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Landfill fire and airborne aerosols in a large city: lessons learned and future needs

Raúl G. E. Morales S.[1] · Richard Toro A.[1] · Luis Morales[2] · Manuel A. Leiva G.[1]

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Abstract Landfill fires are relatively frequent incidents that can result in severe environmental impacts. On the morning of January 15, 2016, a fire occurred at the Santa Marta landfill (Lf) in the metropolitan area of Santiago (SMA), Chile. The fire triggered public alarm. In the present work, the impact of the landfill fire on the air quality of the SMA and the possible impacts on human health are analyzed. According to the information collected, the fire began after a collapse in the landfill on January 15, 2016. The fire could not be controlled by the Lf operating company, and authorities acted late in responding. The results revealed that at the focal point of the fire, particulate matter with an aerodynamic diameter smaller than 2.5 μm ($PM_{2.5}$) reached concentration levels on the order of 1000 μg m^{-3}. Three days after the start of the fire, hourly $PM_{2.5}$ concentration levels above 200 μg m^{-3} were recorded, at a distance approximately 20 km northeast of where the fire occurred. The $PM_{2.5}$ concentration levels recommended for the protection of the health of vulnerable persons were subsequently exceeded. These results suggest that a preventive measure should have been the evacuation of the most pollution-sensitive population. An inappropriate management of the emergency was demonstrated. Legislation should be improved by stipulating which sanitary Lfs should be equipped with firefighting equipment. Territorial planning should be improved by considering geographic and meteorological aspects.

✉ Manuel A. Leiva G.
manleiva@uchile.cl; manleiva@me.com

[1] Department of Chemistry and Center for Environmental Sciences, Faculty of Sciences, University of Chile, Santiago, Chile

[2] Department of Natural Resources, Faculty of Agronomic Sciences, University of Chile, Santiago, Chile

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Introduction

Approximately 54% of the global population lives in urban areas, and it is estimated that this number will increase to 66% by 2050 (UN 2016). The consumption of goods and services generates large amounts of municipal solid waste (MSW), to the extent that it has become an environmental problem in a significant number of the world's cities (Cointreau 2006; Vergara and Tchobanoglous 2012). It is estimated that, at present, the waste generated by people living in cities worldwide is 1.3 trillion tons per year (WB 2014). This situation is compounded daily by increases in generated waste and the absence of adequate solutions for the handling and final disposal of MSW (Cointreau 2006; Ma and Hipel 2016).

In developing countries such as Chile, the most widespread practice for the final disposal of MSW is the use of sanitary landfills (Lf) (Paula Estevez 2003; Bräutigam et al. 2012; Hoornweg and Bhada-Tata 2012; Kumar 2016). This method uses engineering principles to confine solid waste to the smallest possible area by reducing its volume (Bagchi 2004). In these enclosures, solid waste is mixed daily, spread in thin layers, and compacted and buried under a layer of earth or plastic foam on top of previously waterproofed soil. Although one of the objectives for the final disposal of MSW in Lf is minimizing environmental damage, there are inherent risks to this operation (Butt et al. 2008; Manfredi et al. 2010). Lf fires are one of the most severe causes of environmental damage (FEMA 2002; Wichmann et al. 2006; EAUK 2007; Vassiliadou et al. 2009; Weichenthal et al. 2015).

Lf fires are unexpectedly common (FEMA 2002; EAUK 2007; Powell et al. 2016). In the USA, for example, 840 Lf fire incidents occurred during the period 2004–2010, of which > 25% were repeat incidents at a specific site (Powell et al. 2016), resulting in subsequent losses of materials and machinery and damage to people. These incidents demonstrate that Lf fires are difficult to control and have a major impact on the structure of Lfs and the environment.

Lf fires emit toxic gases that are harmful to public health and the environment, depending on the composition of the MSW (Ruokojärvi et al. 1995; Lemieux et al. 2004; Vassiliadou et al. 2009; Estrellan and Iino 2010; Downard et al. 2015; Weichenthal et al. 2015; Purser et al. 2016). In general, these fires occur at low temperatures and under anoxic conditions. Hydrocarbons, chlorinated materials, and pesticides in these conditions produce a variety of toxic gases that may contain dioxins/furans (Ruokojärvi et al. 1995; Chrysikou et al. 2008; Vassiliadou et al. 2009; Shih et al. 2016), polynuclear aromatic hydrocarbons (Stamand et al. 2008; Vicente et al. 2016), respirable particulates (PM) (Kumar et al. 2015), and heavy metals (Sahariah et al. 2015), among other harmful compounds (Nammari et al. 2004; Moqbel 2009; Rao et al. 2017). These emissions may pose a risk to human health, especially among vulnerable populations, such as the elderly, children, pregnant women, and/or people with pre-existing chronic respiratory conditions (Krzyzanowski and Cohen 2008; Giusti 2009; Lippmann 2012; Dhabbah 2015). Given the large number of Lf fires that occur globally and the level of atmospheric pollution they produce, the present work analyzes the air quality impacts caused by the fire that occurred January 18–20, 2016, at the Santa Marta landfill (LfSM), one of the most important Lfs in the metropolitan area of Santiago (SMA), Chile, which receives approximately 4000 tons of garbage daily (CD 2016; CSM 2016; T13 2016). The fire caused public alarm because a large percentage of the population of Santiago awoke on January 19 to a dense cloud of smoke and foul odors (burnt plastic) (see Fig. 1).

