAR presents larger emissions for most of the pollutants except for CH_4 and $PM_{2.5}$. The differences between both inventories can partly be explained by the use of different emission factors, in particular for the residential sector where emission factors incorporate information on firewood and local operation

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conditions. ~~However, as mentioned above~~Although both inventories use similar emission factors, differences in CO_2 emissions between both inventories ~~also points to~~indicates biases in the quantification of the activity.

This inventory (available at ~~https://doi.org/10.5281/zenodo.4784286~~https://doi.org/10.5281/zenodo.4784286) (Alamos et al., 2021)) will support the design of policies that seek to mitigate climate change and improve air quality by providing policy makers, stakeholders and scientists with qualified scientific spatial explicit emission information.

1. Introduction

Air pollution is one of the main environmental challenges in Chile; in 2018 more than 9 million of its population (out of 17 million) were exposed to concentrations of fine particulate matter ($PM_{2.5}$) above the national air quality standard~~,~~ (50 and 20 µg/m3 for annual and 24-h standard, respectively), and around 3,640 cases of premature mortality were estimated due to cardiopulmonary diseases (MMA, 2019a). Urban areas of central and southern Chile are among the most polluted in Latin America with ~~important~~serious consequences for human health (Romero-Lankao et al., 2013) including an increase in hospital admissions and mortality associated with cardiovascular and respiratory diseases (WHO, 2016).

The current air pollution and climate change problems are directly related to atmospheric emissions of criteria pollutants - which affect air quality - and greenhouse ~~gas~~gases (GHG). Identifying the origin and estimating the emissions of these pollutants by source type is a prerequisite for quantifying the impact of anthropogenic activity on air quality and climate, and thus developing effective mitigation strategies. Additionally, having GHG emissions and criteria pollutants consistent with each other is key in the design of policies that allow addressing climate change and air quality in an integrated manner (Melamed et al., 2016).

Currently, emission inventories of GHG in Chile are produced within the framework of their national determined contributions (NDCs) as part of the commitments with the Parties to the United Nations Framework Convention on Climate Change (UNFCCC). Emission inventories of criteria pollutants are developed for the most polluted cities within the framework of the decontamination plans to develop mitigation strategies to improve urban air quality. The national GHG emissions are prepared by a team of professionals from the Ministry of Environment (MMA from Spanish Ministerio del Medio Ambiente) responsible for the development and ~~update~~updating of the GHG emission inventories, whereas the ~~latter~~decontamination plans are prepared by consultants hired on a case-by-case basis. Furthermore, while GHG inventories are performed consistently over the years, urban emission inventories of criteria pollutants are not necessarily consistent with previous versions and/or emission inventories of other cities. Additionally, the ~~Register of~~Pollutant Release and Transfer ~~of Pollutants~~Register (RETC from Spanish Registro de Emisiones y Transferencia de Contaminantes) from the MMA gathers the emission declaration from the industrial sector and combines it with emission ~~estimate~~estimates from the residential and transport ~~sector~~sectors from different

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state agencies to build a national emission inventory. This information is available to the population through a dedicated web platform (www.retc.cl).

While the national GHG inventory provides annual emissions at a national and regional scale, inventories of criteria pollutants provide annual emissions at a communal[1] level ~~(~~for the case of RETC~~),~~ or for an entire city ~~(~~for the case of Decontamination Plans~~). However,~~. Thus, none of these inventories ~~(GHG and/or criteria pollutants) do not~~ have the spatial ~~nor the temporal~~(gridded) resolution necessary for air quality modelling. Regional air quality (AQ) assessments in South America have relied on global emission inventories to understand the interactions between emissions, air quality and public health (e.g. Longo et al., 2013; Rosario et al., 2013; Klimont et al., 2017; UNEP/CCAC, 2018). Furthermore, a comparison of global emission inventories against city-scale emission inventories for five South American cities (namely, Buenos Aires, Bogota, Lima**,** Rio de Janeiro and Santiago) revealed that although total emissions are in general comparable for these cities between the inventories, large differences exist for sectoral estimates (Huneeus et al., ~~2020~~2020a). Given that mitigation of air quality depends on identifying the dominating emission sectors, using global emission inventories is not recommended to define mitigation policies due to the risk of identifying the wrong target (Huneeus et al., ~~2020~~2020a). Therefore, national inventories built on local data are needed to understand the contribution of human activity to air quality and climate change and to design effective mitigation policies.

This paper presents the first gridded national inventory of anthropogenic emission for Chile of criteria pollutants as well as GHG (hereafter INEMA from Spanish **I**nventario **N**acional de **EM**isiones **A**ntropogénicas). The paper is structured as follows; the data and methodology used to estimate the emissions of each pollutant and sector are presented in section 2 while in section 3 the main results are shown, differentiating between the main pollutants and sectors that acquire relevance in the different regions of Chile. Discussion of the main results and uncertainty analysis of the estimated emissions are presented in section 4. Finally, in section 5 the main conclusions of this work are presented.

2. Methodology and data

The INEMA inventory includes yearly emissions of ~~Carbon Dioxides~~carbon dioxides (CO_2), ~~Nitrogen Oxides~~nitrogen oxides (NOx), ~~Sulfur Dioxides~~sulfur dioxides (SO_2), ~~Carbon Monoxide~~carbon monoxide (CO), ~~Volatile Organic Compounds~~volatile organic compounds (VOCs), ~~Ammonia~~ammonia (NH_3) and ~~Particulate Matter~~particulate matter (PM_{10} and $PM_{2.5}$) from the residential (section 2.2), industry (section 2.3), energy (section 2.3), mining (section 2.3) and transport sectors (section 2.4)

[1]The commune is the smallest administrative and territorial unit in Chile, and is equivalent to what is known in other countries as a municipality.

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for the years 2015 to 2017. Additionally, the residential and transport sector include emission estimates of ~~Methane~~methane (CH_4) and ~~Black Carbon~~black carbon (BC), while for the industry, mining and energy sector emissions of ~~Arsenic, Benzene, Mercury, Lead, Toluene~~arsenic, benzene, mercury, lead, toluene, and ~~Polychlorinated~~polychlorinated dibenzo-p-dioxins and ~~Furan~~furan (PCDD / F) are also reported. Emissions are grouped into sectors following the IPCC (2006) classification (Table 1). It's important to clarify that in this inventory residential emission estimations only consider firewood combustion, while the IPCC subcategory 1A4b considers all emissions from fuel combustion in households.

Throughout this paper we will follow the EDGAR nomenclature and use the term “sectors" to refer to emission activities (Crippa et al., 2018) and emissions will correspond to annual fluxes. Furthermore, emissions of NOx correspond to emission of NO_2+NO and thus the units are ktNOx/annum while for VOC and NMVOC the corresponding unit are ktVOC/annum and ktNMVOC/annum.

Sector considered on this paper	**IPCC Code**	**IPCC ~~Sector~~Categories**	**Pollutants considered in our inventory**
Energy	1A1	Energy Industries	CO, CO_2, VOC, NOx, NH_3, $PM_{2.5}$, PM_{10}, SO_2, Benzene, Arsenic, Toluene, PCDD/F, Mercury, and Lead
Industry	1A2 and 2, excluding 2C	Manufacturing Industries and Construction; Industrial Processes and Product Use	
Mining	2C1, 2C2, 2C3 and 2C4	Metal Industry	
Residential firewood combustion	1A4b	Residential ~~and others energy sector~~	CO, CO_2, NMVOC, NOx, NH_3, $PM_{2.5}$, PM_{10}, SO_2, CH_4 and BC
Transport	1A3b	On road transport.	CO, CO_2, NMVOC, NOx, $PM_{2.5}$, PM_{10} CH_4 and BC

Table 1 Pollutants and sectors considered in the Chilean inventory(INEMA) according to IPCC (2006) classification

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The atmospheric emissions for each sector and pollutant are obtained by weighting the total ~~fuel consumption (~~activity level~~)~~ by an emission factor (EMEP / EEA, 2016), as shown in eq. (1).

$$\sim\sim E_{ijz} = \sum_{ijz}[NA_{ijz} * EF_{ij}]\sim\sim \; E_{iyz} = \sum_{iyz}[AL_{iyz} * EF_{iz}] \qquad (1)$$

where E_{izj} is the total emission for species or pollutant i on year ~~z~~y and sector ~~j~~, ~~NA_{ijz}~~z, AL_{ijz} is the activity level of pollutant i, in sector ~~j~~z on year ~~z~~y, and EF is the emission factor for pollutant species i, type of source ~~j~~z. No interannual variability is assumed for the EFs. The following subsections present detailed methodology and considerations for ~~each sector~~the estimations of each 2015-2017 emission sectors

2.1 Study area.

Chile spans from 17 ° 29'57 "S to 56 ° 32'12" S and has a population of over 19 million inhabitants. The administrative political division is made up of 16 regions containing 56 provinces and 346 communes, presenting considerable differences in size and population density. Furthermore, each commune contains urban and/or rural areas, with the exception of some purely urban communes in ~~the~~ larger cities. The territory can be broken down into 3 large macrozones with ~~diverse~~distinctive climatic ~~and~~, geographical and demographic characteristics (Fig 1). The northern zone, with the regions of Arica and Parinacota, Tarapacá, Antofagasta, Atacama and Coquimbo, has an arid climate and includes the presence of the Atacama Desert, the driest desert outside polar regions (Rondanelli et al., 2015). Between 32- and 38-degrees south ~~latitude~~ is the central zone with the regions of Valparaíso, Metropolitana, O'Higgins, Maule, Ñuble and Biobío. A Mediterranean climate with rainy winter and dry summer seasons prevails in this area. The regions of Araucanía, Los Ríos, Los Lagos, Aysén and Magallanes are located in the southern zone characterized by a temperate rainy climate, where low temperatures and abundant rainfall stand out. These conditions are accentuated further south, although the rainfall drastically decreases in the highest mountainous areas and south of the Strait of Magellan where a tundra-type climate predominates (Sarricolea et al., 2017).

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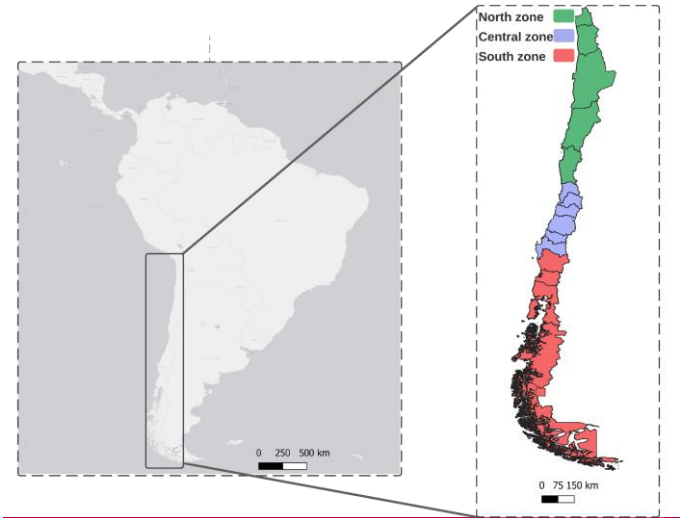

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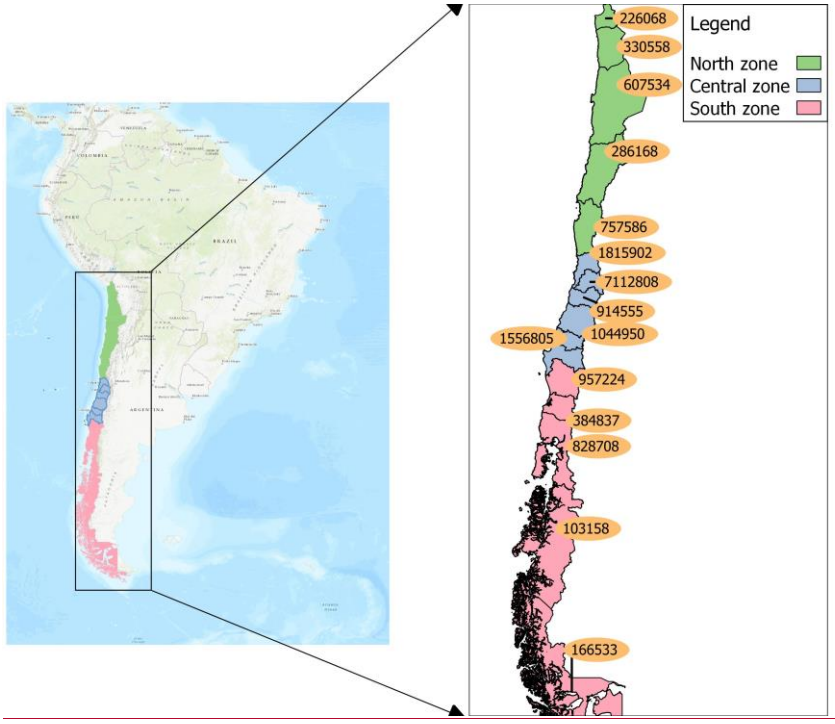

Figure 1 Continental Chile highlighting three macrozones defined for the paper, namely the northern (green), central (blue) and southern zone (red). Divisions within each macrozone indicate limits of the 16 administrative regions. Population in each one of these 16 regions is indicated in the orange ellipses.

