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RESEARCH ARTICLE

Evolution of air quality in Santiago: The role of mobility and lessons from the science-policy interface

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Worldwide, urbanization constitutes a major and growing driver of global change and a distinctive feature of the Anthropocene. Thus, urban development paths present opportunities for technological and societal transformations towards energy efficiency and decarbonization, with benefits for both greenhouse gas (GHG) and air pollution mitigation. This requires a better understanding of the intertwined dynamics of urban energy and land use, emissions, demographics, governance, and societal and biophysical processes. In this study, we address several characteristics of urbanization in Santiago (33.5°S, 70.5°W, 500 m a.s.l.), the capital city of Chile. Specifically, we focus on the multiple links between mobility and air quality, describe the evolution of these two aspects over the past 30 years, and review the role scientific knowledge has played in policy-making. We show evidence of how technological measures (e.g., fuel quality, three-way catalytic converters, diesel particle filters) have been successful in decreasing coarse mode aerosol (PM10) concentrations in Santiago despite increasing urbanization (e.g., population, motorization, urban sprawl). However, we also show that such measures will likely be insufficient if behavioral changes do not achieve an increase in the use of public transportation. Our investigation seeks to inform urban development in the Anthropocene, and our results may be useful for other developing countries, particularly in Latin America and the Caribbean where more than 80% of the population is urban.

Keywords: Air quality; mobility; urbanization; climate mitigation; policy-science interface; Chile

1. Introduction

Interest in urbanization is growing within both research and policy communities, and the process represents an important driver of global change and a distinctive feature of the Anthropocene (Baklanov et al., 2016; Boone, 2014; Brondizio et al., 2016; Kolbert et al., 2017; Pincetl, 2017; Seto et al., 2016). According to the United Nations, although cities covered less than 2% of the earth's surface in 2011, they were responsible for 78% of the world's energy consumption and produced more than 60% of all carbon dioxide (CO_2) emissions (UN-HABITAT, 2011). The fraction of global CO_2 emissions related to energy use is expected to grow given global urbanization trends (Hutyra et al., 2014). Nevertheless, urban development paths present opportunities for technological and societal transformations towards energy efficiency and decarbonization (Bai et al., 2016; Jorgenson et al., 2014; Pincetl, 2017). In this context, improving both GHG and pollutant mitigation policies requires better understanding of the intertwined dynamics of urban energy and land use, emissions, demographics, governance, and societal and biophysical processes, particularly in low and mid-income countries

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(CEPAL, 2017; Marcotullio et al., 2014; Romero-Lankao et al., 2014).

In this study, we address several characteristics of urbanization in Santiago (33.5°S, 70.5°W, 500 m a.s.l.), the capital city of Chile, a country with GDP of more than 22,000 USD/capita (https://data.oecd.org/chile.htm). Specifically, we focus on the multiple links between mobility and air quality, describe the evolution of these two aspects over the past 30 years, and review the role scientific knowledge has played in policy-making. We chose the Metropolitan Area of Santiago (hereafter Santiago) for study because of data availability, and because its development shares several characteristics with other urban centers in Chile (Henríquez et al., 2006), and other metropolis in terms of air quality and climate both in South America (Gallardo et al., 2012a), and elsewhere in the world (Zhu et al., 2013).

Urban mobility is a key structuring component of the urbanization process (Justen et al., 2012; Kelly and Zhu, 2016). It affects and responds to land use change, infrastructure building, socio-economic fluctuations, urban policies, urban form, lifestyles, and other elements of urban development (Justen et al., 2012; Tironi and Palacios, 2016). Mobility, therefore, has direct consequences on energy consumption, emissions patterns, and human well-being. It has received increasing attention not only from transport engineering and urban management fields, but also from the perspective of climate and health assessments (IPCC/WGIII, 2014; WHO, 2016).

Globally, the trend in CO_2 emissions from fossil fuel combustion for transportation has been increasing. According to statistics from the International Energy Agency (http://www.iea.org/statistics), since 1870 transport emissions and emissions from other energy consumption sectors have risen exponentially. Worldwide, transport accounted for 23% of all fossil fuel related CO_2 emissions in 2013, with road emissions being the most significant, accounting for almost 70% and growing at a rate of 68% between 1990 and 2013. Emissions from other modes of transport also grew steeply during the same period – marine transport by 64% and aviation by 90%. Despite technological advances leading to significant reductions in pollutant and greenhouse gas (GHG) emissions per vehicle and the implementation of attainment plans and other reduction measures, transportation in and around cities remains a major source of emissions that create detrimental impacts on human health, ecosystems, and the climate (Fuglestvedt et al., 2008; Kelly and Zhu, 2016; Shindell et al., 2011; Yan et al., 2014).

The case of Santiago presents multiple similarities with the global situation described above. According to the Mitigation Action Plans and Scenarios (MAPS) project (http://www.mapschile.cl/), the Chilean transportation sector is currently responsible for nearly 25% of Chile's equivalent carbon dioxide emissions (CO_{2eq}), which for 2015 were estimated at roughly 120 M ton CO_{2eq}, excluding Agriculture, Forestry and Land Use (AFOLU). Without considering mitigation, the transport sector is expected to remain around a 25% by 2030, with total emissions (excluding AFOLU) of ~180 M ton CO_{2eq}. This transport sector growth is explained by the increase in the number of trips in private cars, domestic flights, and to a lesser degree by increased trips by commercial trucks. Moreover, the Santiago transportation sector was estimated to contribute approximately 40% of the city's total fine particle matter (PM2.5) in 2011–2012, whereas in 1998–1999 transportation emissions were estimated at 24% of the total urban particle production (Barraza et al., 2017). A substantial upward trend of 28.6 ± 13.8%/decade from 2004–2014 in nitrogen dioxide (NO_2) is evidenced by satellite retrievals (Duncan et al., 2016), suggesting a continued growth of emissions from the transport sector despite stricter emissions standards and significant investments in public transport over the past 30 years.

Health in human settlements evolves along with urbanization and changes in population density, size, and energy consumption patterns. The physical and social environment, as well as access to health services, are determinants of population health (Vlahov et al., 2007). The Anthropocene poses multiple challenges to human health worldwide (Whitmee et al., 2015), and air pollution is responsible for one in every nine deaths each year (WHO, 2016). Extensive literature in the fields of environment, epidemiology and economics analyzes the impacts of outdoor air pollution on health outcomes (e.g., REVIHAAP, 2013). Evidence exists of both short (day-to-day) and long term (years) exposure to gaseous and particulate air pollution (Kim et al., 2015), and the need for interdisciplinary frameworks for study has been pointed out (West et al., 2016). Challenges to public health have historically been addressed by the direction of economic resources to efforts to reduce mortality levels and improve quality of life (Glaeser, 2011). Current levels of air pollution in Chilean cities and elsewhere in the world will require additional resources to achieve clean air and the resulting benefits in terms of health and well-being.

Given its dual role as GHG and pollutant emitter, the transport sector offers an opportunity for win-win mitigation actions to reduce Chile's carbon footprint and near-term climate impacts, and to diminish the adverse health impacts of air pollution (Creutzig et al., 2015; Kelly and Zhu, 2016). In its Nationally Determined Contribution (NDC) to the Paris Agreement, the Chilean government included mitigation options that consider, among others, measures related to black carbon (BC) mitigation in urban areas and within the energy sector (INDC, 2015). For instance, Chile is rapidly introducing non-conventional renewable energy (NCRE) sources, especially solar, which has grown from an installed capacity of 617 MW in 2015 to 2789 MW in 2018 (IEA, 2018). NCRE is projected to be responsible for 60% of Chilean electricity generation by 2035 (ME, 2015). Moreover, steps towards electromobility are currently being implemented (ME/MTT/MMA, 2017). Thus, coherent policies are moving towards sustainable energy and transportation.

In section 2, we review observed urbanization trends for Santiago and Chile at large regarding population, economics, land use change, mobility, and emissions from the transport sector. In section 3, we analyze the corresponding changes in air quality in Santiago over the last

30 years, including local and downwind impacts, as well as the policy framework within which these changes have occurred. In section 4, several aspects of the policy-science dialogue and interface surrounding urbanization, with emphasis on mobility and air quality, are summarized and discussed. Within this framework, we analyze proposed measures relevant to mobility, air quality and climate mitigation. A summary and conclusions are presented in section 5.

2. Observed urbanization trends

In this section, we describe relevant urbanization trends in Santiago and their main consequences as they relate to future mitigation options.

Demographic and economic changes

Chile presents relatively high urbanization. The latest official census data for 2002 (http://www.ine.cl/) estimated the urban population at 87%. By 2010, the urban population of Chile was estimated at 89%, or approximately 15 million (OECD, 2013). Chile presents higher urbanization than the Latin America and Caribbean (LAC) region, which itself is the world's most urbanized region of the world (UN-HABITAT, 2012). In 2012, the OECD defined 29 Functional Urban Areas (FUAs) in Chile (OECD, 2013), with the Metropolitan Area of Santiago and its 47 municipalities and more than 6.5 million inhabitants considered the only large metropolitan area in Chile. The Valparaíso and Concepción metropolitan areas have approximately one million inhabitants each, housed within nine and six municipalities, respectively. See **Figure 1**.