Based on meteorological data and particulate matter with an aerodynamic diameter smaller than 2.5-μm ($PM_{2.5}$) concentration levels obtained from the network of monitoring stations in Santiago (SINCA 2016), the spatial and temporal ranges of the LfSM fire on the air quality of the SMA were analyzed. These measurements were performed by modeling air parcel trajectories (Stein et al. 2015), which accounted for the dynamics of the cloud of pollutants from the fire during its development and the days after its development, a period that is typically characterized by good air quality resulting from the ventilation of the atmospheric basin during the summer months. Additionally, a critical review of the actions taken by environmental authorities and the regional government is presented. This work augments the limited literature that addresses these types of incidents and aims to

Fig. 1 Panoramic view of Santiago, in the early morning hours of Monday, January 19, 2016. (source: El Dinamo online, https://goo.gl/Dvuexj)

establish practices and propose actions that enable better preparation for this type of environmental incident in the future.

Materials and methods

Description of the study area

The LfSM (33°41′50″S, 70°48′00″W) is located in the foothills of the Santa Marta mountain range, in the town of Talagante, at a property known as Santa Elena de Lonquén, southwest of the SMA (33°27′00″S, 70°40′00″W—see Fig. 2). The Lf covers 8.76 km^2 of the property's 29.6-km^2 area, where the treatment of MSW and assimilable waste is performed (CD 2016; CSM 2016). Every year, the LfSM receives approximately 1.3 million tons of garbage (~ 4000 tons/day) from 19 municipalities in the southern sector of Santiago. The LfSM began operating on April 18, 2002, and it was originally designed to have a 20-year lifetime and maximum monthly capacity of 60 thousand tons of MSW. However, it currently receives approximately 110 thousand tons of MSW per month (CD 2016).

The populated urban areas within a 10-km radius of the LfSM are Lo Herrera (5250 inhabitants), Calera de Tango (23,150 inhabitants), and Buin and Maipo (7880 inhabitants combined) (INE 2017). The locations of these localities are presented in Fig. 2. Toward the northwest, within Santiago's urban radius, is the town of San Bernardo (287,439 inhabitants) (INE 2017). The SMA (~ 7 million inhabitants) covers approximately 1400 km^2; it is, on average, 500 m above sea level and is surrounded by a ring of mountains belonging to the coastal and Andes mountain ranges (Fig. 1).

The climate in the SMA is Mediterranean, with an average temperature of approximately 14 °C. The wind system is characterized by a valley-mountain breeze, where during the day, the prevailing winds blow from southwest to northeast (Seguel et al. 2012). The vertical air exchange in the cold months is controlled by surface and subsidence thermal inversions, the latter caused by the presence of the subtropical anticyclone of the eastern South Pacific. This condition provides a very stable atmospheric gradient that reduces the vertical dispersion of air pollutants, especially during the fall and winter periods (Rutllant and Garreaud 1995).

Aerosols and meteorological measurements

In 1997, Santiago's regional government established an air quality pollution monitoring program that currently consists of 11 continuous monitoring stations that measure particulate matter, among other pollutants, and meteorological variables (temperature, relative humidity, and wind direction and speed; see Fig. 1 and Table 1) (SINCA 2016). $PM_{2.5}$ concentrations at the stations are measured using tapered element oscillating microbalance (TEOM) equipment, (Thermo Scientific Air Monitoring Instruments, Franklin, MA, USA).

Modeling the surface distribution of pollutants

The spatial distribution of the $PM_{2.5}$ concentrations corresponding to the emission data measured at each of the

