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ORIGINAL PAPER

An interdisciplinary approach for air quality assessment: biomonitoring using *Tillandsia bergeri* and risk perceptions in the environmentally sacrificed province of Chacabuco, Chile

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Abstract Awareness of air pollution and the associated environmental and health risks is growing worldwide. In order to answer the socio-environmental challenges posed by climate change, natural resource degradation and industrialization, scientists are advocating more holistic research linking environmental quality and public health. However, few studies have managed to integrate local communities' concerns and knowledge with easy-to-use biomonitoring systems to produce science that contextualises their environment risk. This case study was carried out in an "environmental sacrifice zone" located in the Chacabuco province (Chile), where there have been no prior air quality studies or monitoring despite local populations suspecting metallic contamination. An interdisciplinary approach was proposed to create an innovative air quality assessment, combining both social and geographical data for risk perception and biomonitoring experiments with epiphyte plants (*T. bergeri*) in strategic sites. The cross-analysis of inhabitant interviews and cognitive maps shows that air pollution is perceived to be of greater risk in the northern and central part of the province. Microscopic and spectroscopic

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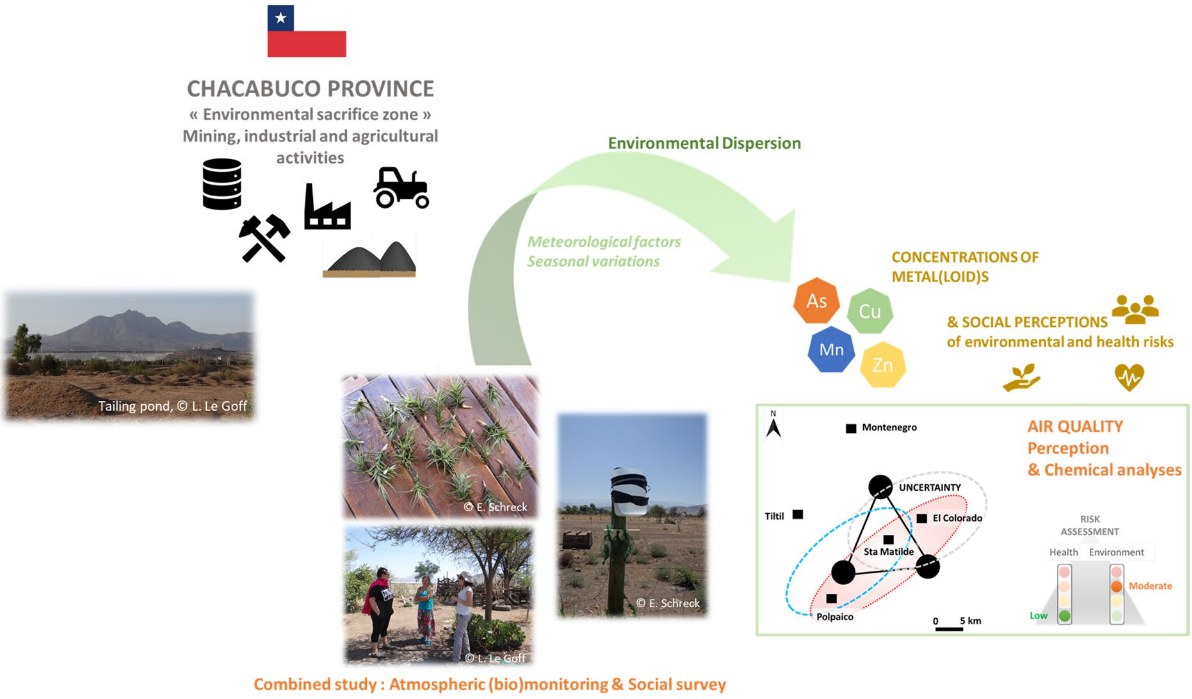
techniques highlight different origins of metal(loid)s in the air. Epiphyte plants reveal a site-dependent accumulation of pollutants (As, Cu, Cr, Mn, Pb, Ni, Zn). The collection of dust in Owen gauges and subsequent health risk assessment do not show evidence of hazard quotient or cancer risk. But enrichment factors and pollution indexes highlight that three sites can be classified as impacted, suggesting that more attention should be paid to chronic exposure and long-term environmental effects in this area. The social perception of air pollution appears to be correlated to the geochemical identification of some existing sources of metal(loid)s.