Chilean urban expansion can be traced back to the first half of the Twentieth Century, when migration from the countryside and the mines to the cities swelled in hope of employment opportunities and better salaries following the Saltpeter crisis (Badia-Miró and Ducoing, 2015; Collier and Sater, 2004). Santiago, the capital city, was the main recipient of migrant workers and faced a worker housing crisis during the 1930s and 1950s (Hidalgo and Sánchez, 2013). Chilean population expanded almost two-fold between 1930 and 1950, and continued to grow rapidly during the 1960s and 1970s. By 1960, Chile's urban population was 68%, with Santiago home to 43% of the country's inhabitants and nearly half of the industrial labor force, including highly skilled workers (Collier and Sater, 2004). Several of these urbanization trends are illustrated in **Figure 2**.

Despite a relative slowdown over the past ten years, Chile's economic growth has been significant over the last fifty years as compared to its LAC neighbors (de Gregorio, 2004; de Gregorio, 2008). The average yearly per capita income growth rate from 1960 to 2015 for Chile is the highest in the region, at 2.7%, compared to a LAC average of 1.8% (WB, 2016). This performance, together with integrative social policies (O'Ryan et al., 2008), has allowed for the reduction of poverty levels from 45.1% in 1987 to 14.4% in 2013 (WB, 2016). Although Chile is in good standing in terms of per capita Gross Domestic Product (GDP) in LAC, it presents pervasive and high inequality, with a Gini coefficient of 0.47 in 2013, which makes it one of the most unequal countries in a region characterized by inequity (OECD, 2015; PNUD, 2017; Solimano and Schaper, 2015). Inequity at the national level is also expressed within the country's urban areas, particularly in Santiago, which is a socially, economically and environmentally segregated city (Carpenter and Quispe-Agnoli, 2015; OECD; OECD, 2015; Romero et al., 2012; Sabatini and Salcedo, 2007).

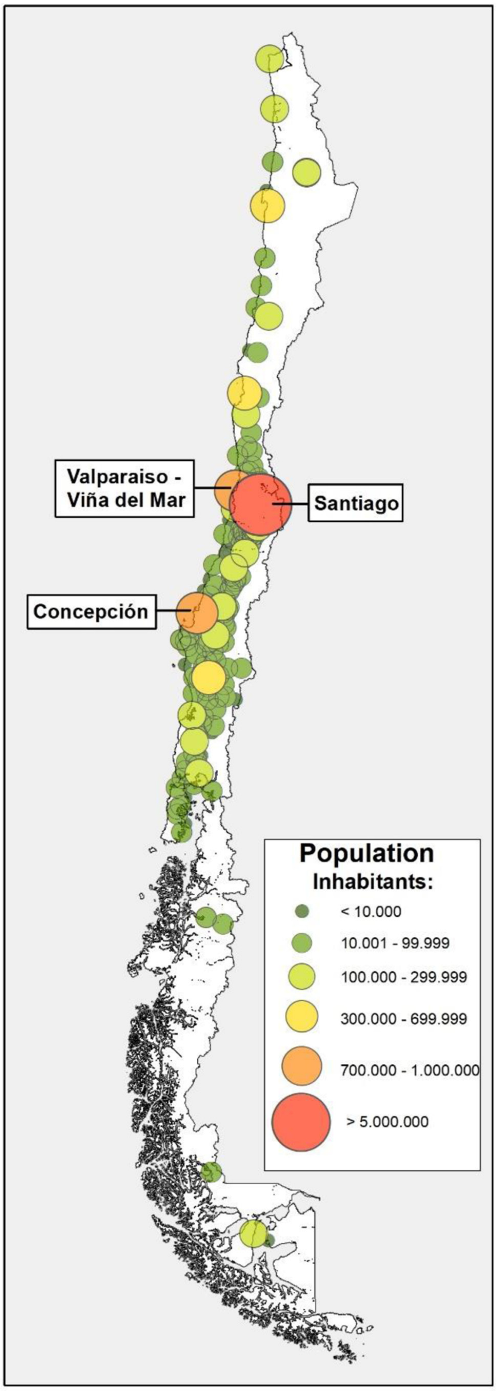

Figure 1: Spatial distribution of population in cities of continental Chile with more than 5000 inhabitants in 2012. Source: Ministry of Housing and Urban Planning. DOI: https://doi.org/10.1525/elementa.293.f1

Urban economies in Chile and throughout the region are key to national development. Nearly 70% of economic

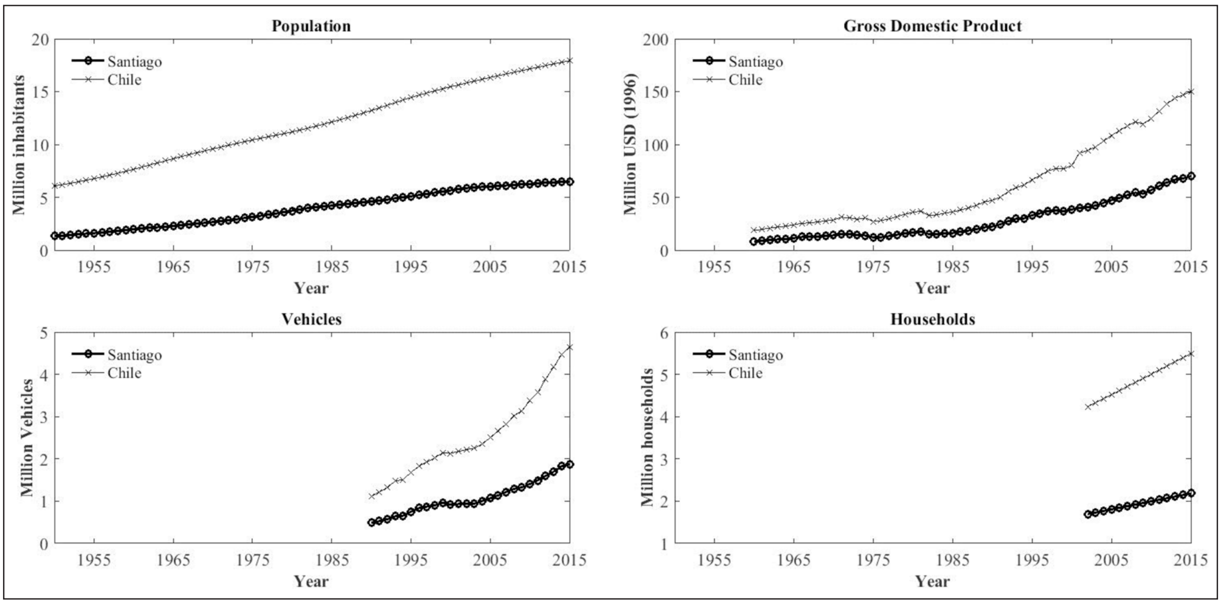

Figure 2: Urbanization statistics for Santiago and Chile. Population (United Nations, https://esa.un.org/unpd/wup/), gross domestic product (Central Bank of Chile, http://si3.bcentral.cl), vehicles (Institute for National Statistics of Chile, http://www.ine.cl), and households (Ministry of Housing and Urbanism, Chile, http://www.observatoriohabitacional.cl/) in the Santiago Metropolitan Region and Chile between 1950 and 2015. DOI: https://doi.org/10.1525/elementa.293.f2

growth between 2003 and 2006 occurred in six cities: Santiago, Concepción, Valparaíso, Antofagasta, Puerto Montt and Temuco (OECD, 2013). However, this growth is not directly correlated with per capita GDP in Chilean cities; although positive, this relationship is weak (OECD, 2013). An Organization for Economic Co-operation and Development (OECD) analysis attributed this behavior in part to the negative externalities of housing development and to rising inequality in urban areas, particularly in Santiago and Temuco, which counteract the positive externalities of urbanization.

Land-use and land-cover changes
Urban growth trends in Chile are diverse, showing substantial increases (>1.5% from 2002–2012) in mid-sized cities such as Temuco (Santiago et al., 2016). Santiago, on the other hand, appears to have grown at a slower rate over the same period (~1%), through urban sprawl in its outer belt and particularly toward the south and southeast. In order to illustrate these changes, the methodology presented by Zhao et al. (2016) was modified to produce land cover maps for Santiago and surrounding areas for 1986, 1996, 2006 and 2016 (Ceballos et al., 2018). According to this analysis, Santiago has experienced a marked territorial expansion from 522 km^2 in 1986 to 776 km^2 in 2016 (See **Figure 3**). **Table 1** summarizes 1986 and 2016 proportions, gains, losses, swaps, and net changes for each land cover. Extensive urban land cover showed the highest gain, while the least change was observed in snow and glaciers. Managed vegetation, mainly agricultural areas, followed by bare soil and rocks, experienced the highest loss over the last 30 years due to replacement with new urban areas, including housing and roads. An increase in urban concrete corresponding to roads and other concrete-covered surfaces is also apparent. The spread of residential areas occurred in all directions around the city, but was limited to the east by the Andes Mountains above 1000 m a.s.l. The southern areas of the city experienced generalized urban expansion with a clear delineation of island cities in the southwestern section of Santiago. An important industrial area in northern Santiago also appeared during the time period with a mix of extensive, intensive, and concrete urban coverage. Quantitative change (net change), was highest for bare soil and rocks (about 32% of total change), whereas the change attributable to location (swap) is highest for managed vegetation (about 76% of total change). Land swap dynamics accounted for 73% of total landscape change, and correspond in part to interannual crop rotations.