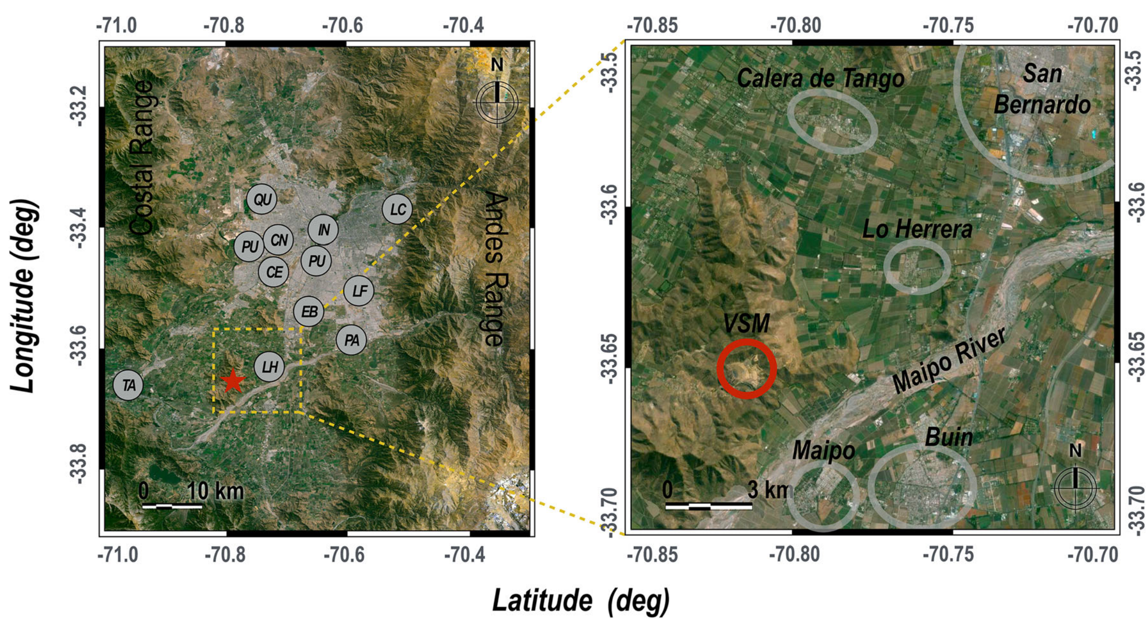

Fig. 2 Satellite photograph of Santiago indicating the locations of the city's air quality monitoring stations (left), the fire sector boundary (in yellow), and an enlargement of the same area (right) where the LfSM is located (in red). (source google earth v7.1.5.1557, 2016-03-02, DigitalGlobe 2016. http://www.earth.google.com, accessed 2017-03-10)

Table 1 Air quality monitoring stations in the metropolitan area of Santiago (see Fig. 1)

Label	Station	Latitude (S)	Longitude (W)	Altitude (m)
IN	Independencia	− 33.4189°	− 70.6489°	559
FL	La Florida	− 33.5133°	− 70.5859°	601
LC	Las Condes	− 33.3734°	− 70.5209°	802
PO	Parque O'Higgins	− 33.4608°	− 70.6585°	541
PU	Pudahuel	− 33.4345°	− 70.7478°	496
CE	Cerrillos	− 33.4896°	− 70.7170°	507
EB	El Bosque	− 33.5439°	− 70.6638°	580
CN	Cerro Navia	− 33.4297°	− 70.7298°	501
PA	Puente Alto	− 33.5915°	− 70.5948°	670
TA	Talagante	− 33.6738°	− 70.9531°	323
QU	Quilicura	− 33.3659°	− 70.7482°	487
LH	Lo Herrera	− 33.6708°	70.7508°	515

network's air quality stations was interpolated using a stochastic geostatistical method to estimate the value of a random variable (z) from a set of neighboring sample points. To perform this estimation, the method uses a variogram estimator, which describes the spatial continuities from the sample data (Webster and Oliver 2007). Specifically, for this study, the ordinary block kriging method was utilized with a linear variogram and "leave-one-out" cross-validation for the estimation of errors. This method has also been used successfully to interpolate weather data (Martínez-Cob 1996; Vicente-Serrano et al. 2003; Morales-Salinas et al. 2015).

Modeling air parcel trajectories

In this study, the computerized air parcel trajectory modeling program known as Hybrid Single-Particle Lagrangian Integrated Trajectory (HYSPLIT) version 4.8, developed by the National Oceanic and Atmospheric Administration Air Resources Laboratory (NOAA ARL), was used (Stein et al. 2015; Rolph 2016). Forty-eight hours of direct trajectories were calculated every hour beginning at 12:00 AM on January 18, 2016, yielding a total of 48 trajectories. The starting point of the trajectories was the site of the fire at the LfSM (latitude − 33.694669, longitude − 70.803662, and an altitude of 562 m above sea level), corresponding to the altitude of the highest point of smoke generated from the fire. For the calculation, the set of meteorological data archived in the ARL server, model GDAS0P5 with a horizontal resolution of 0.5°, was used. Finally, the resulting 48 trajectories were plotted as a density map using the software QGIS version 2.12.1-Lyon (QGIS 2016).