Graphical abstract



Keywords Socio-environmental study · Atmospheric pollution · Chile · Epiphyte plants · Atmospheric dust collection · Health risks

Introduction

Metallic pollution in the environment is nowadays of great interest because of increased knowledge of metal(loid) bioaccumulation and their toxic effects in biological systems (Rahman et al., 2019). Metal(loid) toxicity is an unavoidable reality from an environmental, ecological and nutritional point of view (Nagajyoti et al., 2010). Toxicity by inhalation via atmospheric particulate matter remains of high concern and can severely threaten human health (Sun et al., 2021). Trace metal(loid)s emitted through industrial or mining activities in the atmosphere can enter the respiratory system and lead to chronic inflammatory and respiratory diseases (Boamponsem et al., 2010; Goix et al., 2013; Serbula et al., 2017, Wise et al., 2017). Among these trace elements, arsenic (As) appears to be one of the main causes of mortality worldwide (ATSDR, 2007). Direct ingestion of contaminated water is the primary cause of As poisoning, but it can also occur through inhalation or skin absorption. One-off exposure to very high doses (several mg per day) can cause diarrhea, vomiting and muscle cramps, even leading to death (Jahandari & Abbasnejad, 2024). However, the global population is more exposed to a chronic risk (Demissie et al., 2024), which can lead to hyperpigmentation, keratosis, encephalitis-like nerve problems and cardiovascular complications (Abdul et al., 2015). Inorganic As is considered to be highly carcinogenic (Muñoz et al., 2017) and implicated in lung, kidney and bladder cancers, as well as skin diseases (ATSDR, 2007). In addition, inhalation of lead (Pb) is severely toxic, causing reversible (anemia and digestive troubles) or irreversible (damage to the nervous system, encephalopathy and neuropathy) troubles (Selinus & Alloway, 2013; World Health Organization, 2022). Nickel (Ni), is responsible for lung, larynx and prostate cancers. Short-term exposure to high levels of Ni can involve skin irritation, respiratory problems, nausea, vomiting, and diarrhea, while chronic exposure to low Ni concentrations has been reported to cause lung and nasal cancer and kidney damage (Genchi et al., 2020; Selinus & Alloway, 2013). Chromium (Cr) is a toxic element for humans and can cause health problems such as respiratory diseases (Selinus & Alloway, 2013). Inhaling dust contaminated with Cr can lead to skin irritation or gastrointestinal problems, and can contribute to the development of cancer (Selinus & Alloway, 2013). Copper (Cu) is an essential micronutrient for plants, animals, and humans; nevertheless, excessive concentrations can become toxic and lead to liver and kidney damage, anemia as well as neurological disorders in humans (Selinus & Alloway, 2013). Excessive amounts of zinc (Zn), another essential nutrient, may result in the development of irritation, headaches, stomach aches, vomiting and diarrhea (World Health Organization, 2022).