The dynamics described above have been analyzed by several authors (Banzhaf et al., 2013; Hidalgo et al., 2008; OECD, 2013; Puertas et al., 2014). These authors demonstrate that the periurban development observed for Santiago has produced segregated communities with poor connectivity and detrimental environmental and socio-economic impacts. Nevertheless, further sprawl surrounding Santiago is expected over coming decades, with real estate and transportation being the most influential factors contributing to this process (Justen et al., 2012; Puertas et al., 2014).

Mobility changes
Along with migration from rural to urban environments and land use changes, Santiago's mobility habits have changed over time. Users have changed how and where they travel and the origin-destination surveys (ODS) performed by the Ministry of Transportation and Telecommunications (MTT) in Santiago every ten years provide some insights into these patterns, as presented in **Table 2**. Available information allows for a comparison

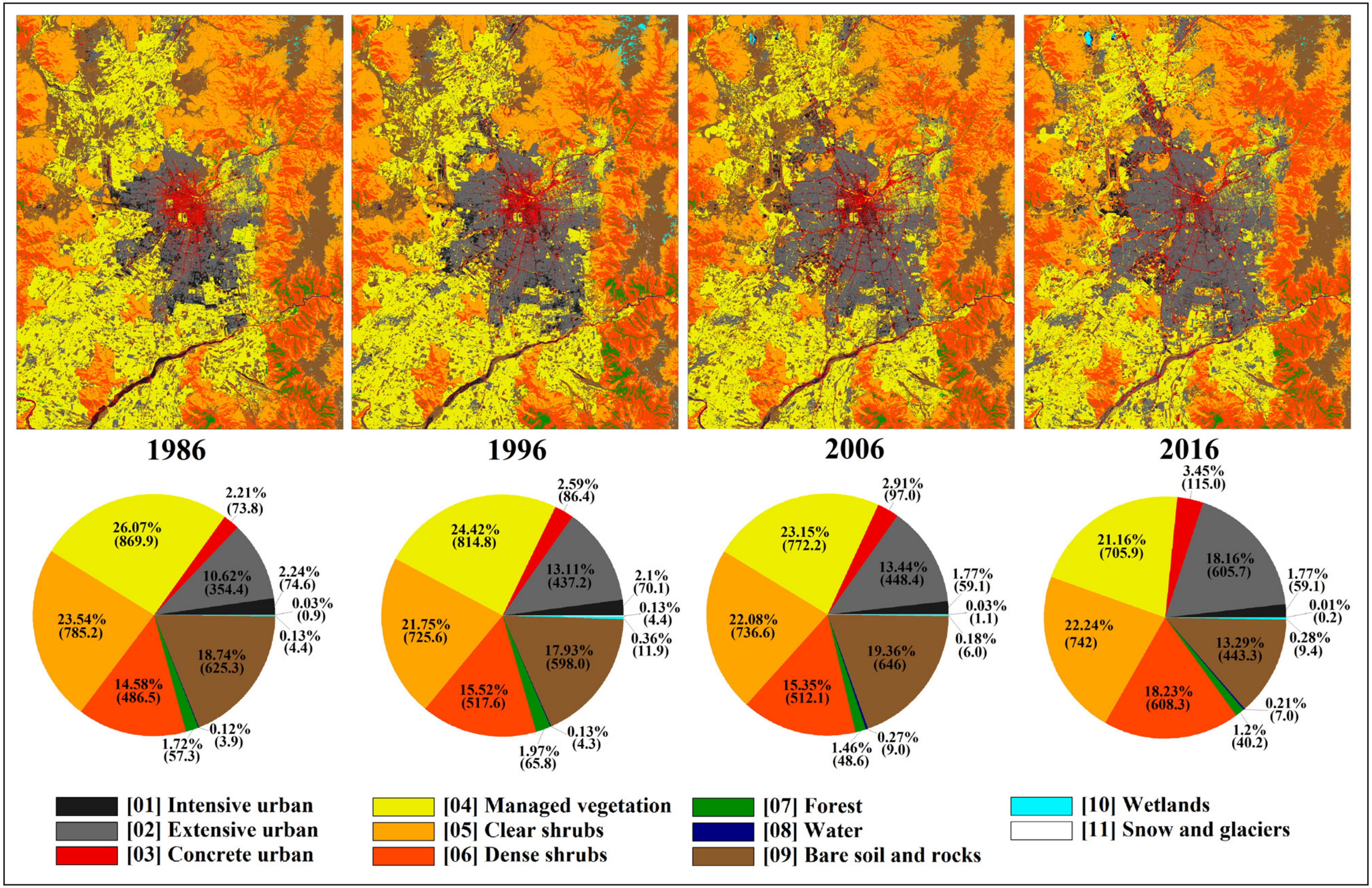

Figure 3: Land coverage maps for the Metropolitan Area of Santiago for years 1986, 1996, 2006 and 2016. Pie charts provide the proportion of each land cover class for each year in %, with km^2 in parenthesis. Original methodology by Zhao et al. (2016), and current processing described in Ceballos et al. (2018). DOI: https://doi.org/10.1525/elementa.293.f3

Table 1: Summary of landscape changes in percentage between 1986 and 2016[a]. DOI: https://doi.org/10.1525/elementa.293.t1

Land Cover Type	Gain	Loss	Total Change	Swap	Abs. Net Change
[01] Intensive Urban	1.42	1.86	3.27	2.84	0.44
[02] Extensive Urban	10.6	3.99	14.6	7.98	6.60
[03] Concrete Urban	2.79	1.21	4.00	2.43	1.57
[04] Managed Vegetation	7.11	11.6	18.7	14.2	4.45
[05] Clear shrubs	6.75	7.04	13.8	13.5	0.29
[06] Dense shrubs	4.94	2.37	7.31	4.74	2.57
[07] Forests	0.34	0.66	1.01	0.69	0.32
[08] Water	0.16	0.10	0.26	0.20	0.06
[09] Bare soil and rocks	5.65	11.0	16.6	11.3	5.32
[10] Wetlands	0.21	0.17	0.39	0.35	0.04
[11] Snow and Glaciers	0.01	0.03	0.03	0.01	0.02
TOTAL	**40.0**	**40.0**	**80.0**	**58.2**	**21.7**

[a]Values are presented in percentage calculated with respect to a total surface of 3336 km^2. Codes for land cover type are shown in Figure 3.

Table 2: Summary of Origin-Destination Surveys for 1991, 2001 and 2012 as reported by (SECTRA, 2002; SECTRA, 2012). DOI: https://doi.org/10.1525/elementa.293.t2

Variable	1977	1991	2001	2012	% Change 1991–2001	% Change 2001–2012
Households (Thousands)		1163	1523	1938	31%	27%
Inhabitants (Thousands)		4502	5539	6268	23%	13%
Vehicles (Thousands)		421	696	1115	65%	60%
Total Trips (Thousands)			15586	17544		13%
Non-motorized			*6293*	*6752*		7%
Motorized		*5807*	*9292*	*10792*	60%	16%
% of Trips in private cars	11.6	19.7	37.7	46.4	91%	23%
% of Trips in public transport	83.4	70.5	55.8	46.9	–21%	–16%

of trip structure observed in 1991, 2001 and 2012, with some figures available for 1977. A nearly 30% increase is observed in the number of households from survey to survey, which was accompanied by a 23% population increase between 1991 and 2001, and of 13% over the past decade, indicating a reduction in average household size. Nevertheless, the number of vehicles in Santiago increased at a rate much higher than both households and population.

In terms of travel patterns, over one third of trips in Santiago are short walking trips. The number of motorized trips shows a clear and constant migration from public transport to private cars, which represents an unfortunate trend from many perspectives and particularly in terms of emissions. Less trips by public transport were reported for 2012 than for 2001, despite increases in population and total number of trips. A more detailed analysis of the 2012 ODS shows that private car usage is particularly high for purposes other than work and study. Trip purposes are distributed between work (29.4%), study (17.7%) and shopping (16.9%). The remaining 36% corresponds to various activities including social activities, health related activities, and errands. The dominant travel mode for work is public transport (43.3% of total trips and 54.5% of motorized trips), while study and shopping trips are predominately non-motorized (walking and biking). Motorized study trips are primarily undertaken by public transport (48.5%), while motorized shopping trips are mostly made by car (60.7%).

Within Santiago's public transport system, the most important transport modes are Metro (subway) and bus, currently integrated within the Transantiago system launched in February 2007. The first Metro lines were built in the 1970s and operated independently of the bus system. The implementation of Transantiago integrated bus and Metro fares and implied a comprehensive shift from a multi-owner and disorganized public bus fleet towards an integrated system operated by seven private bus companies (selected through an international bidding process) and the state owned Metro Company. Currently, the system has five lines and 103 km of Metro line, with 6.600 buses running over 61.7 km of segregated roads, 31 km of exclusive roads and 119.3 km of bus-only tracks (http://www.dtpm.cl/). Currently an additional Metro line is under construction and operating in 2018, extending total Metro coverage to 140 km. The next extension has already been announced, which will create a 27 km connection between the east and northwest sectors of the city.