Results and discussion

Chronology of the fire at the Santa Marta landfill

According to the investigation report performed by an investigative commission of Chile's Congressional Chamber of Deputies (CD 2016), it was determined that the fire occurred after the collapse of an MSW accumulation cell (see Fig. 3a, b). The material displaced after the collapse exceeded the limits of the areas that were waterproofed and authorized for waste disposal. The surface of the material exposed to the air after the collapse was approximately 40-m wide by 900 m downslope (see Fig. 3b). This event occurred 3 days before the fire began, i.e., on Friday, January 15, 2016, a period in which the nearby population, primarily those from the Lo Herrera sector, perceived foul odors. The company managing the Lf reported the collapse to the health authority on January 16; then, the regional government was informed and on Monday, January 18, the Environment Superintendent was informed. However, that same day, 3 days after the collapse occurred, at 5:00 PM, firefighters were notified of the presence of a large column of smoke on Santa Elena Mountain, which was moving eastward toward the SMA (see Fig. 3c).

The fire was first visible in Santiago on Tuesday, January 19, at 6:00 AM (see Fig. 3d). The smoke column moved at ground level uphill from the Lf toward the nearest town of Lo Herrera, approximately 5 km from the focal point of the fire. As a consequence, the Lo Herrera population was severely affected by an acute exposure to gases, aerosols, and unpleasant odors from the fire (CNN-Cl 2016). Subsequently, a dense cloud of smoke extended more than 30 km, through the SMA's highly populated urban areas, such as Puente Alto, San Bernardo, and La Granja, passing through the center of Santiago.

On Tuesday, January 19, government authorities formed an emergency committee and the total closure of the Lf was requested. Firefighters performed extinguishing work with the cooperation of the company that owns the Lf. There was public concern about the visible layer of smoke covering the city and the strong smell of burnt plastic. In turn, television news programs and the written press reported the news (EFE 2016; T13 2016). The authorities stated that the fumes were non-toxic, which was quickly denied by health and environmental science experts.

On Thursday, January 21, the Ministry of the Environment installed an air quality monitoring station to measure the concentration of $PM_{2.5}$ in Lo Herrera (see Fig. 2 and Table 1). Finally, at approximately 8:00 PM on Friday, January 22, the fire was extinguished.