2.2 Residential sector

Emissions from residential sources come from the combustion of all fuels used inside of homes, such as gasoline, kerosene and biomass, among others. However, in this first version of INEMA, the residential sector will focus on emissions from firewood combustion only given its dominant role in air quality in central and southern Chile (Saide et al., 2016; Huneeus et al., 2020b) The inclusion of additional fuels is left for future versions of this inventory.

Estimates ~~from~~for the residential sector include emissions ~~produced by the~~from biomass combustion ~~of biomass~~ for heating, cooking and heating water. Firewood is acquired mostly through informal wood markets and the few regular and consistent

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information ~~existing~~that exist to characterize its consumption is collected through household surveys (REDPE, 2020). In this ~~study~~article, three studies with regional representation (conducted in the last ten years) ~~with regional representation~~ are used to estimate the total firewood consumption in central and southern Chile.

The first one of ~~these~~the three aforementioned studies was conducted by the Universidad Austral de Chile (UACH). Firewood consumption in the residential sector was estimated based on existing studies for the years between 2005 and 2012 for each region in southern and central Chile (UACH, 2013; hereafter UACH13). Another study was mandated by the Ministry of Energy to the Corporation of Technological Development (CDT from Spanish Corporación de Desarrollo Tecnológico; https://www.cdt.cl), a private non-profit organization created in 1989 by the Chilean Chamber of construction. This study collected information on firewood consumption from the residential, commercial, public services, and industrial sectors for the entire Chilean territory for the year 2014. In each of the 16 Chilean regions, a total of 300 households in urban areas and 65 in rural ones were surveyed (CDT, 2015; hereafter CDT15). Finally, the most recent survey was done by the Forestry Institute (INFOR from Spanish Instituto Forestal) collecting samples ~~for~~of between 300 and 500 households for a single year between 2015 and 2018 in the 6 Central-Chilean regions considered in the study (INFOR, 2019; hereafter INFOR19) (Fig 2). Despite their differences, these studies agree that the consumption increases towards the south - consistent with lower temperatures and the corresponding higher energy requirement of dwellings (Fig 2). ~~For several individual regions, however~~However, significant differences in wood consumption are found between these datasets within several individual regions.

Activity levels in INFOR19 are higher than the ones estimated in CDT15 and methodological shortcomings that potentially explain this underestimation have been identified (Reyes et al., 2018; Reyes 2017). For this reason, firewood consumption from CDT15 is only used for regions lacking alternative data (all regions north of Santiago). For the regions of O'Higgins, Maule, Bio-Bio, Ñuble, Araucanía and Los Ríos, the data reported in INFOR19 are used, whereas for the regions Los Lagos, Aysén, and Magallanes, the information from UACH13 is selected over CDT15. Consumption estimates from UACH13 are consistent with the results from INFOR19 for regions with data from both sources (Fig 2). ~~We highlight~~It's worth noting that only INFOR19 provides firewood consumption at the communal level, the remaining studies estimate the firewood consumption at the regional ~~level~~scale. Regardless of the spatial disaggregation, in each study an average household firewood consumption (AHFC) is computed at a communal level. For regions where the data are available at a regional level~~,~~ (see figure 2, those with information from CDT15 and UACH13), the same average consumption is assumed for all communes contained ~~in~~within the same administrative region.

A bottom-up approach is used to standardize the different information sources for the study period. The activity level of residential emissions is obtained at communal level (c), differentiating between urban and rural areas (a) as follows:

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$$\sout{A_{y,c,a}}AL_{y,c,a} = HN_{y,c,a} * PF_{y,c,a} * AHFC_{c,a} \quad (2)$$

Where $\sout{A_{y,c,a}}AL_{y,c,a}$ is the activity level corresponding to the residential fuelwood consumption for the year y in commune c for urban/rural area a; $HN_{y,c,a}$ is the number of total dwellings in year y in commune c in area a registered in INE (2019); $PF_{y,c,a}$ is the "penetration factor" representing the percentage of houses that use biomass in the year y in commune c and area a obtained from the Chilean Ministry of Social Development (MDS from Spanish Ministerio de Desarrollo Social; 2015; 2017) and $AHFC_{c,a}$ is the average household firewood consumption in commune c and area a.

The MDS conducts every two years the National Socio-Economic Characterization Survey (CASEN) for the entire country. This survey contains information on the type of fuel used by households for heating, cooking food, and domestic hot water production, allowing to derive the penetration factor (PF) of biomass. For \sout{those}the isolated communes where this survey is not applied, the PF is taken for each region at urban or rural level considering the regional PF value from CDT (2015).

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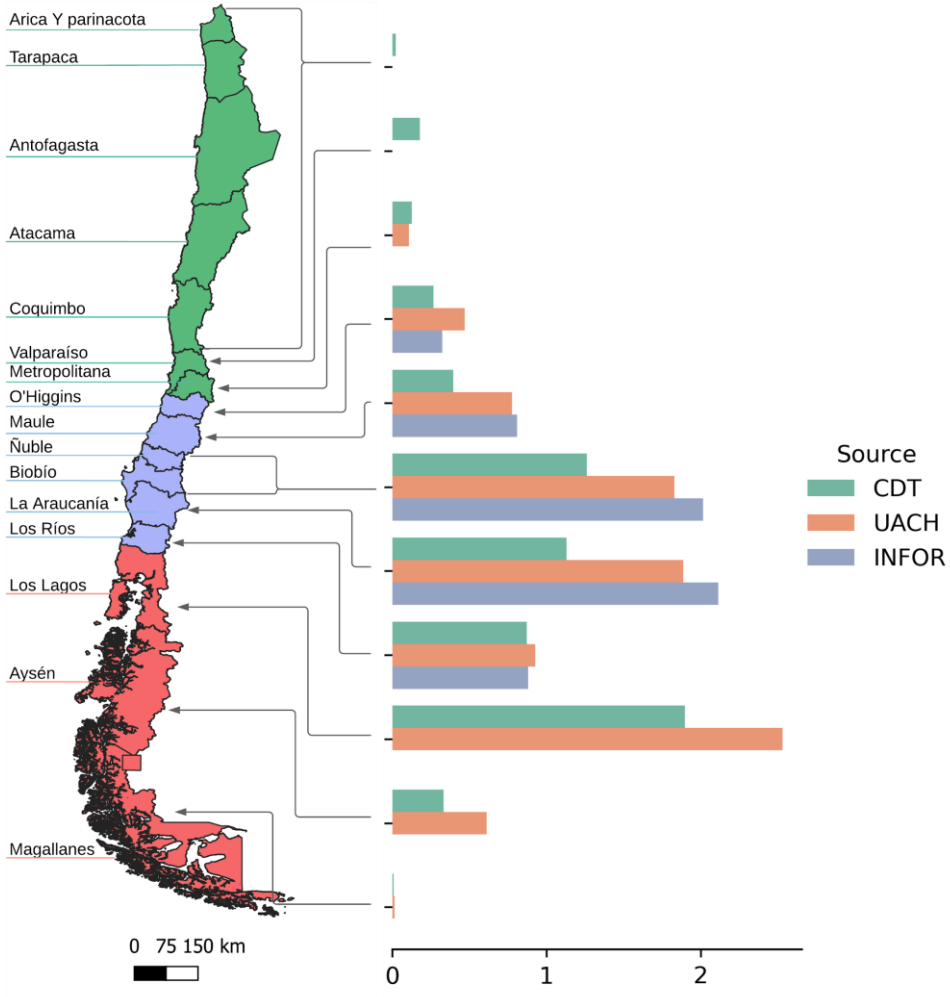

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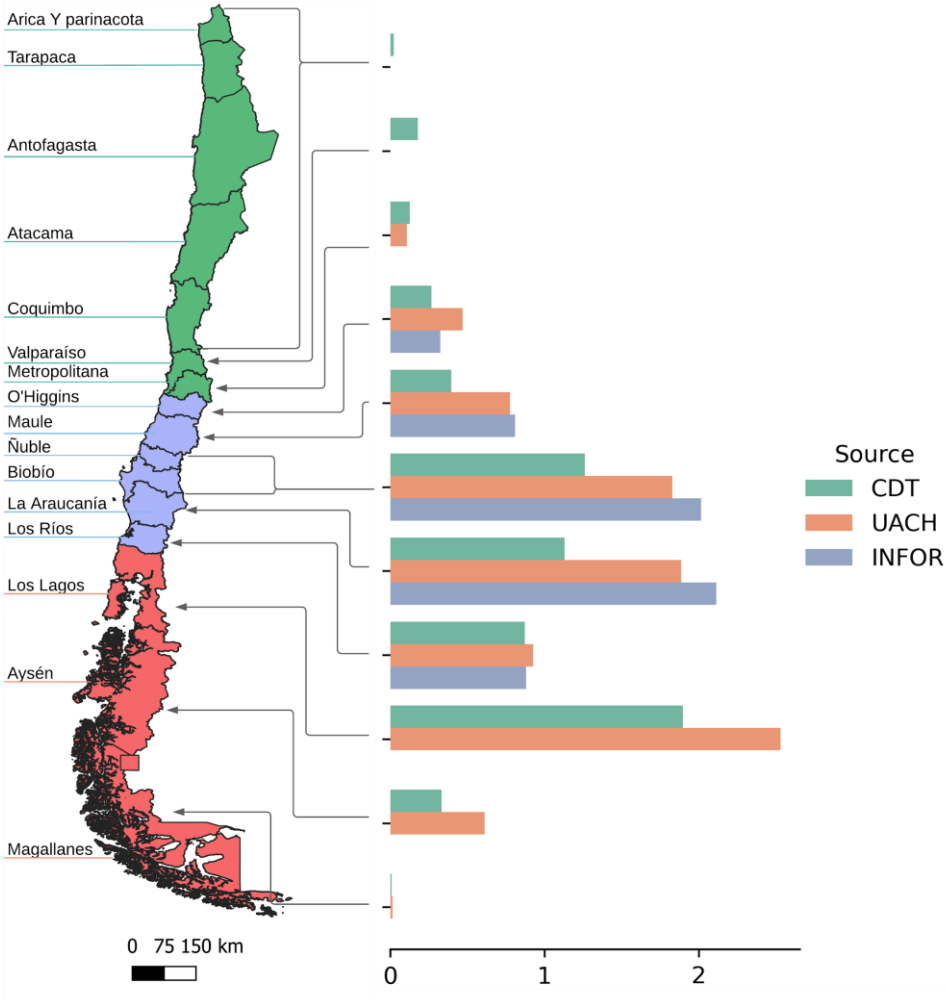

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Figure 2 ~~Total~~2017 Annual fuelwood consumption on kilotonnes by region according to UACH (2013, red), CDT (2015, green) and INFOR (2019, blue). Regions are colored according to the data source used in each region.