Recent awareness of potential atmospheric pollution has encouraged the development of air quality biomonitors (Schreck et al., 2020) in potentially impacted zones. The usual techniques for air quality monitoring are expensive and require electricity to operate efficiently. In recent years, several studies designed to monitor air composition in communities living in close vicinity to industrial or mining areas have used plants (trees, grass, mosses, epiphyte plants, etc.) (Aksoy et al., 1999; Isaac-Olivé et al., 2012; Murakami et al., 2012; Schreck et al., 2020; Silva-Barni et al., 2019). Among the various studied species, epiphyte plants such as *Tillandsia spp.* remain really useful due to their substrate independence (Silva-Barni et al., 2019), and their specific physiological structures. Their trichomes and pluricellular epidermal structures allow them to be highly specialized at uptaking humidity and aerosols from the air (Brighigna et al., 1997), as well as absorbing nutrients. The *Tillandsia* species appears to be efficient, easy to set up and an inexpensive tool to track contaminant dispersion in the atmosphere (Schreck et al., 2016). They are easy to sample and grow, and are widely distributed throughout North, Central and South America (Stefano et al., 2006). The *Tillandsia bergeri* species is a popular cultivated plant in private gardens in Argentina and central Chile (Mez, 1916). The biomonitoring role of *Tillandsia* species has been relatively well studied for *T. capillaris* (Goix et al., 2013; Rodriguez et al., 2011; Schreck et al., 2016) and *T. usneoides* (Martínez-Carrillo et al., 2010; Pellegrini et al., 2014; Schreck et al., 2020; Zheng et al., 2016). But to our knowledge, very few studies (Silva-Barni et al., 2019) have been reported concerning the use of *T. bergeri* as a long term (e.g. several months) monitoring tool for pollution tracing and dispersion.

The province of Chacabuco is located in the central zone of Chile, between the Coastal range and the Andes, to the north of Santiago, in the Metropolitan region. It is administratively composed of three municipalities: Colina, Lampa and Tiltil (Figure 1). Central Chile has been under the grip of a mega-drought since 2010 (Garreaud et al., 2020). This situation has led to problems of water availability and inequalities in access to water (Le Goff, 2024). This mega-drought also raises questions about water management and distribution, and the potential risks of water pollution and its impacts on health (Le Goff et al., 2022). In this context of uncertainty and difficulty, this region has recently become known for various social mobilizations of its inhabitants for the right to live in a healthy environment (Jorge et al., 2020). Tiltil, the northernmost municipality, has been described by the media and by the inhabitants as an “environmental sacrifice zone” (Allain, 2020; Berasaluce et al., 2021; Hormazabal Poblete et al., 2019; Jorge et al., 2020; Le Goff et al., 2022). This qualification is due to the high concentrations of several potential sources of inorganic pollutants, from geogenic but especially anthropogenic sources. Local sources include industrial areas, mining activities,