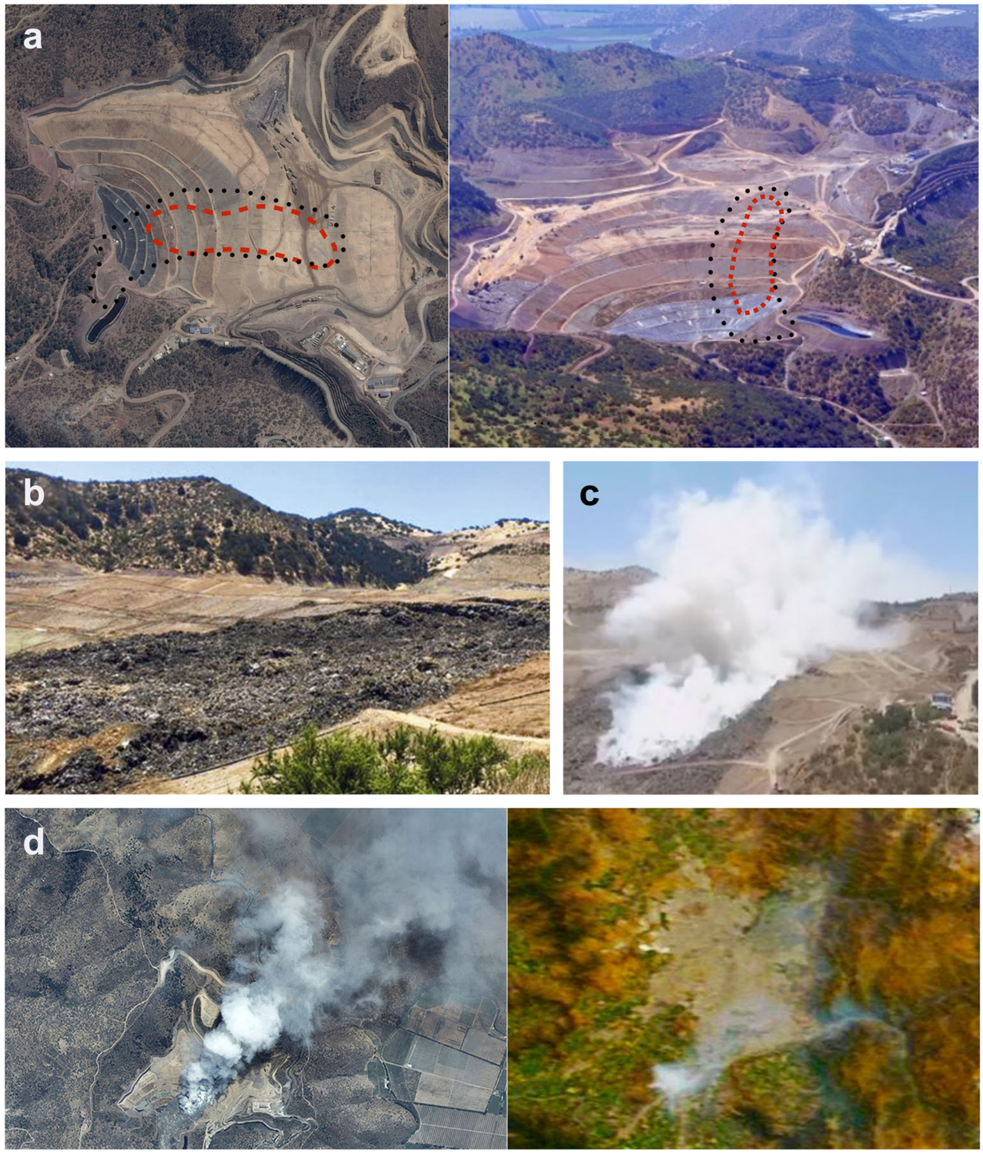

Fig. 3 **a** Aerial view of Santa Marta landfill. The black line delimits the area of the collapse. The red line delimits the fire zone (source right: google earth v7.1.5.1557, 2016-03-02, Digital Globe 2016. http://www.earth.google.com, accessed 2017-03-10; left: photography Consortium Santa Marta, https://goo.gl/lFxA8m, accessed 2017-03-10). **b** Side view of the collapsed area at the landfill (source La Tercera Newspaper, https://goo.gl/9vVSeD, accessed 2017-03-10). **c** Image showing the first moments of the landfill fire (source C13 Broadcast, https://goo.gl/xSJvLi, accessed 2017-10-14). **d** Aerial and satellite view of the fire smoke plume (NASA, Worldview, 2016-01-19 10:30 AM local time, source: https://worldview.earthdata.nasa.gov, accessed 2017-03-10)

Air quality and concentrations of breathable particulate matter

Figure 4 shows the time series of the hourly data records of $PM_{2.5}$ concentrations recorded between January 14 and 22 by each of the city's air quality monitoring stations (SINCA 2016). The closest stations were located more than 20 km from the fire, including the mobile station installed by environmental authorities in Lo Herrera, a populated area that was closest to the event. The launch of this mobile air quality monitoring station (Fig. 4k, LH) on January 20 occurred approximately 3 days after the fire began and 1 day after the fire was contained and extinguished, which explains the limited amount of data reported by this station. The center of Fig. 4 (Fig. 4m) shows the result of the interpolation of the $PM_{2.5}$ concentration obtained by modeling the surface distribution of contaminants.

Figure 4a shows that the maximum $PM_{2.5}$ concentrations are recorded on January 19, with higher than average values for a typical summer day at some of the air quality monitoring network stations that are closer and northeast of the fire, such as El Bosque (Fig. 4a, EB), Puente Alto (Fig. 4b, PA), and La Florida (Fig. 4c, LF). On the same day, lower $PM_{2.5}$ concentrations were recorded at the Las Condes station, located northeast of the city (Fig. 4d, LC), and at the Independencia station (Fig. 4e, IN), located in the city center. These observations confirm the extent of the fire emissions crossing the entire city from south to north. At both monitoring stations northeast of Santiago as well as at the Quilicura (Fig. 4g, QU),