~~In this study, we use the local EFs from SICAM (2014) and also used in MMA (2019b) to estimate emissions of NOx, $PM_{2.5}$, PM_{10}, and SO_2 (Table A1 in Supplementary Material) and those estimated from MMA (2019b) for CO_2 and NH_3. Among other factors, the EFs vary~~Emission factors for residential combustion of firewood vary, among other factors, according to the efficiency of the technology used (e.g., fireplace, wood stove, simple heater, heater with temper, etc.), the humidity present in the wood, and the device's operating conditions[2] (Jimenez et al., 2017; Guerrero et al., 2019; Schuefftan et al., 2016). ~~For~~ Given that EMEP/EEA and IPCC's EFs do not include these aspects and which can lead to a negative bias in the estimated emissions, we use the local EFs from SICAM (2014) and also used in MMA (2019b) to estimate emissions of NOx, $PM_{2.5}$, PM_{10}, and SO_2 (Table A1 in Appendix A) and those estimated from MMA (2019b) for CO_2 and NH_3. However, for species absent in the aforementioned studies, EFs are taken from EMEP/EEA (2019) and IPCC (2006); namely for CO and NMVOC's (Non-Methane VOCs) ~~we use~~ EFs for dry firewood from EMEP/EEA (2019~~;~~)) is used while for CH_4 the EFs estimated on the tier 1 approach from IPCC (2006) ~~are used. However, EMEP/EEA and IPCC's database do not present EFs for wet firewood and bad operation of heating devices. To compensate for this, we follow USACH (2014) and apply correction factors of 1.5 for wet firewood combustion and 3 for poor operation~~is used. Finally, we follow EMEP/EEA (2016) and consider BC to represent 10% of $PM_{2.5}$ emissions.

2.3 Transport sector:

Estimated emissions from the transport sector consider exhaust emissions from vehicles traveling on public routes nationwide, in urban and interurban areas, for the years 2015 to 2017. Rail, air and sea modes are not included, nor are off-road machinery. Also, resuspended dust from paved and non-paved roads are not considered in this analysis. Approximately 60 % of the national roads in Chile are non-paved. Emissions were calculated per region based on estimates of number of vehicles and their activity level. A more detailed description of the method applied to estimate transport emissions can be found in Osses et al. (2021, this issue)

The different types of vehicles and their activity levels per region come from information obtained from official reports of government agencies. This information includes statistics on fleet composition as the number of registered vehicles by region (INE 2017b), average annual mileage by vehicle type (SCSS, 2014; MAPS, 2013) and fuel sales for road transport by region

[2] A bad operation condition occurs when combustion is carried out with the stove draft closed.

~~[3] "Any copper smelter or any other industrial source emitting ash where a thermal treatment of mineral or metallurgical compounds of copper and gold is carried out, whose ash content in the feed is greater than 0.005% by weight on a monthly basis" taken from the Decree 28 on Emission Standard from copper smelters and arsenic emission sources.~~

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(SEC, 2017). Vehicle categories considered are: light passenger, commercial and taxi vehicles; 12- and 18-meter buses; light, medium and heavy duty trucks; and two-wheeled vehicles. Each of these categories is subdivided according to the type of fuel used (gasoline or diesel) and the emission standard in its European equivalent (EURO standard). ~~Total~~Estimates of total fuel consumption ~~of~~from registered vehicles ~~was estimated and~~ were compared to real fuel ~~sales~~use for each region~~.~~, using information on sales of diesel and gasoline for the transportation sector, by political region, provided by the Electricity and Fuel Superintendence (SEC, www.sec.cl). A correction factor to the total number of registered vehicles in each region is applied, to make these two fuel consumptions equal, correcting for those vehicles that are registered but do not contribute to actual driving activity. Thus, the number of active vehicles in a region was inferred and ~~the number of vehicles per region was~~ adjusted accordingly. The distribution of vehicles into urban and interurban activity per region was based on a proportional regional distribution provided by SCSS (2010). The combination of categories, fuels and emission standards generates a total of 70 types of vehicles for the emission analysis, distributed regionally and distinguishing between urban and interurban activity.

Activity level was expressed in *VKT* (vehicle kilometre travelled) calculated as the sum of the number of vehicles per mileage per type of vehicle (eq. 3) expressed as follows

$$VKT = \sum_{i,j,k}^{N} N_{i,j,k} \sum_{v,r,k}^{N} N_{v,r,k} * KM_{i,j,k} KM_{v,r,k} \qquad (3)$$

where $N_{i,j,k} N_{v,r,k}$ is the number of vehicles of type ~~i~~v in region ~~j~~r and road class k (urban or interurban~~);~~ $KM_{i,j,k}$) and $KM_{v,r,k}$ are the kilometers travelled per year by vehicles type ~~i~~v, in region ~~j~~r and road class k.

The estimate considers that all vehicles that enter Chile are required to comply with the European EURO regulations or their US equivalent. Consequently, the assignment of emission factors for each of the vehicle types was carried out by applying COPERT V values (EMEP/EEA, 2019), adapted to the Chilean fleet (Gomez, 2020). Total emissions are calculated by multiplying *VKT* by an emission factor in grams per kilometer. The result is a regional emission database distinguishing by urban and interurban emissions, for CO, CO_2, VOC, NOx, $PM_{2.5}$, PM_{10} CH_4 and BC.

2.4 Point sources: ~~Energy, Mining~~energy, mining and ~~Industry~~industry sectors

Emissions from point sources and for species listed in table 1 are not estimated by our work but downloaded from the Register of Emissions and Pollutant Transport (RETC from spanish Registro de Emisiones y Transporte de Contaminantes, https://datosretc.mma.gob.cl/group/emisiones-al-aire~~).~~) from the Ministry of Environment. ~~This~~ Every year, this register receives ~~all~~ self-reported emissions ~~by the~~from industrial facilities in accordance with current environmental regulations (MMA, 2019b). No verification nor quality control of the declared emission estimates are conducted by the Ministry, nor is it done in this work. Although self-reported emissions estimates could have strong biases, they are currently the sole estimates

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of industrial emissions and are therefore used in this work. This limitation will be considered when analysing and discussing the results. Industries are not ~~obliged~~obligated to declare CH_4 and NMVOC but only total VOCs. Therefore, when analysing VOC emissions from the energy, mining and/or industry sector we will be referring to total VOCs.

~~The facilities that must declare their emissions are;~~

Establishments with economic activities (given by their International Standard Industrial Classification or ISIC) that meet any of the following criteria are subject to declare their atmospheric emissions to RETC:

- Pulp and Paper Production~~,~~; Primary and Secondary Smelters~~,~~; Thermoelectric Power Plants~~,~~; Cement~~,~~; Lime and Gypsum Production~~,~~; Glass Production~~,~~; Ceramic Production~~,~~; Iron and Steel Industry~~,~~; Petrochemical Industry~~,~~; Asphalt Production.
- Industries with generator sets greater than 20kW, and industrial and heating boilers with fuel energy consumption greater than 1 Mega Joule per hour.
- Establishments with electricity generation units, made up of boilers or turbines, with a thermal power greater than or equal to 50 MWt
- Establishments whose fixed sources, made up of boilers or turbines, individually or as a whole, add a thermal power greater than or equal to 50 MWt
- Establishments corresponding to copper smelters and arsenic emitting sources

~~In this work,~~

Agricultural emissions, thermoelectric plants that are a part of cogeneration processes, and other activity sectors not mentioned explicitly above or that don't meet one of the above criteria, are not obligated to declare unless they are in a geographical zone with an existing atmospheric decontamination plan.

Emissions from point sources are differentiated between ~~Energy, Mining~~energy, mining and ~~Industry~~industry sectors. The energy sector includes production and distribution of fuels and the generation of electric energy while ~~Mining~~mining includes the production and smelting of metals. The remaining point sources will be aggregated into a single sector to which we will refer as Industry henceforth.

This database includes more than 8324 point sources along the territory, most of which have associated coordinates~~. Those without~~, however, a large number of sources exist in the database where only the commune of emission is known (along with additional information such as the company name, activity type, and description) but not their coordinates. Approximate coordinates of these sources without a specified location, and whose contribution to their respective commune was larger than 20%, were ~~pinpointed~~obtained by pinpointing them on google earth using the ~~facilities names and the address~~information provided in their declaration ~~if their contribution to the total communal emission was larger than 20%. Point~~. The remainder

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of the point sources without a geographic location ~~contributing with emissions less than the above threshold~~ were not explicitly included in the inventory, however, their emissions were distributed among the located sources~~.~~ (including those manually geo-referenced) within the same commune. For a given species ~~and,~~ sector and ~~within each~~ commune, the spatial distribution of the emissions of located sources ~~were~~was scaled to fit the total (located + non-located) emissions ~~in that commune and sector~~.

2.5 Spatial distribution of emissions:

While point source emissions from ~~Industry, Mining~~industry, mining and ~~Energy~~energy sector are spatially distributed using their coordinates (section 2.4), those from the transport and residential sectors are estimated at the regional or communal level and thus need to be distributed to the final ~~distribution~~grid of 0.01ºx0.01º (approximately 1x1 km) ~~by means of a proxy~~ (Fig 3).

Residential emissions were initially estimated at the communal level and distributed onto a regular 0.01ºx0.01º grid (approximately 1x1 km) based on population density from the last census conducted in 2017 (INE 2017a~~)~~). The information is available at the census block scale~~. The latter~~, which is the smallest territorial scale for which relevant information from the census exists, it consists of a group of adjoining or separate dwellings, buildings, establishments and/or properties, delimited by geographical, cultural and natural features. The population distribution was obtained by projecting the 0.01ºx0.01º lat-lon grid (epsg:4326, WGS 84) onto the information contained in the census blocks and retrieving the aggregated information. We used the population density to distribute the emissions with the assumption that firewood is consumed similarly among the population despite the limitations it presents. This, due to not having information available at the census block scale that would allow to make a finer spatial disaggregation according to population characteristics such as income. Furthermore, the CDT15 database reveals that households with higher incomes have higher firewood consumption levels per capita, but less dwellings use firewood for heating and cooking, being difficult to establish a clear relationship between income and firewood consumption.

The spatial distribution of transport emissions within each region was performed by projecting the road network of each region onto the grid ~~with cells~~ of 0.01x0.01 degrees of latitude and longitude (approximately 1x1 km). QGIS open source software, the official database for Chile´s road network and regional limits (BCN, 2020) was used to characterize the Chilean road network and was complemented with information from Open Street Map (OSM, 2020) to organize it into a hierarchy comprising freeways, arterials, collectors, and local roads of 77800 km of both rural lands and main cities. Road vehicle flow per type of road was estimated applying a road weight factor, based on toll barrier vehicle counts at interurban roads and origin-destiny surveys in urban roads. Average weight factors are 54% for freeways, 23% on arterials, 16% for collectors and 7% on local roads. In each region, urban emissions were distributed among cities based on population (INE, 2017a) first and

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then within each city emissions were distributed applying the aforementioned weight factors. Thus, urban emissions in each cell depend on the population and the roads in the cell.