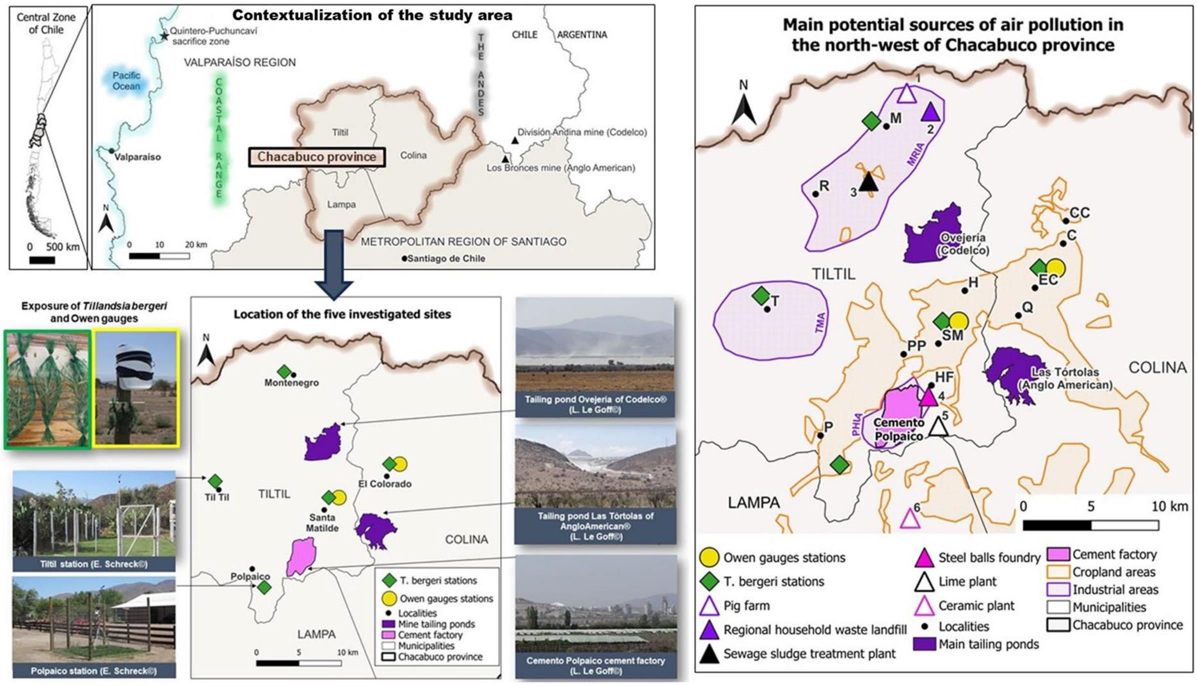


Fig. 1 General contextualization of the study area, location of air quality sampling points and main suspected harmful industries at the northern part of Chacabuco province. The numbers correspond to harmful industries: 1/ Porkland®, 2/ Lomas El Colorado (KDM®), 3/ El Rutal (Aguas Andinas®), 4/ Magotteaux Andino S.A. (Ex-Proacer Ltda.), 5/ Limestone plant, and 6/ Ceramica Santiago S.A. The initials correspond to localities: M: Montenegro; R: Rungue; T: Tiltil; P: Polpaico; HF: Huertos Familiares; PP: Punta Peuco; SM: Santa Matilde; H: Huechún; EC: El Colorado; Q: Quilapilún; C: El Canelo; CC: Casas de Chacabuco. The acronyms correspond to productive areas: MRIA: Montenegro-Rungue Industrial Area (regional household landfill, pig farm, sewage sludge treatment plant, old industrial sites); TMA: Tiltil Mining Area (operating and abandoned mines); PHIA: Polpaico-Huertos Familiares Industrial Area (cement factory, steel milling and casting plant, lime plant, tailing pounds)

household waste dumps, pesticides and fertilizers used for agriculture and coal deposits. Various regions of Chile have already been studied in terms of impact of inorganic contamination: for example the coastal industrial zone of Quintero-Puchuncaví, one of the most emblematic sacrifice zones in Chile (Gayó et al., 2022), the Alto El Loa Indigenous Development Area in Northern Chile (Zanetta-Colombo et al., 2022), the Northern Atacama region (Tapia et al., 2018), the Antofagasta region (Valdés et al., 2015), the Biobío region (Rodríguez-Oroz et al., 2011) and Talcahuano city (Tume et al., 2018) in southern Chile. By contrast, the Chacabuco area remains poorly described. A recent study performed by Tapia et al. (2024) reported that concentrations of chemical elements determined between 2015 and 2018, in soils, water and plants from different locations near the Ovejería tailings dam in this area were found to be within national and international (WHO) limits for metals and pH. But, according to our analyses of stagnant surface waters and ground water in deep wells in this region (Le Goff et al., 2022), traces of metallic contamination, especially in arsenic (As), manganese (Mn) have been found in the province of Chacabuco, exacerbated by the current dry climatic conditions.

Despite these recent environmental studies, many questions remain unanswered, especially concerning air quality. The local population suspects arsenic and other toxic metal(loid)s pollution, as highlighted by Le Goff et al. (2022). Indeed, during interviews, residents regularly expressed their fears about the risk of pollution in these highly industrialized surroundings. The inhabitants of Tiltil, in particular, shared their impression of living in a downgraded and environmentally sacrificed area. They expressed uncertainty about water and air quality, and concern about their ensuing consequences for human health (Le Goff et al., 2022).