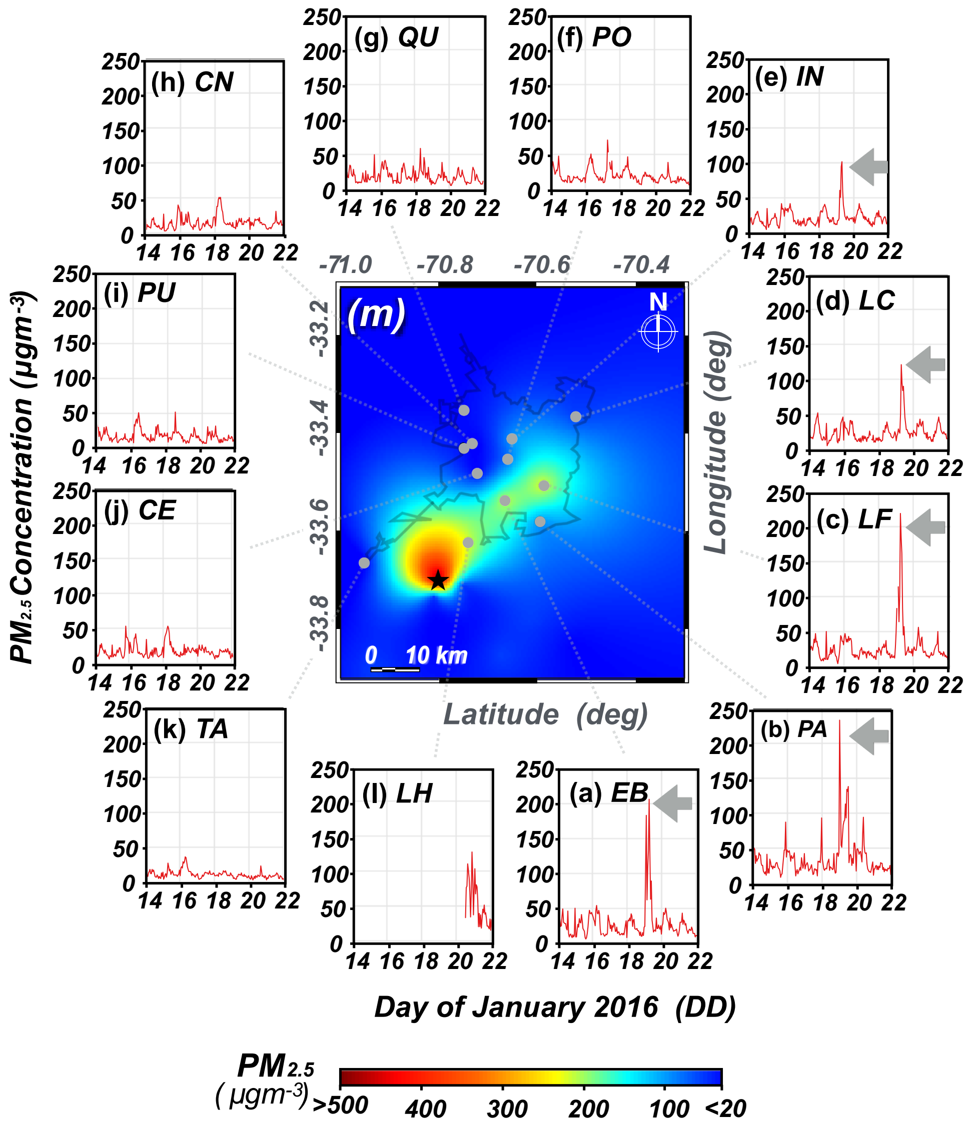

Fig. 4 **a**–**l** $PM_{2.5}$ concentrations for Santiago's network of air quality monitoring stations from January 14 to 22, 2016. **m** Modeling of the surface distribution of contaminants by interpolation at 8:00 AM on January 19 (see the Materials and methods section).

Cerro Navia (Fig. 4h, CN), Pudahuel (Fig. 4i, PU), Cerrillos (Fig. 4j, CE), and Talagante stations, located northwest of the fire (Fig. 4k, TA), no deterioration in air quality was observed to have occurred during the event. In contrast, data from these stations confirms the good air quality that is typically observed during the summer in Santiago.

However, the interpolation of the $PM_{2.5}$ concentrations recorded at 8:00 AM on January 19 at the different stations corroborates the previous observations and illustrates the transport system of the fire emissions. Due to the delay in the installation of the mobile station, more than 3 days after the start of the fire, there are no data records of $PM_{2.5}$ concentrations in the fire focal point. Therefore, the $PM_{2.5}$ concentration at the fire focal point was estimated using an interpolation procedure and trial and error tests that allowed the concentrations observed in the nearby air quality stations to be described with 20% uncertainty. This procedure estimated the $PM_{2.5}$ concentration at the fire focal point to be 1000 μg m^{-3}, a sufficiently high value for an Lf fire but also one of the authors consider moderate with respect to the magnitude of the impact observed in the city during the first hours of the morning of January 19.

It should be noted that the $PM_{2.5}$ concentrations recorded at the stations located in Puente Alto, La Florida, and El Bosque, the areas closest to the focal point of the fire, are the most populous residential areas in Santiago, totaling more than one million inhabitants combined. These stations recorded hourly concentration levels that were higher than 200 μg m^{-3}, despite being within an approximately 20-km radius of the fire's focal point.

The distribution of $PM_{2.5}$ in the city most affected by the fire reached concentration levels was considered enough to affect the health of those exposed inhabitants living within a 10-km radius and northwest of the focal point of the fire.

Exposure during the first 24 h of the fire, which includes the populated area of Lo Herrera, exceeded the concentration level threshold recommended by the World Health Organization (WHO 2006) and Environmental Protection Agency Victoria Australia (EPA-AU 2016). Specific considerations were not made regarding the toxicity of the gases and particles of this type of fire. However, the results suggest that preventive measures should have been taken to evacuate people from the Lo Herrera sector, particularly those individuals who are most sensitive to pollution such as children, older adults, and pregnant women as well as people with chronic respiratory diseases; others should be allowed to determine their own fate and make personal or family decisions to leave those areas of high-concentration gases and particulate matter.

Direct trajectories and meteorology

The trajectories of the contaminated air parcels originating at the Lf fire moving toward Santiago are shown in Fig. 5a, represented as a density map of 48 direct trajectories calculated each hour from the focal point of the fire, using HYSPLIT, from 5:00 PM on Monday, January 18, until 5:00 PM on Wednesday, January 20, 2016. Similarly, Fig. 5b–l presents the wind roses obtained from data corresponding to the same modeling period for each of the city's air quality monitoring stations, which were recorded on an hourly basis.