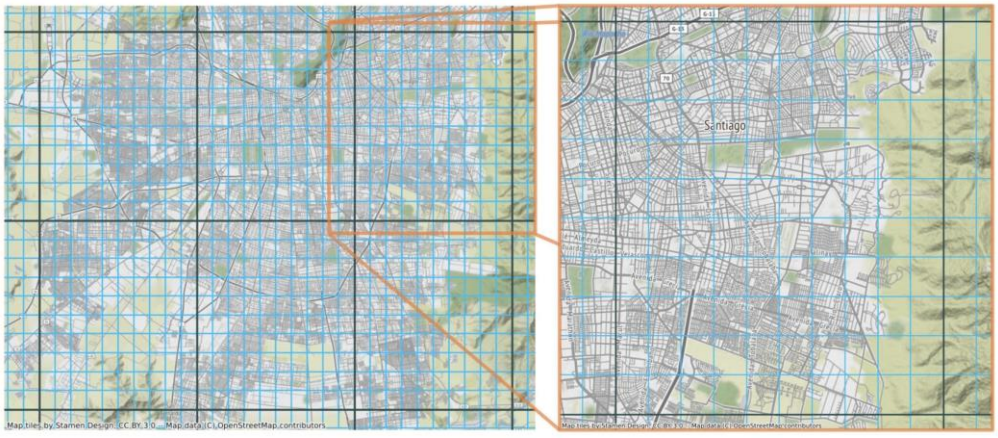

Figure 3 Map of Santiago at different scales: in blue the utilized 0.01° x 0.01° grid (approximately 1x1 km), and in black the 0.1° x 0.1° EDGAR V5.0 grid for comparison. © OpenStreetMap contributors 2021. Distributed under the Open Data Commons Open Database License (ODbL) v1.0

2.6 uncertainty on residential emissions:

Emissions represent a large source of uncertainty in air quality modelling (Thunis et al., 2016), of which uncertainty in emission factors dominate over the better-known activity data (Scarpelli et al. 2019). To assess the uncertainty of the residential sector we construct a range of possible estimates using different sources of information for the level of activity and emission factors. Two possible activity levels were considered, the lower limit is given by the CDT15 information for the whole country (CDT, 2015), while the upper limit considers the activity levels used in this inventory (section 2.1). For emission factors we consider four possible datasets. The upper estimates are based on the EF's used in the RETC database until 2014 while the lower limit considers the EF's estimated on IPCC (2006), and EMEP/EEA (2019) for different species. Also, EF's used in the current inventory and those proposed by US EPA (1996a; b) are considered. Eight possible residential emission levels were estimated by considering all possible combinations between the two activity levels estimation and the four EF's datasets. These eight

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emissions estimates are then normalized by INEMA's emissions and therefore, for a given specie, a resulting value of four represents an estimate four times larger than INEMA while a value of 0.2 corresponds to an estimate five time smaller than INEMA and the corresponding range of uncertainty of the estimated emission of the given specie would be a factor of 20. The analysis (section 4) focuses on the largest (considering INEMA's activity level and RETC EFs) and lowest (considering CTD15 activity level and EMEP/EEA EFs) emission estimate.

3. Results:

Total national emissions remain mainly stable for most species between 2015 and 2017 with a slight increase for $PM_{2.5}$, NH_3, SO_2, and CO_2 between ~~2015~~the beginning and ~~2017~~end of the period, whereas CO, VOC, PM_{10} and NOx show a slight decrease ~~during that period~~ (Fig 4~~).~~, the values of emission per sector and year are available on appendix B). While PM_{10} decreases due to decreasing trend in industrial emissions (driven mostly by changes in the manufacturing industry) and stable residential ones, NOx remains mostly constant due to a decrease in energy emissions and the slight increase in the rest of the sectors. Almost half of the NOx emissions are from the transport sector while the industry and energy sector combined contribute to almost an equivalent amount of the total NOx emissions. Although the largest contributor to CO_2 emissions in Chile is the ~~Energy~~energy sector due to thermoelectric power plants (MMA, 2017), the increase is associated with the increase of CO_2 emissions in the industrial sector~~.~~ (mainly driven by the forestry along with manufacturing industry). Mining activity, more specifically emissions from copper smelters, dominate SO_2 emissions in Chile. ~~This activity drives~~Starting in 2016, 7 additional copper smelters started declaring their emission to RETC due to changes in the regulatory framework driving an increase in SO2 emissions from 2015 to 2016 that is sustained in 2017. However, the decrease from 2016 to 2017 is the result of reductions in the energy and industry sector combined with mostly stable emissions from the mining activity. Finally, for NH_3 the emissions are dominated by the energy sector followed by emissions from the residential sector and the increase in emissions is explained by increases from the energy and industry sectors. We highlight that the agriculture sector is not included in this inventory due to the lack of high resolution data allowing to spatially distribute this sector's emission onto INEMA's grid and therefore is not reflected in emissions of CH_4 nor NH_3. In general, the agriculture sector dominates NH_3 (Muñoz et al., 2016) and CH_4 (according to MMA, in 2017 more than half of CH_4 emissions in Chile come from agriculture) emissions and for any future study on these species, these sectors would need to be ~~included~~estimated.

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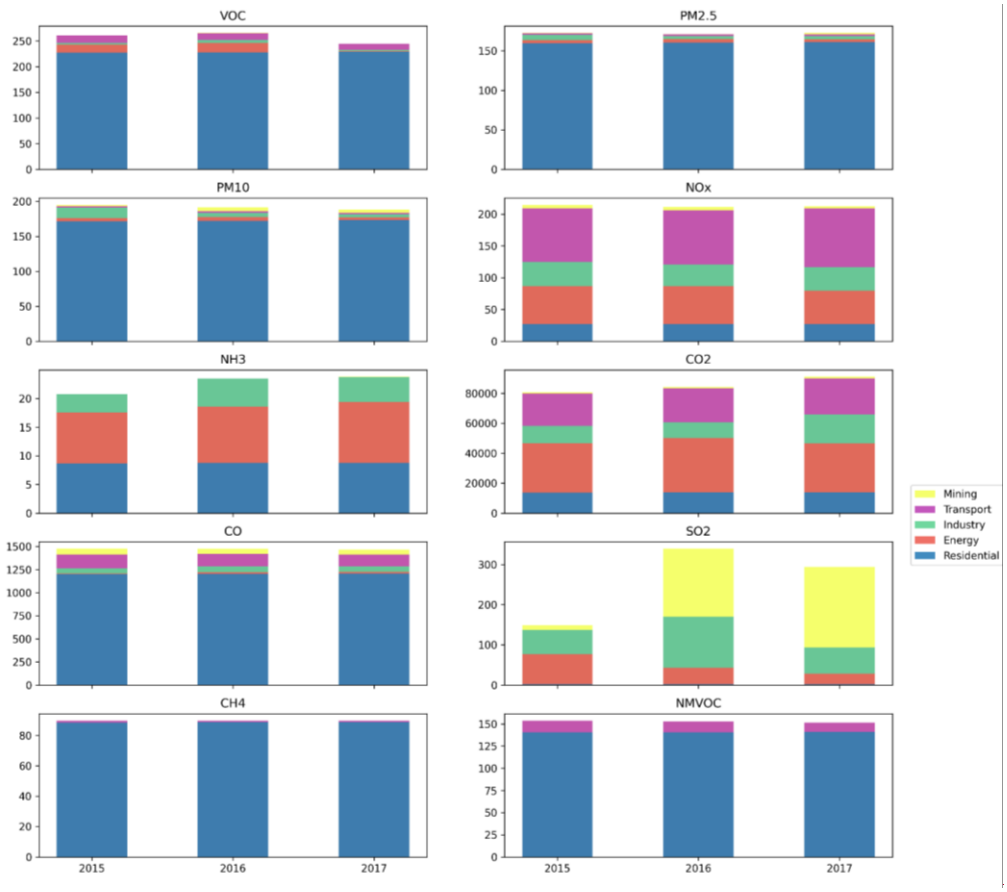

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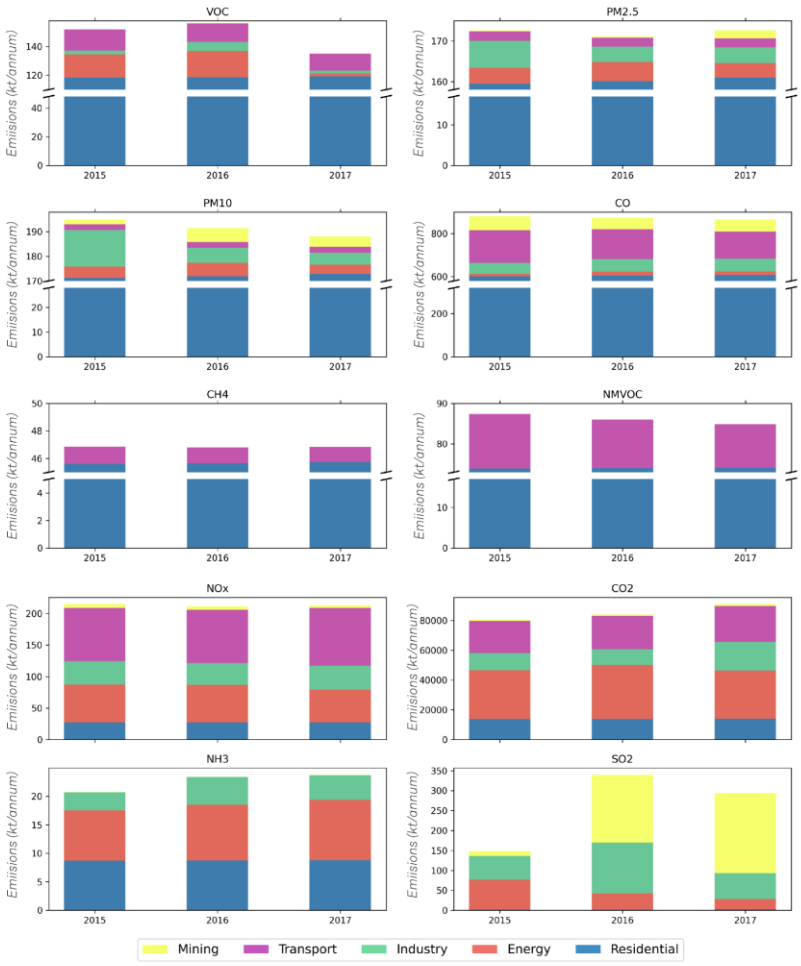

Figure 4 Total national annual emissions distributed by sector for pollutants VOC, $PM_{2.5}$, PM_{10}, NOx, NH_3, CO_2, CO, and SO_2 in kilotonnes for 2015-2017.

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Emissions of NOx dominate in Central Chile due to a larger population (see figure 1), urban centers and vehicular traffic in this area ~~while.~~ CO_2 emissions are distributed mainly in ~~north~~northern and central Chile, where thermoelectric power plants are abundant (Table 2). Furthermore, $PM_{2.5}$ and PM_{10} are mostly emitted in southern Chile with large contributions also in central Chile, mainly from the residential sector in both cases. This sector also makes the largest contribution in CO and VOC. SO_2 has a greater presence in the northern part of the country, consistent with a larger mining activity.