The concepts of risk perception (Douglas & Wildavsky, 1982; Slovic, 1987) and social representations (Jodelet, 2014; Moscovici, 1961) are commonly used in the social sciences to understand how residents interpret perceived changes in their living space. Social representations are the result of the interaction between social perceptions linked to individuals' personal sensory experiences and knowledge linked to the multiple instances of communication and sociability, including those associated with each person's culture (Douglas & Wildavsky, 1982). They reveal multiple realities. The presence of 'biases' (Joffe & Orfali, 2005) and the influence of external factors in the 'social amplification or attenuation' (Kasperson, 1988) of risk perception are limitations. Although imperfect, they are nonetheless essential tools for collecting data that are indispensable for understanding social relations and the relationship between societies and their territories. The gap between the assessment of risks by experts and their perception by the general public is regularly mentioned (Fischhoff et al., 1980; Gilbert, 2003), despite a recent tendency to integrate knowledge from the field (Zwarterook, 2010). In this respect, Slovic (1987) defends the usefulness of taking risk perception into account in risk analysis as an aid to decision-making and as a means of communication between decision-makers, experts and residents in order to produce more effective public health and safety policies. This position is echoed by Proulx et al (2008), who believe that lay analysis of risk would contribute to the public health sector in terms of monitoring health status and health knowledge. Indeed, prolonged daily exposure to sources of pollution identified as dangerous, influences the behaviour and physical and mental health of the individuals concerned. For example, Zhu and Lu (2023) showed that the perception of air pollution had an impact on the mental health and self-estimated physical health of the Chinese population. We therefore advocate the value of mixed research that includes a qualitative approach that enhances the study of risks in their spatial dimension on a local scale (Martinais et al., 2006). In this respect, socio-spatial representations are an ideal way of understanding how space is organised as well as locating perceived risks and local knowledge. The cartographic approach to representations is partly linked to the geography of perception (Bosque-Sendra et al., 1992). According to the authors of the francophone school of the geography of representations, the social context influences the perception of space and, consequently, spatial representations reveal the geographical space of individuals (Dernat et al., 2016).

Analysis of the perception of the risk of air pollution is regularly used in social science research carried out in areas of high industrial density. In the Dunkirk conurbation (France), where there are 13 high-threshold Seveso classified sites[1] (Flanquart & Zwarterook, 2011), according to a survey conducted by Zwarterook (2010), people felt exposed to industrial risk, with 75% of them perceiving a risk of air pollution. Their social representations of air quality were largely shaped by sensory experience, with a third of them associating it with dust deposits. In this case, the spatial dimension of risk perception leads to a tendency to reduce the risk in the vicinity of industries and an overestimation of risk in areas further away. In the province of Chacabuco (Chile), Le Goff (2024) has shown that the socio-spatial representations of residents reflect environmental inequalities exacerbated by growing socio-spatial segregation. The unequal perception of the risk of water and air pollution is linked to the unequal spatial distribution of the risk and is greater close to the industrial zones. Contrary to the findings of Zwarterook (2010), residents living near these sites feel more exposed to the risk of pollution and fear deleterious effects on their health. Consequently, taking an interest in perceived risks provides access to the cognitive and emotional dimensions on an individual scale and to the social, cultural, economic and political context on a collective scale.

Hence, new questions have been raised in this impacted area and a novel interdisciplinary research plan was constructed as a part of an inductive approach, enabling the dialogue between geochemists, geographers and sociologists. The common objectives were (i) to determine the local air quality and the potential influence of industrial and mining activities; (ii) to pilot the use of *T. bergeri* as consistent biomonitors across space and time,

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[1] *Council Directive 96/82/EC of 9 December 1996 modified by the Seveso III directive (2012/18/EU) which aims to improve the safety of European industrial sites containing large quantities of hazardous substances.*

(iii) to identify potential anthropogenic sources of metal(loid)s according to atmospheric processes and transport as well as enrichment factors; (iv) to assess if environmental and human health (through inhalation) are threatened, and finally (v) to investigate the correlation between inhabitant's perceptions, well-being and concerns and the results of chemical analyses such as metal(loid) concentrations in Chacabuco's atmosphere. Through this present socio-environmental study, we plan to verify the concerns and warnings of civil society by addressing scientific questions about the environmental and health issues involved in the cohabitation of industrial and residential areas. This suggests the need to develop measurement protocols assessing the potential risks, for example using oral bioaccessibility tests of potential trace elements.