The calculated trajectories represent the probable trajectories of atmospheric dispersion that followed the discharged emissions from the focal point of the fire. The results show that from the focal point of the fire, there were trajectories toward the east near the fire that later moved in a northeasterly direction.

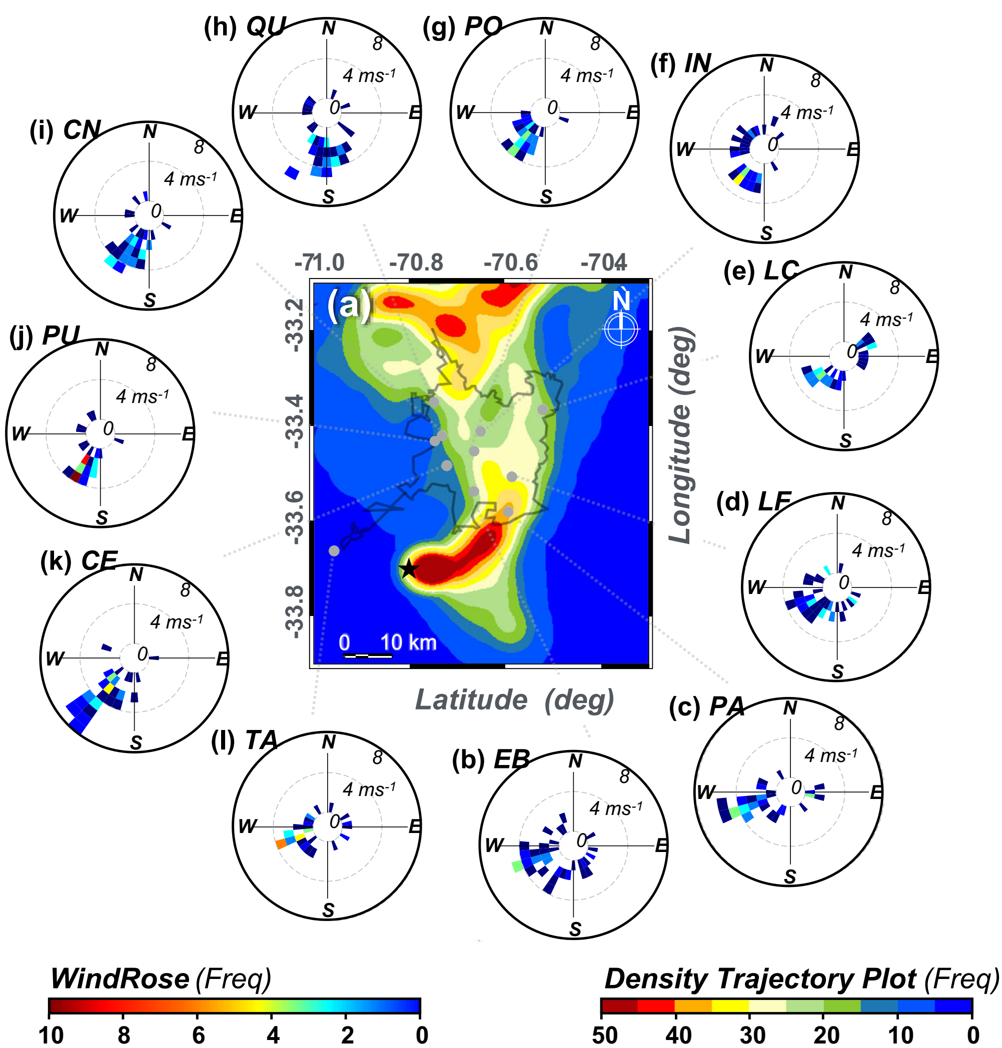

Fig. 5 **a** Forty-eight (48) direct trajectories depart from the focal point of the fire, every hour, from 12:00 AM on January 18 to 12:00 AM on January 20, 2016. **b–l** Wind rose in each air quality monitoring stations from January 18 to 20, 2016

The calculated direct trajectories and their frequency (Fig. 5a) in the modeling period show that many of the trajectories pass through the town of Lo Herrera. This result again confirms that this population was exposed to high concentrations of gas and particle pollution. There are also trajectories southeast of the fire that extend to the towns of Buin and Maipo, indicating that these areas might also have been impacted by emissions from the fire, which cannot be verified as there were no monitoring stations in these areas.

The trajectories calculated with HYSPLIT were adjusted to the observed behavior of the direction of the wind at each monitoring station and to the global phenomenon observed on January 19 across all of Santiago. In other words, in general, at a higher path density, higher concentrations of $PM_{2.5}$ were observed at the monitoring stations.