Pollutant	Total	North	Centre	South
BC	~~15.6~~16	3.2%	35.3%	61.5%
CO	~~1477~~876	~~2.4%~~3.9%	~~39.5%~~48.1%	~~58.1%~~48.%
CO_2	85402	29.6%	52.6%	17.9%
NH_3	23	26.4%	45.7%	27.9%
NOx	~~2132~~213	26.4%	49.9%	23.7%
PM_{10}	191	4.6%	35.2%	60.2%
$PM_{2.5}$	173	3.1%	35.3%	61.6%
SO_2	261	62.3%	35.4%	2.2%
VOC	~~256~~149	~~2.2%~~3.7%	~~35.7%~~43.1%	~~62.1%~~ 53.2%

Table 2 Average annual total emissions [kt/annum] for the period 2015-2017 from ~~Energy, Industry, Residential~~energy, industry, residential, and ~~Transportation~~transportation sectors ~~[in kilotones] in the 2015-2017 period~~ by pollutant and macrozone.

Given the large health impact associated ~~to~~PM2~~with~~ $PM_{2.5}$ and its role in poor air quality in central and southern Chile, we focus now on this particular pollutant and its spatial emission distribution along the territory (Fig 5). More than 90% of the 158 (170) ~~Tons~~kt/annum of $PM_{2.5}$ (PM_{10}) total national emissions for 2017 originated from the residential sector (Fig 5). Emissions in the northern macrozone are mostly from the energy and industry sectors, which are generally located in urban areas. The Mejillones commune concentrates more than 20% of all $PM_{2.5}$ 2017 emissions in the northern macrozone (Fig 6a). More than ~~1,300 tons~~1300 tonnes/annum are emitted ~~per year~~ in this commune, of which 99% come from the energy sector (thermal power plants) concentrated in a few locations.

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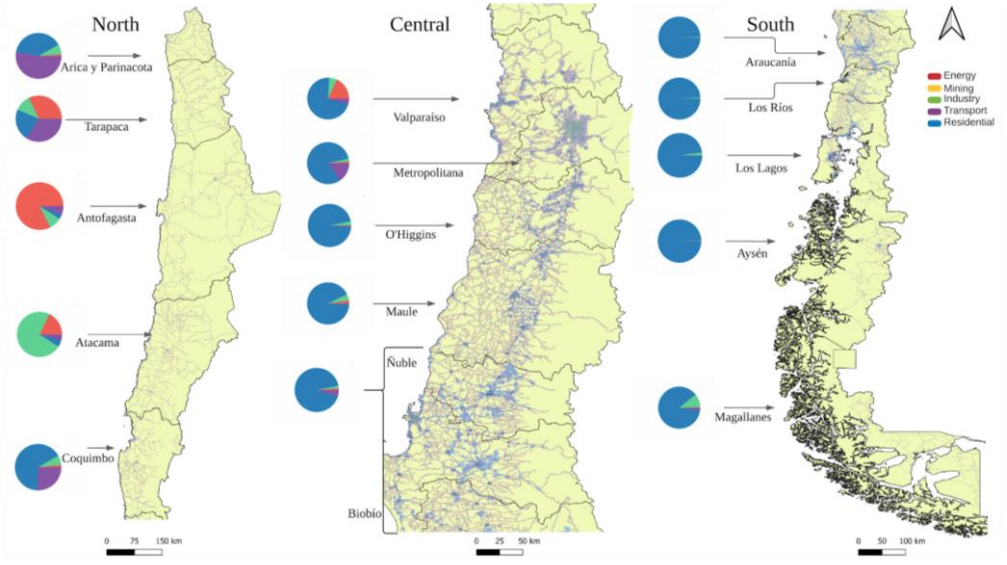
In Central and Southern Chile emissions are largely dominated by the residential sector and are consequently distributed along the territory according to population, with a larger magnitude in locations with a greater number of dwellings and concentrated in the country's central valley. However, contrary to cities of Southern Chile (Fig 6c), significant contributions from other sources are observed in some areas of Central Chile. For instance, Santiago, the capital of Chile (Fig 6b), where more than 40% of the country's population resides, stands out in Central Chile. Although firewood burning for heating and cooking is prohibited in the metropolitan area, it is still the largest contributor to $PM_{2.5}$ in the region due to its use in the outskirts and surroundings; from the 2030 ~~Kt~~tonnes/annum of $PM_{2.5}$ emitted in 2017, 1480 ~~Kt~~tonnes/annum are emitted in the outskirts and surroundings of the city. Within the Santiago metropolitan area, the largest polluter is the transport sector, representing 22% of the total $PM_{2.5}$ 2017 emissions and almost 90% of the 25 ~~annual Kt~~kt/annum of NOx.



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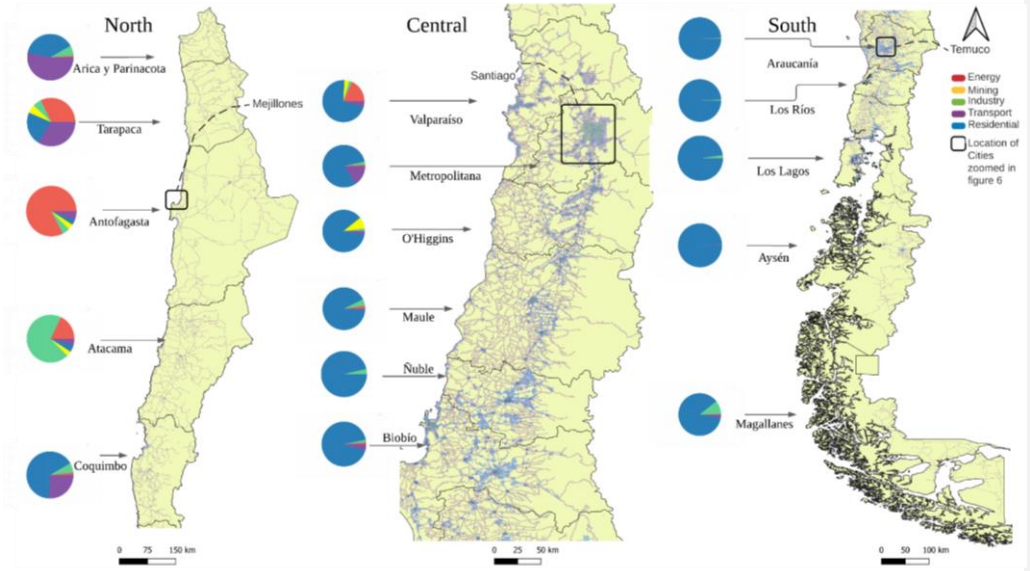

Figure 5 Spatial distribution of the 2017 emissions of ~~particulate matter 2~~$PM_{2.5}$ of the ~~Energy~~energy (red), ~~Industry~~industry (green), ~~Residential~~residential (blue) and ~~Transportation~~transport (purple) sectors in a grid of 0.01 ° x 0.01 ° on a map of Chile according to the macrozones defined for the country (Figure 1). Note that the Metropolitan region includes the capital Santiago and ~ 40% of the population. The pie charts indicate the relative contribution that each source makes to total $PM_{2.5}$ emissions in each region.

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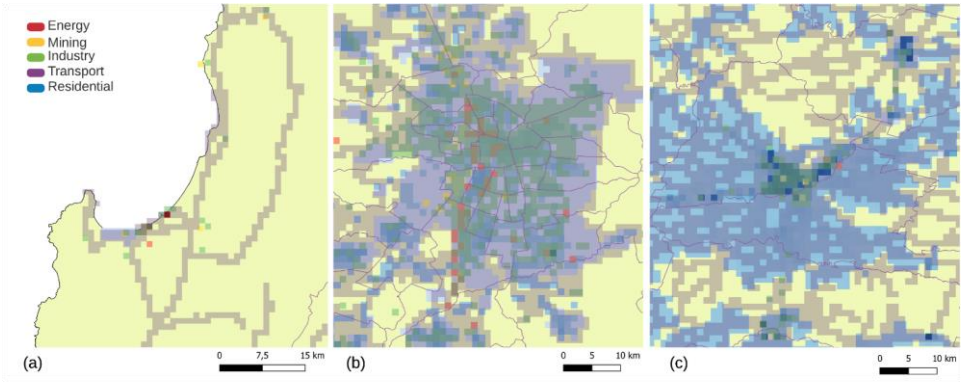

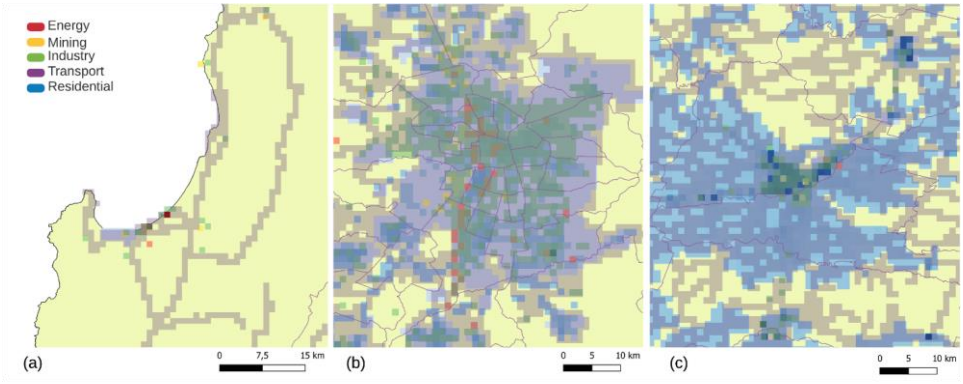

Figure 6 Spatial distribution of the 2017 emissions of $PM_{2.5}$ of the Energy (red), ~~Industry~~industry (green), ~~Residential~~residential (blue) and ~~Transportation~~transportation (purple) sectors in a grid of 0.01 x 0.01 degrees (approximately 1x1 km) for Mejillones (a), Santiago (b) and Temuco and Padre Las Casas Cities (c). These cities are located in the Northern, Central and Southern zones, respectively.

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3.1 Comparison of total emissions by sector and pollutant with EDGAR inventory

Puliafito et al. (2017) and Huneeus et al. (~~2020~~2020a) show that despite consistencies in the magnitude of total emissions of pollutants, global inventories have large discrepancies in sectoral contribution when compared to local or national inventories. We compare estimated emission for 2015 from the present inventory against the EDGAR v5.0 inventory 2015 emissions (Crippa et al., 2019; 2020). Global inventories, such as EDGAR, have been used in South America in the absence of a local inventory for AQ assessments (Huneeus et al., 2020). Both inventories, EDGAR and this work, follow the ~~sectoral classification proposed in IPCC (2006) allowing thus the direct comparison of sectoral emissions.~~same sectoral classification proposed in IPCC (2006) with the exception of the residential sector. While for INEMA the residential sector corresponds to IPCC code 1A4b with only firewood combustion, the residential sector in EDGAR corresponds to the IPCC code 1A4, including residential emissions as well as emissions from commercial, agriculture, forestry, fishing and fish farms. In spite of these differences in activities represented in the residential sector between both inventories, INEMA presents larger total PM2.5 and sectoral residential emissions for all species (Figure 7 and 8).