The market share of the Metro was initially very low (~5% in 1991 and 2001 according to the ODS). This may be explained by the network's small size at that time and by the lack of fare integration with the bus system. The incorporation of new lines and important extensions has had an observable effect on demand; annual Metro passenger flow showed increases between 10 and 20% during years of important infrastructure investments. Following fare integration with buses in 2007, the annual flow of Metro passengers increased by 80%. The market share of Metro in total daily trips in Santiago reported by the 2012 ODS is 12%, including only Metro (5.6%) and bus-Metro combinations (6.4%). The impact of new lines is expected to be smaller, given that lines of highest demand have already been built. Retrospective assessments indicate that the number of passengers by line length was highest for the first and oldest line (L1), and lower for more recent lines (See **Table 3**).

The implementation of Transantiago brought a reduction in the number of buses (from 11 thousand to approximately six thousand units) and bus integration within the existing subway system, and introduced stringent per bus emissions standards and better fuel quality (see next section), which produced multiple impacts on mobility and air quality (Beltrán et al., 2013; Gramsch et al., 2013; Mena-Carrasco et al., 2012; Muñoz et al., 2014; Muñoz and Gschwender, 2008; Tironi and Palacios, 2016; Toro et al., 2014; Yáñez et al., 2010). Nevertheless, implementation has been widely criticized with regards to several technical and political factors including weaknesses in the original structure, lack of supervision, subscription of contracts with incentives towards transport of kilometers instead of passengers, lack of tangible products during key planning stages, and changes in political priorities at the presidential level throughout implementation (Gómez-Lobo, 2012; Olavarría Gambi, 2013).

Over time, a modal shift towards non-motorized alternatives has been encouraged by the provision of new cycle ways, though in small numbers. Over the last few years, the Municipality of Santiago committed to "inverting the transport pyramid" by assigning priority to pedestrians, public transport and the promotion of sustainable means of transport such as bicycles and electric vehicles (See Tohá, 2018). Among other measures, this initiative resulted in a 50% expansion of sidewalk space on key roads in downtown Santiago, as well as the establishment of exclusive public transport roads. A public bike system was implemented in February 2015, and 255 kilometers of bike lanes have been constructed according to MTT statistics. An electric mobility showcase was developed with a small fleet of one bus and three taxis. Discussion of a more substantial effort expressed by new, inter-ministerial electromobility policy is underway (ME et al., 2017). Furthermore, the ongoing bidding process for Transantiago considers the inclusion of 90 electric buses (https://www.dtpm.cl).

Despite these initiatives, the use of private cars is still encouraged in Santiago with the construction of new urban motorways, and as a result of increased demand for motorized trips due to unplanned urban sprawl with heterogeneous distribution of schools and working places. If Santiago continues current trajectories, future scenarios involve increased congestion and travel times (Justen et al., 2012).

Table 3: Description of Metro de Santiago lines and their annual passenger flows[a]. DOI: https://doi.org/10.1525/elementa.293.t3

Metro Line	Year of Construction	Length (km)	Annual Passenger flow (millions)	Passenger flow per line length
1	1975	19.0	261	13.7
2	1978	18.5	121	6.50
5	1997	28.0	147	5.25
4	2005	23.0	120	5.22
4a	2006	7.50	20.8	2.77

[a]Source: built from official information published by the Metro de Santiago Company (Metro, 2016).

Emission changes

The primary technological mitigation measures introduced over the past 30 years in Santiago include stricter vehicle emission standards (EURO 5 is mandatory for light duty vehicles since 2012), improved fuel quality for both gasoline and diesel (unleaded gasoline since 1994 and a maximum of 15 ppm S since 2013), as well as a massive introduction of after-treatment devices (three-way catalytic converters since 1992 and diesel particle filters since 2010) (Corvalán et al., 2002; Corvalán et al., 2005; Gallardo et al., 2012b; Mena-Carrasco et al., 2012; Mena-Carrasco et al., 2014). As previously stated, important operational changes such as Transantiago have also been implemented, as well as stricter emissions standards for buses (Euro III 2002, Euro IV 2010). These technological measures were first introduced in Santiago as well as in the Valparaíso and Bernardo O'Higgins regions (northwest and south of Santiago, respectively). These changes are being progressively introduced in other cities following the installment of infrastructure to ensure availability of the higher quality fuel required by new vehicle technologies.

Developing emissions inventories is an extremely complex process, which requires detailed statistics, process-level understanding, and continuous evaluation and updating, particularly when assessing species whose emissions depend on multiple factors in addition to fuel consumption (Bond et al., 2004; D'Angiola et al., 2010; Lamarque et al., 2010; Yan et al., 2014). Chile lacks sustained, centralized and coordinated monitoring activities and records of reliable and harmonized emissions inventories for urban centers. GHG inventories are developed and coordinated by the Ministry of the Environment in collaboration with other ministries (http://www.snichile.cl/), while other emissions inventories for air quality management and control are undertaken by consultants, often in association with universities. Within this framework, several emissions inventories for mobile sources have been estimated for Santiago, the first in 1998, which included measurements of real vehicles to determine emissions factors using local driving cycles under dynamometer testing (Corvalán et al., 2002; Corvalán et al., 2005). Since then, local authorities in Santiago have requested additional emissions inventories (DICTUC, 2007; USACH, 2014). These methodologies have been in part reproduced in other regions of the country and elsewhere in South America (D'Angiola et al., 2010; González et al., 2017). Recently, the first national inventory for short-lived climate pollutants was undertaken (DICTUC and UTFSM, 2017).

The emissions inventories referred to earlier are published in the form of reports on the Chilean Ministry of the Environment's website; however, their spatial allocation is not readily available. Moreover, underlying statistics and emissions factors are generally not included, making it hard to check for consistency and comparability between inventories. Nevertheless, over the last 30 years, key parameters for emissions estimates in official surveys and databases have been introduced throughout the country. First of all, emissions testing based on international protocols for new models of passenger cars is routine since 1997, made possible by the official homologation center (http://www.mtt.gob.cl/3cv), which also provides continuous information regarding emissions standards and dynamometer emissions testing for heavy-duty vehicles. Second, information for in-use vehicles is provided primarily by well-enforced inspection procedures, which register mileage, emissions control devices, fuel type and, and since 2007, carbon monoxide (CO), hydrocarbons, and nitrogen oxides (NO_x) emissions under acceleration simulation mode (ASM) cycle, which replaced the previous idling procedure (MTT, 2007). Vehicle activity levels are not only measured but also provided by the Ministry for Telecommunications and Transportation using traffic models for 26 cities in Chile, allowing estimates for future projects within city areas. Combining all available information allows for detailed and updated emissions estimates at the street level with daily resolution. However, information is dispersed among several public and private institutions, reported in different formats and/or for different time periods, which makes it difficult to fulfill the potential for accurate emission estimates based on these sources.

Figure 4 provides an estimate of the evolution of transportation emissions for Santiago and Chile since 2000, when the first attainment plan for air quality was launched. Projections are shown for the period 2016–2050. These estimates are based on MAPS's demand projections feeding a transport emissions model (Cortés et al., 2008; Tolvett Caro et al., 2016; Valdebenito Silva, 2017). MAPS was a government-mandated strategy of co-producing scientific evidence to support policymaking on climate change essentially based on agreed stakeholder and expert opinions (Calfucoy and Rudnick, 2016). At the time (~2011), considering a medium high GDP growth (~4%) over the period 2013–2050, a baseline emission scenario

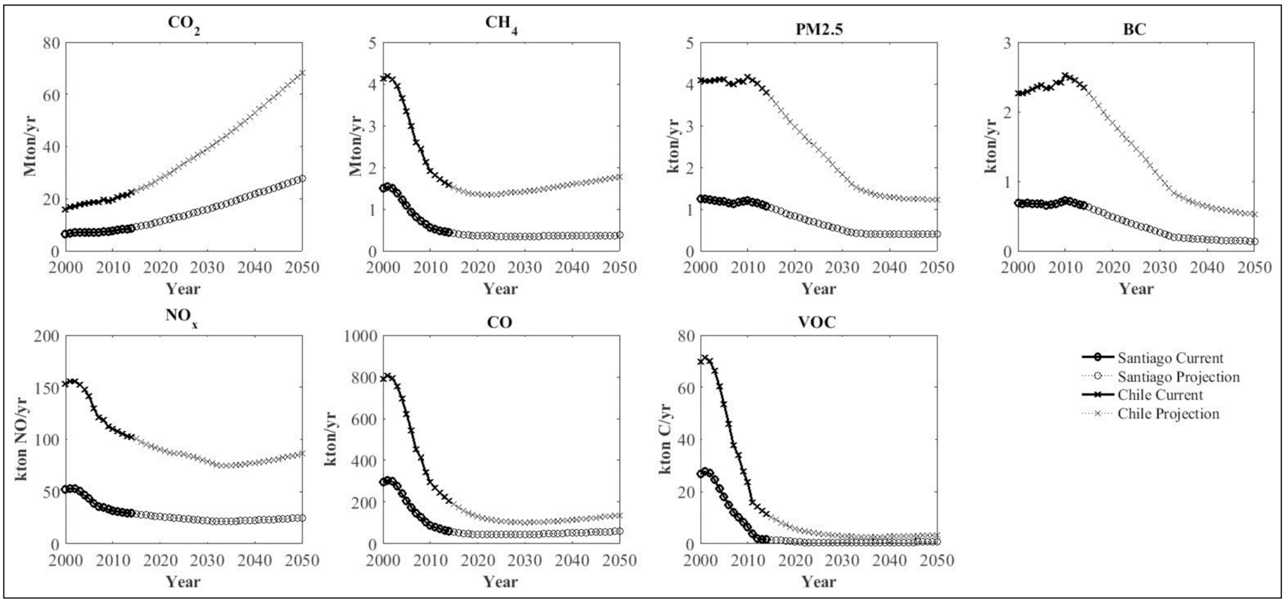

Figure 4: Evolution of CO_2, CH_4, PM2.5, NO_x, CO and VOC emissions from the transport sector for the Santiago Metropolitan Region and Chile since 2000. Projections are shown for the period 2016–2050. These estimates are based on MAPS statistics and a transport emissions model. This figure was adapted for this publication from Tolvett Caro et al. (2016). See text for details. DOI: https://doi.org/10.1525/elementa.293.f4

was built assuming that GHG emissions would grow as a consequence of increase in power generation based on coal, in electricity demand from industry, copper demand until 2030, as well as growth in private passenger transport. Thus, the exercise shown in **Figure 4** is conservative as it does not take into account recent developments in energy policies in Chile.