Toxic compounds in fire fumes

Predicting the toxic combustion of products is complex, and the potential exists for the generation of a wide range of pyrolysis products and depends on the nature of a fire and its ignition conditions (Moqbel 2009; Purser 2016), although every fire is unique and, ultimately, should be considered on a case-by-case basis. Unfortunately, in the case of the LfSM fire, there are no reports on the chemical and physical characterization of the particulate material or gases emitted.

The variety of toxic substances produced by fire emissions includes complex mixtures of organic compounds such as polycyclic aromatic species (PAHs) (Blomqvist 2005; Chrysikou et al. 2008), polychlorinated dibenzo-p-dioxins (PCDDs), and polychlorinated dibenzofurans (PCDFs) or dioxins and furans (Ruokojärvi et al. 1995; Blomqvist 2005; Vassiliadou et al. 2009). These compounds are formed by the incomplete combustion of organic compounds in the repolymerization of hydrocarbon fragments (Altarawneh et al. 2007; Zhang et al. 2015).

Some PAHs are listed as "probably carcinogenic" and others have been shown to be genotoxic (Dybing et al. 2013). There is limited information on the adverse health effects following acute exposure to PAHs (Marinković et al. 2010; Abdel-Shafy and Mansour 2016). Four hundred nineteen compounds related to dioxins have been identified; approximately 30 of them are considered to have significant toxicity (Marinković et al. 2010). Adverse effects from acute exposure to high concentrations of dioxins can appear within days or weeks and are characterized by skin lesions such as acne and dark spots, as well as liver function abnormalities. Prolonged exposure has been associated with the impairment of immune systems, the developing nervous system, the endocrine system, and the reproductive function.

Other substances emitted by combustion under poor oxygen conditions are classified as irritants and/or asphyxiants (Purser 2010a, b). For example, polymers, such as polyethylene or polypropylene, become irritants in the form of acetaldehyde, toluene, benzene, and styrene, whereas paper and carton emit acrolein, and wood emits aldehydes. All of these compounds are irritating to the eyes, skin, and respiratory tract (Purser 2010b). The primary asphyxiants produced during the combustion of organic materials are carbon monoxide, hydrocyanic acid, and carbon dioxide, in combination with deficient oxygen conditions (Purser 2010a). These effects may be enhanced, producing synergistic outcomes that result in greater toxicity. Heavy metals may also be emitted into the atmosphere by the combustion of MSW (Lippmann 2012; Sahariah et al. 2015). Such emissions can occur because of the dispersion of ash formed during the combustion process or from the volatilization of volatile heavy metals (e.g., Hg, As, Cd, Zn, and Pb). In the short term, metals can catalyze free radical reactions that favor processes of oxidative stress in an organism in addition to the possible synergistic effects that all these compounds or toxic elements might have (Lansdown 2013; Gali et al. 2015).

Final remarks

The strong odors perceived in Santiago during the first days of the fire reflect the need to develop appropriate management plans for this type of emergency. Appropriate and timely communication with local populations of the risks associated with exposure to toxic gases and particles that emanate from this type of fire is required, which were not actions taken in this case. In contrast, there was conflicting information as some authorities indicated that the gases were not toxic, whereas public health experts asserted that indeed there were potential health risks to exposed people.

Dumpsites and Lfs should be required to provide, install, and maintain firefighting equipment in a manner like the requirements applicable to buildings and facilities at fire risk. Potential fire hazards are always present during Lf operations and continue even after the closure of the facility due to the generation of flammable gases within the Lf.

Fires in Lfs involve an intensive use of resources and damage to normal community activities including the occurrence of public health problems. Committing firefighting resources to respond to an Lf fire prevents them from being available to meet the needs of the community. Therefore, Lf facilities should be required to prepare a preliminary emergency plan, as is the case with other higher-risk facilities, although Lfs might present limited threats to life or property.

Early intervention is essential to prevent fires from becoming large and difficult to extinguish. Once a fire develops, there are no known alternatives to applying large amounts of water to keep the fire from spreading and providing access for heavy machinery to physically disrupt, remove burning material, and apply more water until all combustible material is definitively extinguished.

The PM concentrations estimated in this study demonstrate that, for future similar situations, it is necessary to have an on-site monitoring station located within proximity of the plume direction, especially if the plume travels at ground level because of low energy provided by a fire in the combustion process, which occurred in the case of the LfSM fire.

Furthermore, the health of the affected population in Lo Herrera must be ascertained to facilitate competent public health organizations in determining whether, a year after exposure, there are any identifiable effects among those individuals affected during the first days of the fire. Health authorities should collect gas and particle samples in situ during high pollution level events such as this environmental disaster caused by an incident of an industrial nature.

Finally, given the regional-scale meteorological conditions of the valley in which Santiago is situated, it is not advisable to continue authorizing the installation of industrial operations and activities subject to probable fires of a magnitude like the LfSM fire, which would consequently impact the densest conglomerates of the city's population via wind systems that carry emissions from South to North.

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Compliance with ethical standards

Competing interests The authors declare that they have no competing interests.

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