The differences for 2015 between both inventories for all pollutants are considerable in terms of magnitude and sectoral contribution, especially for the residential sector (Fig 7 and 8). Except for $PM_{2.5}$ and CH_4, EDGAR presents larger emissions than INEMA. For CO, ~~VOC~~NMVOC and ~~CO_2~~VOC, EDGAR emissions are ~~between 20 and 40% larger~~more than double that of INEMA's, for NOx differences are around 90%, ~~while~~and for CO2 around 40%. While for $PM_{2.5}$ INEMA emissions are 45% larger than those estimated ~~on~~in EDGAR. These differences can partly be explained due to the use of different emission factors in both inventories. ~~The selection of emission factors for residential wood burning which include filterable PM only or filterable PM + condensable PM have an extremely large influence on the estimated emissions (e.g. Denier van der Gon et al.,2015). Moreover, these emission factors~~Emission factors used in EDGAR do not consider wet firewood and combustion with poor operating conditions which considerably increases these pollutants' emissions (Schueftan et al., 2016; Guerrero et al., 2019). ~~The~~In contrast, the current inventory (INEMA) ~~however,~~ considers emission factors for several species that take these conditions into account. For NOx the larger emissions in EDGAR are from the transport, energy and industry sector. While EDGAR and INEMA have comparable CO_2 emissions for the transport, mining and residential sector, they differ significantly for the ~~Energy~~energy and ~~Industry~~industry sector. We note that the estimated emissions in this work for the energy and industry sectors are in line with what Chile reports to the UNFCCC (~~34*10³ KT~~34000 kt for energy and ~~18*10³~~18000 for industry~~) (MMA, 2020~~, see INGEI on CO_2 graph of figure 8) suggesting a potential source of bias in the activity data used in EDGAR for the energy sector.

EDGAR ~~VOC~~NMVOC and CO transport emissions are larger, due to evaporation emissions, which are not considered ~~on~~in INEMA inventory. Furthermore, smaller EDGAR emissions of $PM_{2.5}$ ~~and VOC~~ are mostly due to differences in emissions

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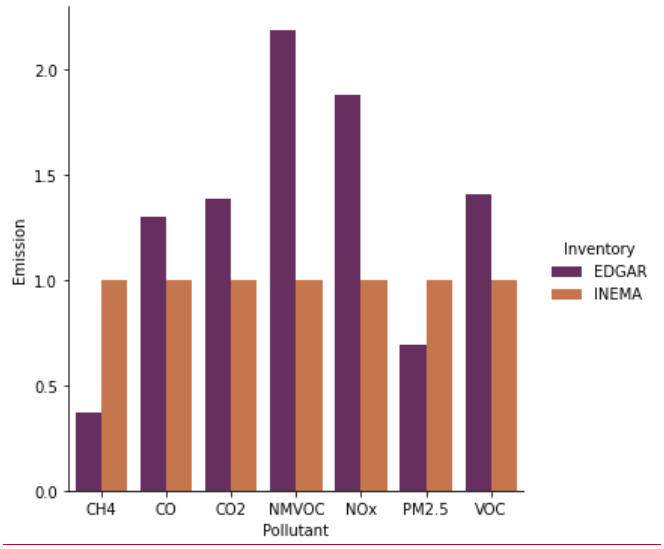
from the residential sector. Although the use of distinct EF by both inventories might explain this discrepancy, differences in estimating activity as highlighted by different CO_2 emissions might also explain part of the difference.



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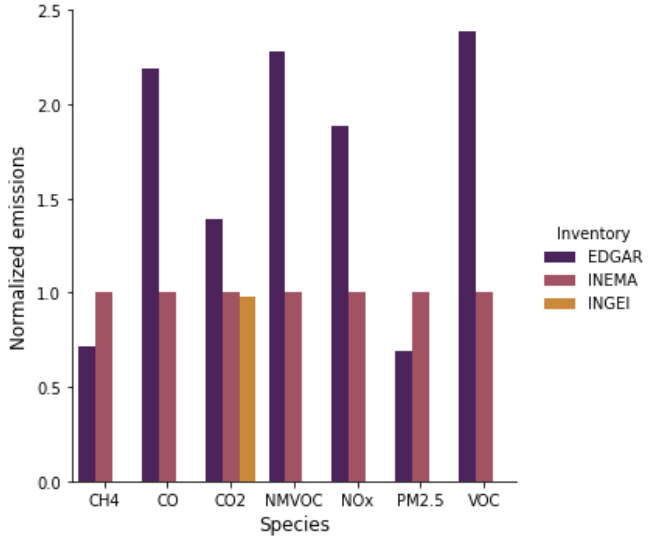

Figure 7 Emissions of CH_4, CO, CO_2, NMVOC, VOC, NOx, $PM_{2.5}$ for 2015 reported by EDGAR v5.0 (purple) relative to the present work (INEMA; pink). EDGAR emissions were normalized by the magnitude of the current INEMA inventory. We note that the residential sector from EDGAR corresponds to category 1A4 from IPCC. This category, in addition to residential emissions, also include emissions from commercial, agriculture, forestry, fishing and fish farms.

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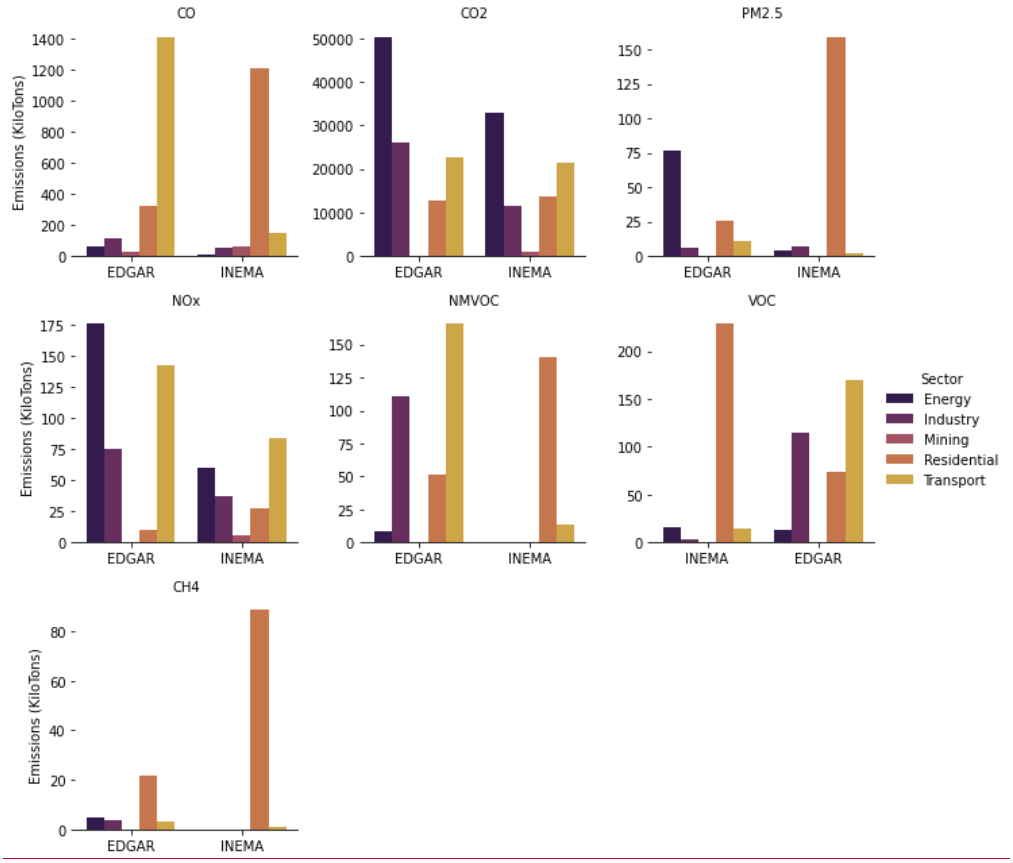

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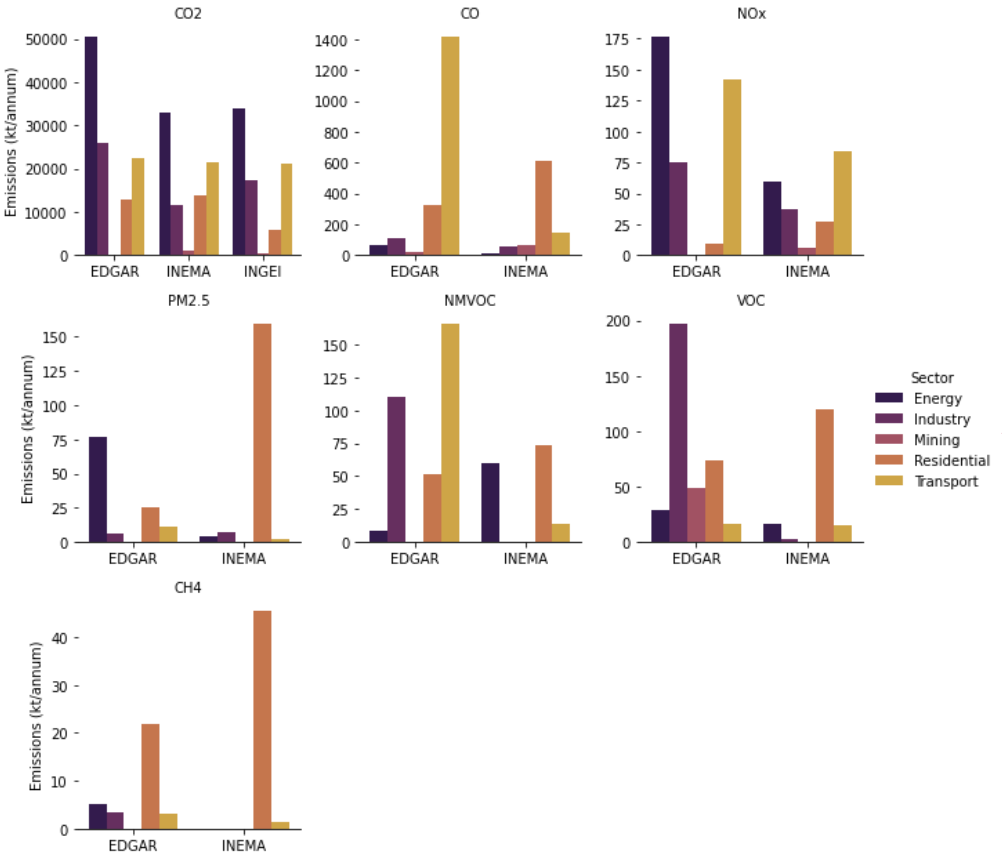

Figure 8 Total 2015 emissions in kilotonnes by pollutant and sectors according to this work and EDGAR v5.0. Sectors considered in both inventories correspond to the classification proposed in IPCC (2006) presented in section 2.

4. Uncertainty and quality of estimations on the residential sector

To examine and estimate ~~Emissions represent a large source of uncertainty in air quality modelling (Thunis et al., 2016) of which uncertainty in~~ emission ~~factors dominate over the better known activity data (Scarpelli et al. 2019). Consistently, for the~~ uncertainties associated with the residential sector ~~in this study, the largest uncertainty in the~~, multiple emissions

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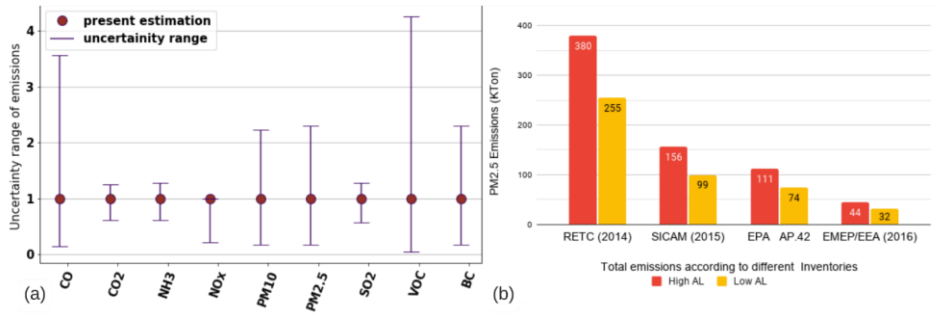
considering different levels of activity and EFs are estimated ~~magnitude is associated with the emission factor.~~(Section 2.6). For VOC, CO, BC and particulate matter emissions, the range of possible residential emissions estimations ~~using varying information sources~~ can reach differences of a factor 84, 24, 13 and 13 respectively (Fig 9a~~).~~) between the upper and the lower estimation limits. For VOC and PM not all differences can be attributed to uncertainty, it is partly related to the choice of what is included in the definition of VOC or PM. For the residential sector in this study, the largest uncertainty in the estimated magnitude is associated with the emission factor. In the case of $PM_{2.5}$ emissions, differences in the estimated magnitude following the different emissions factors can reach up to factor 8 whereas differences in the activity data are less than a factor two (Fig 9b). However, the final uncertainty is even larger when considering the combined uncertainties from each parameter (Fig 9b). CO_2, NH_3, and SO_2, have lower uncertainty ranges (Fig 9a) due to the greater consensus on their EFs in the literature (MMA,2019b; IPCC, 2006; US EPA (1996a; b); SICAM, 2014) and the fact that these are single well-defined species whereas VOC and PM are container definitions; they include a ~~variation~~variety of species and/or sizes. For CO_2, NH_3, and SO_2 the possible estimations of the lower and upper limits differ by a factor 2, while for NOx this value can reach up to a factor 5.