In our exercise, emissions results were compared with existing national emissions inventories both for local pollutants and GHG, as well as CO_2 road transport values reported by IEA, with good correlation for PM2.5, NO_x and CO_2 (within 10%). Future projections show an increase in CO_2 emissions following less intense increases in transport activity levels and suggesting a decoupling of emissions from transport activity. NO_x decreases after the application of EURO 5 and EURO 6 emissions standards in 2014 and 2018, respectively, but is projected to increase again after ageing and deterioration. A reduction in PM2.5 and BC emissions appears by 2015. Whereas the introduction of new technologies (particle filters, electric vehicles) leads to emissions reductions, deterioration after 5–10 years (Corvalán and Vargas, 2003), and activity growth in terms of vehicle kilometers travelled, can cause emissions to rebound. National and Santiago trends show a similar pattern, considering that the adoption of new vehicle technologies will take place throughout Chile's 15 regions over the course of one year.

Estimates of mobile emissions (Cf. **Figure 4**) have been validated in terms of their consistency with concurrent estimates (e.g., regionalized greenhouse gas inventories), and compared with available estimates (DICTUC, 2007; DICTUC and UTFSM, 2017; USACH, 2014) but their accuracy requires further testing. Validation can be performed using *in situ* measurements and direct and inverse modeling techniques generally addressing CO and PM2.5 emissions (Gallardo et al., 2012b; Jorquera and Castro, 2010; Mazzeo et al., 2017; Mena-Carrasco et al., 2012; Saide et al., 2011; Saide et al., 2016; Schmitz, 2005). Extensive validation for other species has been hampered by the lack of speciated observations for particles and hydrocarbons, as well as by the lack of vertically resolved observations.

3. Evolution of air quality and its impacts

In this section, we identify the main trends in air quality and impacts, and relevant knowledge gaps.

Air quality monitoring and trends

Air quality monitoring has taken place in Santiago almost continuously since 1988, and in a standardized manner since mid-1997 when the first attainment plan was implemented (Gallardo et al., 2012a; Toro et al., 2015). These measurements were initially undertaken by the Ministry of Health, and since 2011 have been coordinated by the Ministry of the Environment. Instruments and quality control procedures for the Santiago monitoring network have followed the recommendations of the US Environmental Protection Agency (EPA) since 1997, and are subject to public scrutiny (http://sinca.mma.gob.cl) and to occasional external review panels. The most frequently measured species are: CO, sulfur dioxide (SO_2), ozone (O_3), nitrogen monoxide (NO), NO_x (NO_x = NO + NO_2), as well as particulate matter of 10 mm in diameter or smaller (PM10) since 1988; and PM2.5 since 2000. Since 1988, particulate matter has been collected at three sites using a dichotomous filter sampler providing 24-hour concentrations and elemental composition for PM10 and PM2.5 (Artaxo et al., 1999; Barraza et al., 2017; Gramsch et al., 2009; Jhun et al., 2013). No long-term, reliable measurements of volatile organic compounds are available for Santiago. Moreover, except for the elemental composition of the particles referred to earlier, neither speciation or size distribution studies of aerosols nor hydrocarbon speciation measurements are regularly carried out by environmental authorities. Such studies have been sporadically contracted by authorities or undertaken by academia, which severely hampers our ability to address underlying processes and better define mitigation options. Only recently was a mobile station acquired by the Ministry of the Environment that allows for simultaneous measurements of aerosol size distribution between 6 nm and 10 mm, mass concentrations of PM2.5 and PM10, O_3, NO_2, black carbon (using a multi wavelength aethalometer), and CO_2.

In addition to these measurements, authorities and academia have carried out several specific, short-term campaigns addressing the photochemistry, vertical stratification, and radiative properties of aerosols e.g., (Didyk et al., 2000; Elshorbany et al., 2009; Escribano, 2014; Muñoz and Undurraga, 2010; Préndez et al., 2013; Rappenglück et al., 2005; Seguel A et al., 2009; Seguel et al., 2013; Villena et al., 2011).

The monitoring network has evolved to increase its coverage as Santiago has expanded. In previous investigations, we have analyzed this evolution and evaluated the representativity and specificity of the network's stations (Henriquez et al., 2015; Osses et al., 2013). These analyses indicate that Parque O'Higgins is the most representative station of the Santiago air quality network, i.e., it captures the average behavior of the network. Based on this fact, and the length of the observational record (~30 years), we use this station to illustrate the overall evolution of air quality in Santiago since the late 1980s. Details on the data analyzed are presented in Supplemental Material. As presented in **Table 4**, significantly declining trends in monthly averaged values of PM10, PM2.5, SO_2 and CO can be observed at this site and elsewhere in the basin (not shown). Nitrogen oxides have been measured *in situ* less continuously (and less carefully) than particles, making it harder to assess trends. Nevertheless, NO_2 trends (not shown) from *in situ* monitors in Santiago do not indicate the substantial upward trend derived from remotely sensed data (Duncan et al., 2016). Satellite data are nonetheless consistent with the two-fold increase in the number of vehicles between the late 1990s and 2015. Moreover, monthly mean ozone levels show an overall decline, particularly since 2008. These trends require further investigation, in particular the assessment of potential biases in the satellite-derived NO_2 trends stemming from the relatively coarse spatial resolution (up to 13 km × 24 km), the

Table 4: Decadal trends in monthly averaged pollutant concentrations/mass mixing ratios as measured at Santiago downtown (Parque O'Higgins station)[a]. DOI: https://doi.org/10.1525/elementa.293.t4

Species (unit)	Decadal linear trend (*species unit per 10 years*)	Period	Number of data points (months)
PM10 (mg/m^3)	–22.3 ± 11.4	June 1987–December 2015	348
PM2.5 (mg/m^3)	–8.42 ± 5.30	April 1998–December 2014	228
SO_2 (ppb)	–2.50 ± 0.94	July 1997–December 2016	237
CO (ppm)	–0.44 ± 0.20	April 1997–December 2016	240
NO (ppb)	–15.4 ± 4.93	March 2009–December 2016	96
NO_2 (ppb)	–4.64 ± 2.20	March 2009–December 2016	96
NO_x (ppb)	–18.7 ± 6.79	March 2009–December 2016	96
O_3 (ppb)	–2.09 ± 1.09	April 1997–December 2016	240

[a]In the case of particles, we use data collected with a dichotomous sampler for PM10 and PM2.5 for 1988–2015 and 1998–2015, respectively (Barraza et al., 2017). In the case of gaseous pollutants we use data available at http://sinca.mma.gob.cl/index.php/region/index/id/M as in January 21 2018. Trends are calculated using the methodology described by Lamsal et al. (2015). The uncertainty in the linear trend is calculated according to Tiao et al. (1990). See Supplemental Material for details regarding data handling.

high-reflectivity of the area (Escribano et al., 2012), and from the spatial heterogeneity of emissions (Duncan et al., 2016).

For all species and stations, maximum values have declined more than average or median values (not shown), consistent with the focus placed on short-term air quality standards. Air pollution research and management initiatives were triggered by severe problems associated with particle concentrations. Emphasis was therefore placed on short-term and local-scale analyses designed to deal with acute problems (i.e., extreme pollution events by particles), while less attention has been paid to long-term, large-scale effects, and ozone pollution (See section 4). This is illustrated again for Parque O'Higgins in downtown Santiago, where the data series for ozone and particulate matter are shown against current air quality standards for Chile (See **Figure 5**). Ozone shows nearly unchanged behavior between 1997 and 2007, and declining trends thereafter for 8 hour running averages. This entails further investigation. PM10 concentrations show a sharp decline between 1997 and 2000, and a less marked decline afterwards. However, while the daily standard is nearly met, the annual standard is far from compliance with current health thresholds (Cf. **Figure 5**). PM2.5 concentrations also show a clear downward trend after 2008, but neither short-term nor long-term standards for PM2.5 are achieved. Notably, a primary air quality standard for PM2.5 was introduced only in 2012.