Material and methods

Site description for air quality (bio)monitoring experiments

The study area is located between the Cordillera de la Costa to the west (max. 2,000 m locally) and the Cordillera de los Andes to the east (max. 6,000 m locally), joined by the Chacabuco range (max. 2,000 m) to the north (Errázuriz et al., 1998). It occupies the northern part of the tectonic Santiago basin, which is characterised by fluvio-glacial and volcanic sedimentary fill. According to Köppen's classification, the local climate is 'warm temperate with winter rainfall' or 'temperate Mediterranean'. Precipitation is concentrated during the cold winters, while summers are dry, with a dry period normally lasting between seven and eight months (Errázuriz et al., 1998). Since 2010, the central zone of Chile has been experiencing a period of 'mega-drought', with an annual rainfall deficit of around 25-40%, reaching 70-80% in 2019 (Garreaud et al., 2020). The surrounding mountains influence air circulation. Dominant south-westerly winds combined with frequent winter calm periods favour the concentration and accumulation of atmospheric pollutants (Errázuriz et al., 1998).

Human activity has developed mainly in the intermediate depression, known locally as the central valley, which is renowned for its fertile soils (Santibañez, 1984). Mining infrastructures are present in both the valley and the surrounding mountain ranges (Le Goff, 2024). Small-scale market agriculture has gradually given way to mining, agro-industry exports and real estate projects. Between 2002 and 2017, the province absorbed 12.8% of metropolitan growth (population census from INE Chile). Existing infrastructure, such as the Polpaico cement plant (Cemento Polpaico) created in 1955, has been joined by new infrastructure, including the Metropolitan Region's two largest tailings ponds, Las Tórtolas (Anglo American) created in 1996, and Ovejería (Codelco) created in 1999 (Jorge et al., 2020). The deliberate concentration of polluting companies in the north and south-west of the province has thus created an area that is unevenly affected from an environmental point of view.

The local population is mainly employed in three areas: in agriculture as farm labourers or seasonal workers on the large export farms; in the mining industry, especially in the municipalities of Tiltil (where there are seven copper, calcium carbonate, gold and limestone mining sites) and Colina (with one copper mining site); and in personal services as housekeepers or gardeners for the wealthier population that has recently settled in the privileged districts to the south of Colina. Colina is a commuter town for people who work in Santiago (PNUD, 2018).

Like other Chilean environmental sacrifice zones, the municipality of Tiltil is more inclined to receive undesirable activities from the administrative entities to which it belongs, as it is a large, peripheral municipality with a high rural population, a higher poverty rate than the regional average and a lower level of education (Le Goff, 2024). The 'harmful and dangerous, active and abandoned' industrial activities authorised by the 1994 Metropolitan Regulation Plan have produced negative externalities affecting air, soil and water quality (Municipalidad de Tiltil, 2017). As far as air quality is concerned, the municipality of Tiltil is located in a 'saturated zone' ('zone in which one or more environmental quality standards are exceeded', art. 2 of law no. 19. 300[2]) for ozone, respirable particles (PM_{10}), total suspended particles and carbon monoxide; and in a 'latent zone' ('zone in which the measured concentration of pollutants

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[2] *MMA, 1994, APRUEBA LEY SOBRE BASES GENERALES DEL MEDIO AMBIENTE,* https://www.bcn.cl/leychile/navegar?idNorma=30667

in the air, water or soil is between 80% and 100% of the value of the corresponding environmental quality standard', art. 2 of law N° 19.300) for nitrogen dioxide (Municipalidad de Tiltil, 2017). In 2013, the health authorities of the Santiago Metropolitan Region identified 50 stationary sources that were responsible for 80% of particulate emissions in the municipality of Tiltil, combined with insufficient ventilation conditions in the area (Ibid.). Within the Metropolitan Region, Tiltil has the highest concentration of deaths associated with respiratory diseases, suggesting air quality problems (PNUD, 2018).