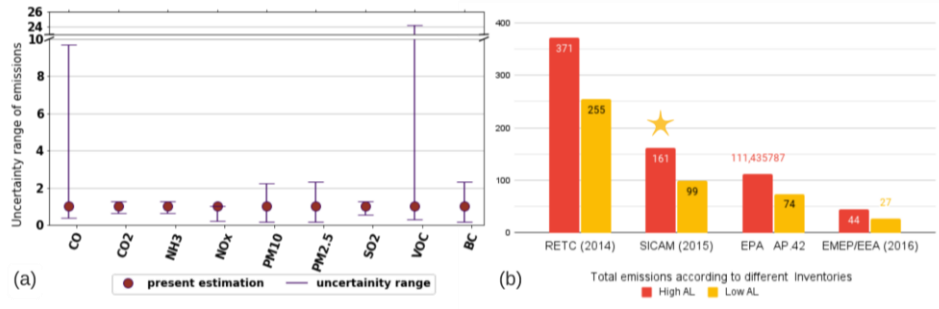


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Figure 9 a) uncertainty range of residential emissions considering the possible estimation that can be made with the different sources of information evaluated in this work. ~~b) $PM_{2.5}$~~The units on the y axis are the ratio of total 2017 emissions from one set of assumptions to the INEMA estimate. The y axis is broken for better visualization b) 2017 $PM_{2.5}$ emissions uncertainty range disaggregated according to different emission factors (groups of columns) and activity levels (colors). In yellow are the inventories constructed using CDT information ~~(CDT, 2015),~~ which provides the lowest possible activity level (AL) while in red are the activity levels used in this inventory (section 2.1). The first group of columns represent estimated $PM_{2.5}$ emissions based on EF from RETC while the second group correspond to the estimate based on EF used in the current inventory~~.~~ (the bar used on INEMA's inventory is marked with a star). The third and fourth group of columns correspond to the estimate based on EF proposed by US EPA (1996a; b) and EMEP/EEA 2019~~,~~ respectively.

The final EF's used in this study ~~results from~~ (see table A2, in Appendix A) are obtained by aggregating several ~~EF~~EFs, each one ~~of which corresponds~~corresponding to a specific emission ~~conditions,~~condition and/or fuel ~~components that~~ component. They determine the magnitude of the emitted flux~~,~~ (see table A1), by weighting each EF according to distribution parameters estimated ~~on~~in household surveys. The most relevant parameters that were considered when weighing the EFs are~~, among others,~~: the quality and efficiency of the ~~used~~ technology used (appliance type), the ~~tree species, the~~ humidity of firewood fuel, and the operating conditions of the devices (Jimenez et al., 2017; Guerrero et al., 2019; Schuefftan et al., 2016). Each of these EFs has its uncertainty, which depends on the quality and the number of laboratory tests carried out to determine its robustness (RTI International, 2007). Despite the ~~magnitude of data and~~ studies carried out, the uncertainty associated with EF estimation is considerable. EMEP/EEA 2019 indicates that for a standard heater~~,~~ the associated uncertainty to the estimated CO and $PM_{2.5}$ EF can be larger than ten and four times~~,~~ respectively. Additionally, estimating activity data has ~~also~~ sources of uncertainties associated. For ~~instance~~example, to estimate the amount and type of firewood consumed as well as the technology used and operating conditions, household surveys are usually conducted. These studies have big uncertainties, due to high informality surrounding the firewood transactions and markets (Zhao et al., 2011), and depend on the size of the surveyed sample as well as its representativity. The combination of the aforementioned uncertainties (Fig 10) impacts the expected final confidence of aggregated EFs and thus the magnitude of the estimated emissions (EMEP / EEA, 2016)

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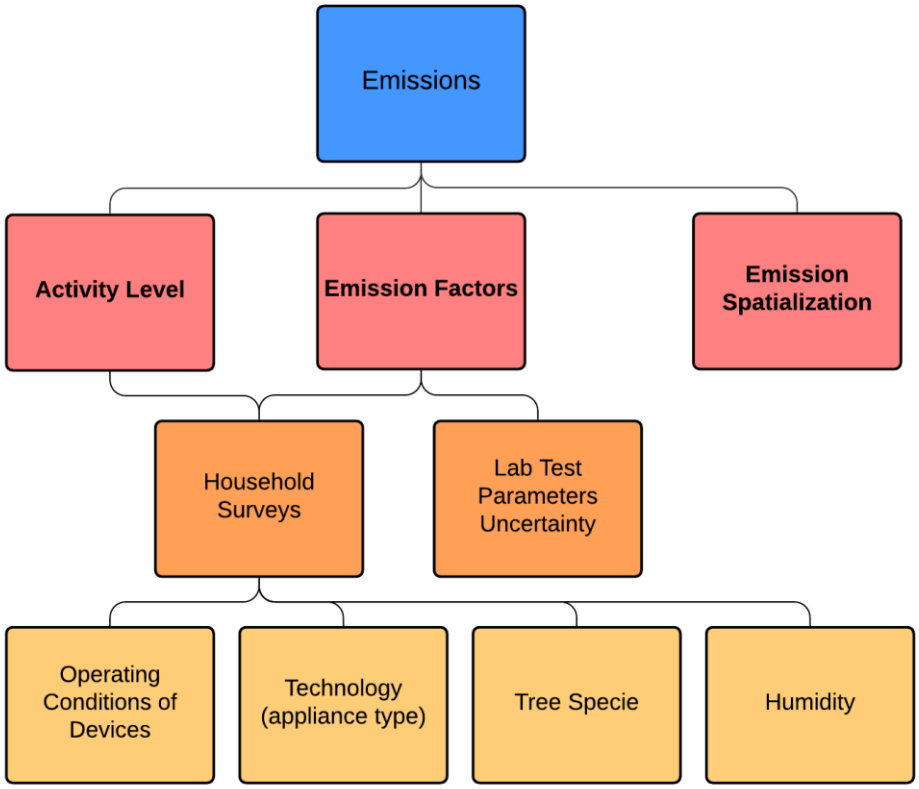

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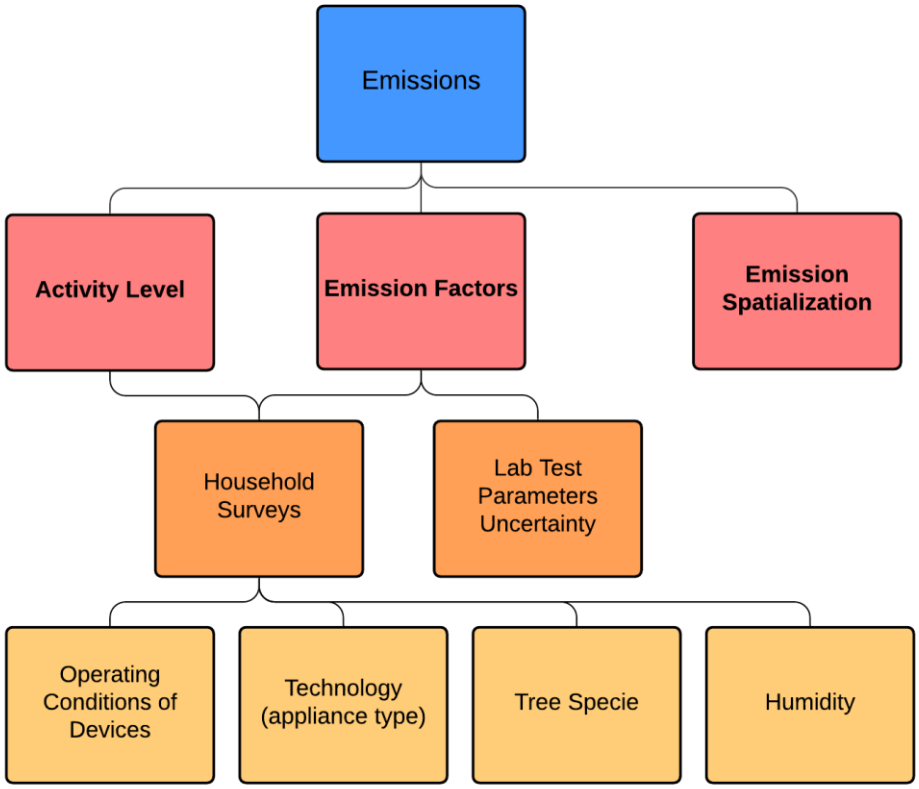

Figure 10 Components that determine the final uncertainty of residential emission estimations

5. Data availability

The emission database described is available at Zenodo (https://doi.org/10.5281/zenodo.4784286) (Alamos et al., 2021). The database consists of one .tar file for each year and sector, containing NetCDF (.nc) files for each pollutant. Each NetCDF contains annual total emissions for the pollutant and year indicated per grid cell

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6. Conclusions

A high-resolution emission inventory (0.01°x 0.01° degrees, approximately 1 x 1 km) of criteria pollutants, CH_4 and CO_2 from transport, industry, mining, energy, and residential sectors in Chile for the period 2015 to 2017 was developed. This is the first time a national gridded emission inventory with consistent CH_4, CO_2 and criteria pollutants was created for the entire country. Urban and rural emissions from the residential sector are estimated based on firewood consumption data derived from different surveys conducted at the regional and communal level. The transport sector includes vehicles travelling on public urban and interurban routes nationwide. For mining, industry and energy sources, the self-reported emission estimates compiled by the environmental agency RETC are used.

~~While~~ Total national emissions ~~increased~~remained mostly stable between 2015 and 2017 with slight increases for $PM_{2.5}$, CO_2, NH_3 and SO_2 ~~between 2015~~, and ~~2017, they decreased~~small decreases for CO, VOC, PM_{10} and NOx. Estimated total annual average emissions for the period 2015-2017 for PM_{10} and $PM_{2.5}$ were 192 and 173 ~~Kt~~,kt/annum respectively, of which more than 90% is emitted by the residential sector. This sector is also responsible for ~~98~~69% of the ~~1923 Kt~~872 kt/annum CO emissions and ~~88~~78% of the ~~710 Kt~~149 kt/annum VOC emissions. Regarding NOx, total average annual emissions were estimated at 213 ~~Kt~~kt/annum and dominated by the transport sector (87 ~~Kt~~kt/annum) while the industry and energy sector combined contribute an almost equivalent amount ~~to the total NOx emissions~~ with 57 and 36 ~~Kt~~,kt/annum respectively. Additionally, CO_2 emissions (~~85,402 Kt~~85402 kt/annum) are dominated by the ~~Energy~~energy sector mostly due to emissions from thermoelectric power plants (~~33,911 Kt~~33911 kt/annum) followed by the transport and industrial sectors (~~22,770~~22770 and ~~13,804 Kt~~13804 kt/annum, respectively). Mining activity (due to copper smelters) dominates SO_2 emissions in Chile, contributing an average of 201 ~~Kt~~kt/annum of a total of 294 ~~Kt~~kt/annum in 2017.