Human health

Multiple studies have been carried out in Santiago to assess the association between particulate matter and morbidity and mortality (Adonis and Gil, 1993; Bell et al., 2011; Franck et al., 2014; Leiva et al., 2013; Ostro et al., 1995; Suarez et al., 2014; Valdes et al., 2012). However, all of these studies have used exposure-response functions taken from international analyses because no cohort study has been carried out for Santiago. According to the Ministry of the Environment, ten million people in Chile are exposed to poor air quality, as 25 out of the 45 cities with monitoring stations measure particle concentrations that are higher than established Chilean standards (MMA, 2014). This has led to the implementation of several measures to control emissions of air pollutants in 10 urban centers throughout the country.

Primary ambient air quality standards were introduced in Chile in the late 1980s and have become stricter over time (Zhu et al., 2013). Emissions standards for vehicles and industries have become more stringent, and green taxes have been adopted over the past few years (Winkler et al., 2016). To a large extent, this has been possible because of the overwhelming benefit to cost ratio derived from considering the health impacts of air quality. A primary standard for PM2.5 was established in 2012 and the benefits of this policy are estimated at 41 billion U.S. dollars for the period 2012–2031 (MMA, 2012). The benefits to the health sector due to the enforcement of these concentration limits translate into 148 thousand avoided deaths, 244 thousand avoided hospital admissions, 992 thousand avoided visits to emergency rooms for children, 59 million avoided working days lost, and 283 million avoided days with activity restriction. The standard is expected to achieve full enforcement over the 2012–2032 period (graduating from a current annual 25 mg/m^3 limit to 10 mg/m^3 in 2032). The latest attainment plan for Santiago is estimated to have an 8 to 1 benefit-to-cost ratio, with health benefits of approximately 7 billion U.S. dollars (MMA, 2016a).

Regional impacts

In addition to the local and regional direct and semi-direct radiative effects described by Mena-Carrasco et al. (2014), pollution exported downwind from Santiago has been shown to have potential effects on cloud properties far out over the Southeast Pacific (Allen et al., 2011; Saide et al., 2012; Yang et al., 2011). Similar processes may result

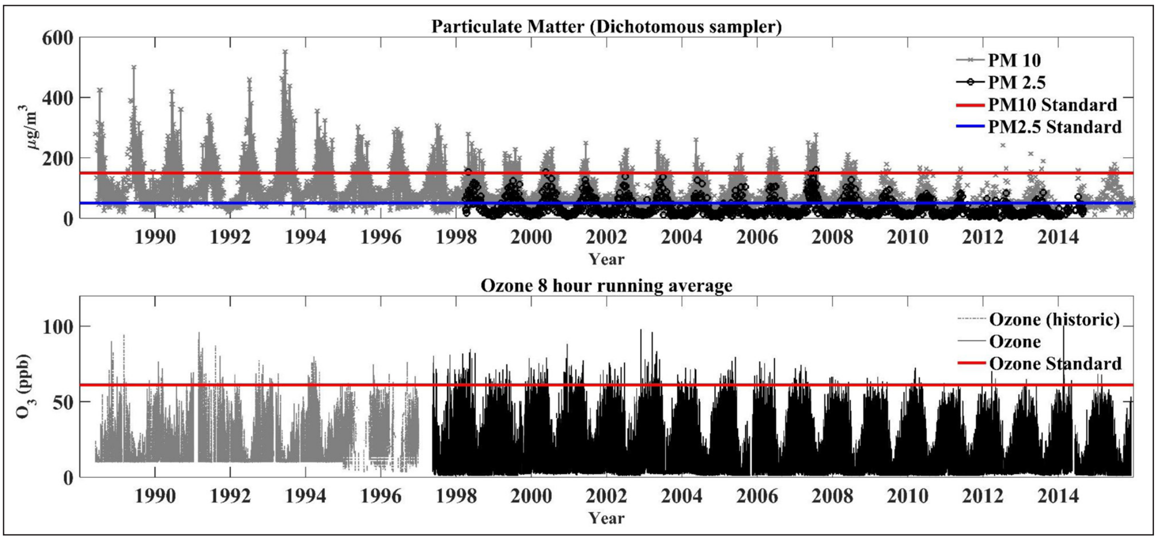

Figure 5: Evolution of particulate matter and ozone in downtown Santiago for the period 1988–2016. The upper panel shows PM10 and PM2.5 24 hour averages collected using a dichotomous sampler as described in Barraza et al. (2017). The lower panel presents 8 hour averages of ozone for the same site. In the case of ozone, the data collected before 1997 are differentiated with respect to later data subject to more careful quality control by environmental authorities. Red and blue lines show daily air quality standards for these pollutants according to current Chilean legislation. Standards are shown only for reference. Particulate matter data were provided directly by officials of the Chilean Ministry of the Environment. Ozone data prior to 1997 were previously downloaded from the website of the Regional Secretariat from the Chilean Ministry of Health (Gallardo et al., 2012a). Ozone data for 1997 onwards are available at http://sinca.mma.gob.cl and were downloaded on January 21 2018. Here we show validated data according to the Ministry for the Environment. See Supplemental Material for details. DOI: https://doi.org/10.1525/elementa.293.f5

in the transport of aerosols and strong acids that may impact stratocumulus clouds and the photochemistry of the coastal ocean, in turn affecting atmospheric photochemistry over land (von Glasow et al., 2013). Santiago's air quality may also have an impact on the Andean cryosphere and hydrological resources, via the deposition of black carbon and other impurities on high-elevation glaciers and snow cover (Molina et al., 2015).

Concern also surrounds the impact of climate change (expressed as declining precipitation and increasing temperatures) on agriculture, wine production and other key economic activities in central Chile (MMA, 2016b). However, to the best of our knowledge, no systematic research activities have been carried out to assess concomitant pollution impacts on agricultural production and food or water security (Tai et al., 2014). Also, very few studies describe the impacts of vegetation on air pollution or vice versa (Escobedo and Nowak, 2009; Escobedo et al., 2008; García-Huidobro et al., 2001; Préndez et al., 2013; Romero et al., 1999). More research on these interactions is needed. As fruit, wine and wood exports are important for Chile's economy (~2,250 million U.S. dollars in 2017, http://www.bcentral.cl/comercio-exterior), it is key to address the impacts of air pollution on agriculture, particularly in the context of a changing climate.

4. Mitigation measures and the science-policy interface

Policy framework for air quality management

Research on air quality in Santiago can be traced back to the early 1960s when the first studies of photochemical smog and atmospheric stratification were performed (Fuenzalida, 1961). By the 1980s, under political dictatorship, studies of pollution meteorology, particle concentrations, source apportionment, and optical properties created public concern and drove incipient public policies (Préndez et al., 1984; Sandoval et al., 1993; Ulriksen, 1980). Although the constitutional recognition of the right to a clean environment was instated under dictatorship, belief in a market driven model of development resulted in policies where environmental concerns were considered factors that should not limit economic growth (as measured by GDP) and that could be resolved retroactively (O'Ryan and Ibarra, 2017). Measures included direct regulations, or command and control instruments.

With the reinstatement of democracy, Chile enacted the Law for the Environment (Act 19300), which consolidated norms and regulations from multiple sectors under a policy directed at fulfilling international commitments (e.g., Rio Declaration) and organizing existing regulations (O'Ryan and Ibarra, 2017). Preventive tools such as environmental impact assessments were also introduced. The National Commission for the Environment (CONAMA, in Spanish *Comisión Nacional del Medio Ambiente*) was created and acquired a pivotal role in the development and implementation of environmental policies, though with only a coordinating role among sectorial ministries. Still, as market oriented development continued and prevailed during democracy, and following recommendations from international bodies such as development banks, national environmental policies began to apply economic or market based approaches in addition to command and control measures. For instance, the introduction of air quality standards resembling those of the United States

Environmental Protection Agency, were accompanied by a cost-benefit analysis that assigned value to the economic and social impacts of improved air quality, particularly for health. Interestingly, this new policy framework introduced transparency within the system with the creation of policy instruments with mechanisms for public participation, including the participation of academia and other stakeholders.

In response to external reviews (OECD/ECLAC, 2005) and the need to efficiently address multiple and complex environmental issues, substantial institutional reform took place by 2010 and led to the creation of the Ministry of the Environment (Act N°20417). In addition to reinforcing transparency, public participation, and precautionary principles, the creation of the Ministry of the Environment enhanced the political and administrative hierarchy of environmental institutions and of environmental issues in general. A Council of Ministers for Sustainability is expected to facilitate coordination among sectors and strengthen the transversal character of environmental policies. Notwithstanding encouraging examples of intersectorial, synergistic and participatory policies such as the energy plan for 2050, weaknesses and inadequacies continue to be observed. Such shortcoming have been identified regarding urbanization and urban development (OECD, 2013; OECD/ECLAC, 2016). A major challenge relates to the prevailing sectorial allocation of funding that promotes competition for resources among authorities, leading to antagonism instead of synergism, and hampering a systemic approach to complex issues such as urban development. Land use, housing, public transport and environmental policies are designed and implemented independently of one another (OECD, 2013). A second major problem relates to the lack of political autonomy and resources assigned to local institutions and authorities (Fenton and Gustafsson, 2017). This issue is exacerbated in large urban areas, particularly in Santiago, where in addition to poor and relatively weak municipal institutions, political leadership is insufficient for governing the Metropolitan Area of Santiago as a whole. Vertical and horizontal coordination deficits among diverse urban authorities have been identified, as well as institutional weaknesses regarding the transparency of decision-making processes and opportunities for public participation (Hölzl and Nuissl, 2010; Hölzl and Nuissl, 2014).

Governments have addressed these issues by creating intersectorial platforms and promoting new policy approaches; however, it appears necessary to strengthen and accelerate the implementation of these policies. As we will show, a shift from top-down technology oriented policies to bottom-up behavior oriented policies will be required to address urban development in general, and air quality in particular.

Mitigation measures

Among the most significant measures adopted in the early 1990s to reduce air pollution in Santiago was the overhaul of 3000 gross polluting buses, the introduction of circulation restrictions for non-catalytic vehicles, and the suspension of large industrial emitters during winter air quality episodes (Barraza et al., 2017; Mena-Carrasco et al., 2014). In addition, agricultural burns in winter were banned, and abatement technologies, attainment strategies and emissions standards were established for large industrial emitters, including specific plans for copper smelters inside and outside the Santiago basin (DS 28, Supreme Decree, http://bcn.cl/1uyuv). By the mid-1990s, emphasis was directed toward fuel quality. Maximum sulfur content in diesel was reduced from 5000 ppm in 1993 to 3000 in 1994, to 1500 in 1997 (Jhun et al., 2013), and to below 15 ppm today. Natural gas was widely introduced in the mid-1990s to replace oil and petrol. This led to further reductions in particle concentrations (Cf. **Figure 5**). In 2001, the light duty fleet of Santiago was composed of 56% catalytic automobiles (http://www.ine.cl/).

A disruption in the trend of particle concentrations, particularly PM2.5, is observed in connection with the interruption in natural gas provision from Argentina in 2006, and the introduction of Transantiago in 2007 (Cf. **Figure 5**). The former event forced industrial combustion of oil and petrol, and a shift to dirtier fuels for domestic heating. The latter transition induced a sharp shift in the modal distribution of transportation, reducing the use of public transport from nearly 70% to approximately 50% of trips, with the reduction mainly occurring among mid and upper income classes. This behavioral change was accompanied by a substantial increase in motorization. In 2007, 287,000 vehicles were added to Santiago's roadways, raising the fraction of catalytic vehicles from 65% in 2006 to 84% in 2007 (http://www.ine.cl/). Not until 2009 did a significant lowering trend in particle concentrations return, with stricter standards for buses and liquid natural gas plants fully operational (Cf. **Figure 5**). Motorization continues to grow at a rate of 5% per year, and emissions mitigation derived from improved public transport, vehicle technology, and improved fuel quality and efficiency has been largely nullified by the ever-rising number of private vehicle journeys over the past decade (Barraza et al., 2017).

A curbing measure of relevance both for local and global pollution was the introduction in 2014 of a green tax (Winkler et al., 2016). This measure addressed emissions from stationary sources, particularly power plants, and resulting from the import of highly polluting light duty vehicles, and primarily affects EURO V diesel cars, commercial vehicles, and light duty trucks.

Another factor contributing to declining particle trends, at least in terms of extremely high values, has been the introduction of state-of-the-science forecasting tools for acute winter air pollution events. By the late 1990s, a multiple regression method was used to forecast the next day's probability of occurrence of heavy pollution episodes in Santiago. Today, a numerical model of CO, in combination with empirical relationships between CO and PM, is used to forecast air quality over 72 hours in Santiago and many other cities in central and southern Chile (Saide et al., 2011; Saide et al., 2016), triggering contingency measures such as decreeing wood-burning bans, vehicular restriction, temporary suspension of stationary sources, warnings to the public, etc. as contemplated in attainment plans.

As we can see, mitigation measures adopted to-date have been mostly technological and mainly oriented toward reducing aerosol levels. Their success is evident as shown in rapidly declining particle levels and of coarse mode aerosols in particular (with a roughly 50% reduction in 20 years) despite population growth, urban expansion, and increasing travel times and motorization rates. The main structural measure over the past 30 years, i.e., Transantiago, resulted in substantial improvement to emissions standards, will be key to implementing Chile's NDC. Nonetheless, the initiative also led to unwanted behavioral changes expressed as a dramatic drop in the use of public transport and an increase in private car ownership. Emissions reduction policies for transportation sources in Santiago have been focused on technological and operational approaches, with fewer policies oriented toward changing cultural behavior or addressing the social aspects of the problem. In light of the experience in other metropolis (Kelly and Zhu, 2016), including demand-side mitigation actions (Creutzig et al., 2016; Creutzig et al., 2015), it appears necessary to adopt similar approaches by reducing light duty vehicle trips (Sager et al., 2011), promoting modal shifts, managing road pricing, and creating low emission zones.

The mitigation measures included in the latest attainment plan for Santiago (MMA, 2016a) are summarized in **Table 5**. Again, these measures are largely technological and focus primarily on reducing PM2.5. Only a few measures emphasize behavioral changes, such as the promotion of bicycling and environmental education. The plan itself has been widely covered by the Chilean media and debated on social media platforms. In our opinion, increasing private car usage, declining use of public transport, and increasingly relevant photochemical pollution and secondary aerosol production require a much stronger focus on behavioral changes, and especially on prioritizing public transport and non-motorized mobility, as recommended by the Presidential Commission on Mobility (Correa et al., 2014). In 2014, Chilean President Michelle Bachelet commissioned a group of scientists, social leaders, politicians and civil servants to critically analyze mobility in Santiago, gather opinions from the public, and propose ideas for an efficient and sustainable mobility plan. The main conclusions of the group indicate that urban mobility provokes and is affected by the congestion that affects almost all cities in Chile, and in turn deteriorates accessibility and quality of life, especially for Santiago's most disadvantaged citizens. The report recognized this as a complex problem requiring an integral approach. Specific proposals were presented as seven lines of action: promote integrated land use and mobility planning; modernize and improve public transport; discourage and rationalize the use of private vehicles; promote non-motorized modes of transport; promote a new culture of urban mobility; define a mobility policy and mobility legislation; and establish an institutional framework for urban governance in cities or metropolitan areas. These measures have not been implemented due to policy, governance and budgetary restrictions, and potentially a lack of sufficient political will.

The latest air quality attainment plan for Santiago has been formulated in an intersectoral and public manner, as mandated by law. More importantly, it emerges concurrently with key policy changes regarding energy and urban planning, and in the framework of Chile's NDC. We have already alluded to the Energy 2050 and electromobility policies. Another important context is provided by the National Policy for Urban Development (MINVU and PNUD, 2014), and the Land Use Policy for Urban Social Integration (CNDU, 2015). The nearly simultaneous

Table 5: Summary of proposed attainment measures to address air pollution from 2018–2028[a]. DOI: https://doi.org/10.1525/elementa.293.t5

Sector	Measures
Transportation	· Euro VI standard requirements for Transantiago fleet · Higher demands on emissions control in vehicle inspection plants · Low emissions zone for good transport · Purchase incentives for hybrid and electric vehicles · Permanent vehicle restrictions between May and August for vehicles with green stamps, based on vehicle age
Industry	· New emissions standards · Continuous monitoring systems for large sources · New standards for energy generators
Residential	· Banning of wood stoves in Greater Santiago · Five-year air quality data evaluated to implement prohibition throughout the Metropolitan Region · Prohibition of the use of salamanders, braziers, open hearth fireplaces and spell heaters is prohibited as of the publication of the Decree
Other	· Creation of a Green Fund for Santiago to support emissions compensation projects · Construction of 300 kilometers of bicycle lanes and installation of 3,000 shared bicycles · 100 hectares of new green areas and vegetation cover surrounding the Santiago basin

[a]Source: http://santiagorespira.gob.cl/ and (MMA, 2016a).

development of these policies and of policy instruments such as the air pollution attainment plan counteract the sectoral tradition of Chilean governance. Nevertheless, challenges and contradictions remain; for example, the Ministry of the Environment is not a member of the National Council for Urban Development (http://cndu.gob.cl/). On the other hand, a growing number of examples illustrate improved sectoral synergism. For instance, electromobility emerges as an intersectoral policy with a concrete, albeit small, expression in Transantiago, and the Ministry for Housing and Urban Planning has launched a program for installing solar power in new and existing social housing.

Regarding win-win options for simultaneously mitigating air pollution and climate forcers, we must point out the explicit inclusion of short-lived climate pollutants in Chile's NDC, as well as the introduction of a green tax to sanction in-practice diesel vehicles. Policies oriented towards a clean energy matrix, the introduction of electric vehicles, and the use of small-scale renewable energy in social housing, echo and enhance the adoption of such win-win options. More importantly, these policies provide a long-term framework for sustained efforts to achieve sustainable urban development, and increasingly ambitious goals for Chile's NDC. The robustness and longevity of such frameworks will depend on their construction, with those policies built upon politically broad and inclusive discussions potentially achieving greater success (Arriagada et al., 2018).