A comparison of the estimated emissions against the EDGARv5 database (Crippa et al., 2019; 2020) shows significant differences for several species. For CO~~, VOC~~ and ~~CO_2~~VOC, EDGAR emissions ~~are between 20 and 40% larger~~double those of INEMA's, while NOx and CO_2 have differences around 90~~%.~~% and 40% respectively. On the other hand, $PM_{2.5}$ emissions estimated in this work are 45% larger than those estimated on EDGAR. These differences are even larger when considering emissions per sector, in particular for the residential and energy sector. Furthermore, a preliminary uncertainty analysis on the residential sector suggests that the main uncertainty source in this work is the diversity in emission factors available, calling for the need to compile emission factors that include local conditions. Uncertainties also exist in activity data as suggested by the difference in CO_2 emissions between INEMA and EDGAR.

We note that what we call "residential sector" in EDGAR corresponds to the IPCC code 1A4 and therefore, in addition to including residential emissions, also includes emissions from commercial, agriculture, forestry, fishing and fish farms. Given that the residential sector in INEMA only considers residential emissions (IPCC code 1A4b) the difference between both

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inventories (INEMA and EDGAR) are actually larger than illustrated in this study. Nevertheless, future versions of INEMA need to estimate the emissions from all activities in category 1A4 and not only residential emissions. This means including not only emissions from commercial, agriculture, forestry, fishing and fish farms activity but also residential emissions from fuels other than biomass.

The dominant contribution of the residential sector to various pollutants, especially particulate matter, highlights the importance of increasing efforts to mitigate this source. Increasing the thermal efficiency of dwellings, improving the firewood combustion quality by reducing the humidity of ~~the~~ burned ~~wood or~~woods, increasing the efficiency of combustion technologies, and implementing educational campaigns that ensure the correct use of the devices, are among the potential policies to achieve this goal. Nevertheless, a consistent and robust estimation of firewood consumption is prerequisite to estimate emissions from the residential sector. This requires the creation of an official database that characterizes firewood consumption throughout the territory. Given the timeliness of the consumption data used in the present work, the absence of such an official database would prevent updating the present inventory in the near future~~.~~ considering there is no activity level data of the residential sector collected regularly for the whole country. Furthermore, additional studies need to be conducted to develop EFs for residential emissions of VOC, CO, NMVOC and CH4 that consider local operating conditions, appliances type, humidity of firewood and tree species.

This is the first version of a national gridded inventory ~~that~~and will need to be further developed and continuously updated. It can be an important reference and benchmark for comparison in the future to track the impact of mitigation or other policy measures. Further, future development of this inventory should consider, for instance including speciation of VOCs, the agriculture sector ~~and~~, off-road vehicle emissions as well as emissions from non-paved roads given that approximately 60% of the national roads in Chile fall into this category and completing the industry sector by locating in the territory the non-documented sources. Nevertheless, this inventory provides policy makers, stakeholders and scientists with qualified scientific spatial explicit emission information to support air quality modelling and the development and further evaluation of policies to minimize (health and climate relevant) atmospheric pollutant emissions.

Author Contributions

NA and NH lead and write the original draft with contributions of all authors. NA, NH, MOpazo, SP prepare and curate the data, MOsses and NP generate and describe the emissions from the transport sector. RR and AS participate in the processing of the residential activity level data. NA generates the residential emission data while NA and MOpazo prepared the industry, mining and energy emission ~~estimate~~estimates. HDvdG and NH designed the algorithm to distribute the residential emissions

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and together with RC provide feedback on the methodology used and the global consistency of the inventory. All the authors review and edit the manuscript.

Competing interests

The authors declare that they have no conflict of interest.

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~~**Appendice**~~

Appendix A

Table A1 shows emission factors (g/kg) for the residential sector by technology (appliance type), humidity and operation device conditions for PM_{10}, $PM_{2.5}$, NOx, and SO_2. For CO and NMVOC's (Non-Methane VOCs) we use EFs for dry firewood from EMEP/EEA(2019;) while for ~~CH4~~CH_4 the EFs estimated on the tier 1 approach from IPCC(2006) are used.

Table A2 shows the aggregated emission factors (g/kg) at a regional level for each pollutant used in the residential sector (eq A1), considering the distribution of technologies and humidity conditions of fuelwood estimated in CDT (2015) for each region, and 30% of devices bad operation, according to RETC (MMA, 2019). For CO_2 and NH_3 are used EFs estimated from MMA (2019b)

$$\cancel{EF_{ij} = \sum_z \sum_{x,j} \sum_{y,j} \left[\left[\left[EF_{i,x,y,z} * T_{y,j}\right] * H_{x,j}\right] * OD_z\right]} EF_{ij} = \sum_z \sum_{x,j} \sum_{y,j} \left[\left[\left[EF_{i,x,y,z} * T_{y,j}\right] * H_{x,j}\right] * OD_z\right] \quad \text{(A1)}$$

Where:

EF_{ijz} is the emission factor for pollutant i on region j

$EF_{i,x,y,z}$: Is lab emission factor estimated for pollutant i, humidity conditions of fuelwood x, technology for combustion y and quality operation device z

$H_{x,j}$: is the proportion of humidity conditions x of fuelwood on region j

$T_{y,j}$: is the proportion of technology conditions for fuelwood combustion y on region j

OD_z: is the proportion of bad operation device condition z considered at a national level

Technology	Pollutant	Dry	Wet	Bad operation
Cook stoves	CH_4	4~~,~~.5	4.5~~7,11~~	~~13,~~4.5
	NMVOC	9	~~14,22~~9	~~27~~9

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	PM_{10}	7.5	13.9	33.8
	$PM_{2.5}$	7.0	12.9	31.5
	CO	60	94,860	18060
	NOx	2.1	2.7	2.7
	SO_2	0.2	0.2	0.2
Conventional stove	CH_4	4.5	7,114.5	13,4.5
	NMVOC	9.0	14,229	279
	PM_{10}	6.2	11.8	45.8
	$PM_{2.5}$	5.8	11.0	42.6
	CO	60	94,860	18060
	NOx	2.0	3	3
	SO_2	0.1	0.2	0.2
Catalytic stove	CH_4	4.5	7,114.5	13,4.5
	NMVOC	5.7	8,9275.7	16,955.7
	PM_{10}	5.2	11	29.5
	$PM_{2.5}$	4.8	10.2	27.5
	CO	60	94,860	18060
	NOx	1.9	2	2
	SO_2	0.1	0.1	0.1
Open fireplace / Others	CH_4	4.5	4.5	–
	NMVOC	9.0	9.0	–
	PM_{10}	12.7	28.5	–
	$PM_{2.5}$	11.8	26.5	–
	CO	60	94,860	–
	NOx	7.7	3.1	–
	SO_2	0.2	0.2	–

Table A1 ~~emission~~Emission factors (g/kg) for the residential sector by technology (appliance type), humidity and operation device conditions

Region	$PM_{2.5}$	PM_{10}	SO_2	CO	NO_x	~~VOC~~NMVOC	CH_4	CO_2	NH_3
North Zone	14.45	15.54	0.15	134,60	3.78	72,727,54	4.5	1366.83	0.87

Valparaíso	14.05	15.03	0.13	123,7160	3.21	59,056,96	4.5	1366.83	0.87
O'higgins	15.60	16.76	0.16	149,7060	3.74	83,957,77	4.5	1366.83	0.87
Maule	13.80	14.82	0.14	128,3360	3.13	7,1158,27	4.5	1366.83	0.87
Bio-Bio	15.07	16.19	0.15	144,1260	3.10	68,157,28	4.5	1366.83	0.87
Araucania	17.80	19.12	0.14	178,0260	2.44	75,037,08	4.5	1366.83	0.87
Los Ríos	15.86	17.04	0.15	177,9560	2.50	67,027,44	4.5	1366.83	0.87
Los Lagos	15.68	16.84	0.14	173,60460	2.39	61,027,31	4.5	1366.83	0.87
Aysén	15.74	16.91	0.15	185,8160	2.38	64,517,77	4.5	1366.83	0.87
Magallanes	17.32	18.60	0.15	171,6260	2.77	77,637,38	4.5	1366.83	0.87
Metropolitana	16.79	18.04	0.14	150,1660	2.76	71,686,96	4.5	1366.83	0.87
Mean	15.65	16.81	0.15	156,1560	2.93	69,007,33	4.5	1366.83	0.87

Table A2 ~~aggregated~~Aggregated emission factors (g/kg) at a regional level for each pollutant used in the residential sector.

Appendix B

Table B1 displays the total emissions (kt/annum) by year and sector for each pollutant of INEMA with information for more than one sector (represented in figure 4).

Specie	Year	Energy	Industry	Minining	Residential	Transport	Total
CH_4	2015	0.0	0.0	0.0	45.6	1.3	46,8
	2016	0,0	0,0	0,0	45.7	1.1	46.8
	2017	0.0	0.0	0.0	45.7	1.1	46.8
CO	2015	10.3	52.7	64.6	601.7	150.7	880.0
	2016	18.4	59.9	52.9	604.2	137.6	873.1
	2017	16.9	59.0	56.0	607.2	126.1	865.2
CO_2	2015	32922.5	11586.6	919.2	13728.0	21524.2	80680.6
	2016	36390.1	10550.9	863.4	13787.4	22514.5	84106.4
	2017	32660.0	19275.8	1185.4	13855.6	24100.9	91077.6
NH_3	2015	8.8	3.2	0.0	8.7	0.0	20.8
	2016	9.8	4.9	0.0	8.7	0.0	23.4
	2017	10.6	4.3	0.1	8.8	0.0	23.8
NMVOC	2015	0.0	0.0	0.0	73.9	13.4	87.3
	2016	0.0	0.0	0.0	74.0	12.0	86.0
	2017	0.0	0.0	0.0	74.1	10.8	84.9
NO_x	2015	60.0	37.6	5.7	27.1	84.5	214.8
	2016	59.5	34.2	5.2	27.2	85.1	211.2
	2017	51.8	37.8	3.9	27.4	92.0	213.0
PM_{10}	2015	4.5	14.9	1.9	171.3	2.4	195.0

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	2016	5.4	6.0	5.8	172.0	2.4	191.5
	2017	3.8	4.8	4.1	172.8	2.4	188.0
$PM_{2.5}$	2015	4.0	6.7	0.3	159.4	2.2	172.6
	2016	4.7	3.8	0.3	160.1	2.1	171.1
	2017	3.7	3.9	2.0	160.9	2.2	172.7
SO_2	2015	75.1	60.0	12.1	1.5	0.0	148.6
	2016	40.8	127.7	169.7	1.5	0.0	339.7
	2017	27.1	64.9	200.9	1.5	0.0	294.3
VOC	2015	16.3	2.7	0.4	118.3	14.6	152.2
	2016	18.1	6.3	0.3	118.8	13.1	156.6
	2017	1.8	2.0	0.2	119.3	11.8	135.3

Table B1 Total emissions (kt/annum) by year and sector for each pollutant represented in figure 4

Con formato: Fuente: 9 pto, Sin Negrita, Inglés (Estados Unidos)

Con formato: Título 3, Espacio Después: 10 pto

Con formato: Color de fuente: Negro

Con formato: Normal, Borde: Superior: (Sin borde), Infer (Sin borde), Izquierda: (Sin borde), Derecha: (Sin borde), Entre : (Sin borde), Punto de tabulación: 7.96 cm, Centrad 15.92 cm, Derecha