Lessons from the science-policy interface

We have shown evidence of multiple instances in Chile where decision makers at all levels seek the advice of scientists and academia. Scientific evidence collected by universities served to show that pollution levels in Santiago were dangerously high in the early 1980s, triggering the development of the first air quality policies. Multiple presidential commissions have been convened over the years, and ministers and high-ranking public officials with a strong academic background are not rare in Chile. However, the policy-science relationship remains sporadic, with short-term consultancy formats often relied upon to address very specific issues, and many times leaving aside peer-reviewed evaluations of reports and studies.

On the other hand, such consultancies are often not highly valued in academic careers, except in terms of publicity or financial resources. In Chile and elsewhere, standards for scientific accountability and societal relevance are increasing, particularly when addressing sustainability issues or the broader context of the Anthropocene (Clark et al., 2016; Hering, 2016; Kirchhoff et al., 2013; Lang et al., 2012).

The prevalence of technological solutions designed in a neoliberal political framework has been accompanied by an overwhelming emphasis on economics, natural, and engineering sciences, with little attention to social and political science in the context of public policies in general, particularly when addressing air quality and global change in Chile. This is also reflected in academia, where a relatively small fraction of experts work in the fields of sociology, anthropology, and political science, and even fewer are dedicated to urban development and global change. Again, this appears to be a common issue worldwide (Urry, 2015). Social scientists, in addition and in collaboration with natural scientists, will be fundamental to supporting decision making in the framework of a rapidly changing world, and both coping with change and promoting the behavioral and technological changes required by a complex climate system and human society.

Relevance to other urban areas in Latin America and the Caribbean

Oftentimes, LAC and South America are referred to as a homogeneous entity, possibly due to the common historic background in connection with the European "conquest" of the territories. However, LAC's physical and human geography is heterogeneous and rich in diversity. Nevertheless, like elsewhere in the world, there is substantial evidence of cooperation and communication regarding policymaking. For instance, Bus Rapid Transit systems appear to have propagated over the continent (Mejía-Dugand et al., 2013). We highlight two examples of Chilean policies that have been adopted by other LAC governments: improvement of fuel quality and vehicle technology regulation. The early introduction of cleaner fuels in Chile had a demonstrative effect on other LAC countries (UNEP, 2016). Likewise, Chilean regulations to foster the introduction of cleaner vehicle technologies was also a pioneer experience in South America (Yang et al., 2017). In light of these exchange experiences and the ongoing research collaboration within LAC (Andrade-Flores et al, 2016), we expect the contents of this study to be useful for other LAC countries.

5. Summary and conclusions

Urbanization is not a new phenomenon in Chile. Chile's urban population reached 50% in the early 1930s, with Santiago today concentrating 43% of the country's approximately 17 million inhabitants, and a similar proportion of the Gross Domestic Product (nearly 250 billion U.S. dollars). A review of Santiago's urban development and the consequences of this process, particularly regarding air pollution, allows for the identification of relevant conclusions for the science-policy interface to support better policy-making. Over the past 30 years, Santiago has increased in size from 522 km^2 in 1986 to 776 km^2 in 2016, through urban sprawl primarily to the south and southeast, which is expected to continue in coming decades. This development has created segregated communities with poor connectivity and experiencing detrimental environmental and socio-economic impacts. A dramatic decrease in public transport use in Santiago has been observed, dropping from 83% in 1977 to 47% in 2012, with a corresponding increase in private car use (from less than half a million vehicles in 1990 to more than 2 million vehicles in Santiago today).

Evidence of a substantial decrease in coarse mode aerosol (PM10) concentrations in Santiago is observed despite the urbanization rates described above. This reflects the success of policy measures adopted since the early 1990s when democracy was reinstated. Policies have been mainly technological (e.g., fuel quality, three-way catalytic converters, diesel particle filters) and operational (e.g., Transantiago, mandatory vehicular inspection). However, these efforts have been counteracted, in the case of PM2.5, by increasing vehicular activity levels. Likewise, a transition to a more oxidative atmosphere, where secondary aerosol formation and photochemical pollution become particularly relevant, also emerges from an analysis of available air quality data. In this context, attention must be paid to the evolution of nitrogen oxides emissions and particles from of the transportation sector. According to satellite data, NO_2 is rapidly growing in Santiago (Duncan et al, 2016), consistently with the growth in the number of personal cars. Likewise, the transportation sector is a growing contributor to PM2.5 (Barraza et al, 2017). The latter calls for limiting emissions from this sector with multiple measures including the promotion of electromobility, stricter vehicle inspections with particular attention to the deterioration of catalytic convertors, and restrictions on diesel cars and trucks. However, these measures will likely be insufficient if behavioral changes do not achieve an increase in the use of public transportation. In Santiago and elsewhere, there is a need for further use of demand-side, beyond technology mitigation actions. To this end, the incorporation of social scientists and communicators within the policy-making arena will be paramount.

Current air quality monitoring facilities allow for long-term analysis of particle and gaseous pollutant concentrations and provide basic information about criteria pollutants in accordance with current air quality standards. Sustained efforts by environmental authorities have been fundamental to successful policy development and implementation. However, these efforts must be enhanced by the inclusion of regular and systematic measurements of speciation and size distribution of aerosols, hydrocarbons, carbon dioxide, methane, nitrogen oxides, and carbonaceous aerosols, particularly black carbon. These data will be key to understanding the sources of secondary pollution, quantifying the efficiency of mitigation measures, and monitoring their progress over time. The inclusion of measurements of aerosol and gas mass, size and optical properties, preferably vertically resolved, would support an assessment of the co-benefits of reducing short-lived climate pollutants, and improvements of current air quality and climate modeling capacities. Wet and dry deposition sampling would be beneficial to assessing long-term trends and impacts (Conradie et al., 2016). These measurements go beyond the current air quality standards established by Chilean law, and their implementation across Santiago and elsewhere throughout the country is potentially impractical and unnecessary. Nevertheless, given the importance of creating science-based policies, we suggest the establishment of at least one monitoring supersite in Santiago, and, eventually, in all major Chilean urban centers. If undertaken jointly with an academic consortium and in collaboration with international cooperation, such an initiative would support long-term collaboration with the scientific community.

Emissions inventories for air quality are also key to developing sound environmental policy. Despite significant progress in Santiago over recent years, inaccuracies, uncertainties, and issues regarding consistency and comparability among inventories have been identified. Extending current GHG emissions estimates to include air quality emissions inventories and short-lived climate pollutants is key. Acknowledging the differences in current approaches to air quality assessments, while identifying the numerous commonalities and the need for consistency in accordance with Chile's international commitments and current scientific understanding, offers the opportunity to improve emissions quantifications. Again, associations with academia beyond specific, short-term consultancies provide a win-win option for both academia and policy-makers.

Cost-benefit analyses for relevant policy instruments have been limited to health impacts, without considering other impacts such as visibility, crop damage, impacts on vegetation, food and water security, contamination of water bodies, and others. Health impact assessments are themselves hindered by a lack of exposure-response functions, based on cohort studies responding to Chile's specific characteristics, and further research and resource allocation are required. Likewise, relatively little attention has been paid to indoor pollution and traffic exposure, and an emphasis on a shift from short-term effects (acute) to long-term effects (chronic) appears necessary, considering the dynamics of an aging population and the decline in high-concentration particle episodes in recent years.

The context of the Anthropocene calls for bold and creative action. Many actions must occur within the city and be echoed and sustained by science, media and political will (Acuto, 2016; Rogelj et al., 2016; Rosenzweig et al., 2010; Weiss, 2015). As is the case for Chile and for Santiago in particular, cities can offer opportunities for technological and societal transformations towards energy efficiency and decarbonization. Nevertheless, if we take for granted that car ownership will continue to grow at current rates, with an energy matrix dependent on fossil fuels, and that cars will become the most important mode of transport for urban and interurban trips, we can expect emissions to continue to grow at current rates, with adverse consequences on air quality and on Chile's carbon footprint. Mobility planning must shift away from motorized vehicles towards public transport as a means to access the city. If unchanged, current development patterns pose limits to economic growth and adversely affect human well-being. Furthermore, these patterns pose risks to achieving sustainable development goals and meeting Chile's commitment to the Paris Agreement.

The evolution of mobility and air quality over the past 30 years demonstrates the success of science-based policies, yet it also shows that technological changes are not sufficient. Sustainable urban development within the context of the Anthropocene requires integrated science and policy that address complexity, emphasize behavioral changes, and move beyond sectoral visions. In this context, we have identified progress achieved to-date in the Chilean context and key opportunities for future development.

Data Accessibility Statements

In addition to publically available air quality data (http://sinca.mma.gob.cl), we present particulate matter time series provided by the Ministry for the Environment. Copies of these datasets are available at: http://www.cr2.cl/recursos-y-publicaciones/AQ-Santiago/.

Supplemental Files

The supplemental files for this article can be found as follows:

- **Supplemental material.** Acquisition and handling of air quality data. DOI: https://doi.org/10.1525/elementa.293.s1

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Competing interests

The authors have no competing interests to declare.

Author contributions

- Contributed to conception and design: LG, MM, RO, CI
- Contributed to acquisition of data: LG, AC, MG, MM, RO, MO, KV
- Contributed to analysis and interpretation of data: LG, FB, AC, MG, NH, FL, CI, MM, RO, MO, ST, AU, KV
- Drafted and/or revised the article: LG, FB, AC, MG, NH, FL, CI, MM, RO, MO, ST, AU, KV
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