The combination of two parameters was decisive in the selection of the sites of interest to be monitored in the north-western province of Chacabuco. On the one hand, interviews enabled us to identify a series of locations socially perceived by residents as exposed to air pollution. In parallel, the analysis of cognitive maps highlighted potential sources of air pollution: mining, industrial and, to a lesser extent, agricultural activities. On the other hand, in order to interpret our air quality analyses more accurately, whenever possible we chose to set up our experiments at sites with local weather stations belonging to farmers. A total of five sites were selected: Montenegro (32°58'0.28"S, 70°50'8.01"W, in the North, away from major mining activities), Tiltil (33°4'38.08"S, 70°55'30.52"W, downtown), Polpaico (33°10'56.41"S, 70°52'32.23"W, in an agricultural site, near the cement factory), Santa Matilde (33°6'33.09"S, 70°47'25.09"W, exactly between the two main mining waste storage tailing ponds) and El Colorado, to the east (33°4'24.30"S, 70°42'30.66"W, in an intensive agricultural site). All these sites are shown in Figure 1. This spatial distribution also offered the possibility of covering different wind corridors on a more local scale.

The monthly rainfall and wind parameters (speed and direction) were recorded in three of the studied sites with farmer's local weather stations, during the periods of biomonitoring experiments. For any incomplete data series, data from other weather stations allowed us to build a more solid analysis. Data were also collected from the Chilean Meteorological Office (DMC, 2024), through (https://climatologia.meteochile.gob.cl) for the station called Peldehue Ad (– 33.11389°, – 70.68583°), located just east of Las Tórtolas tailing pond.

Social representations and perceptions of air pollution risk

Experience as expertise in the risk of pollution for residents

Residents of areas where harmful activities are concentrated feel that their environment is polluted, but they cannot prove it. In the absence of a local environmental monitoring system, they are faced with three obstacles: finding a trustworthy organisation to carry out environmental measurements, having sufficient financial resources to bear the cost and convincing people it is worth pushing for (Le Goff, 2024). Images or archive files are often the only tangible evidence that residents have at their fingertips. This process of gathering evidence is common in cases of socio-technical controversy linked to industrial activities (Callon et al., 2001). In this context of unequal power relations between industry and residents, the personal experience of people living alongside industrial areas is often their only expertise. In this respect, Davies (2018), who looked at people living in the polluted Cancer Alley site in Louisiana in the United States, showed that, on site, "witnessing gradual changes to the local environment has become a barometer for perceiving chronic pollution". The author sees this "slow observation" as both "a useful counterpoint to the slow violence" associated with permanent exposure to pollution in these "toxic sites" and as an act of political resistance that will enable them to do so (Davies, 2018). This is why, in our view, testing hypotheses fueled by the socio-spatial representations and risk perceptions of populations exposed to environmental inequalities is one way of maybe enabling them toone day to achieve environmental justice.

From a comprehensive and inductive approach to a thematic analysis: empirical research in tune with local concerns

Favouring a qualitative methodology based on a comprehensive empirical approach (Charmillot & Dayer, 2007; Charmillot & Seferdjeli, 2002; Dumez, 2013; Wentzel, 2011), we sought to understand how knowledge is constructed and how it interacts with practices in the production of reality. The choice of grounding enabled us to grasp the day-to-day concerns of less visible sections of the population. Using an inductive approach, we opted for thematic analysis (Paillé & Mucchielli, 2016) to analyse the qualitative data. It enables recurring themes to emerge in the discourse, so that categories of analysis can be constructed from the participants' experiences (Ezzy, 2002). The inductive approach recognises the role of local people in the construction of scientific knowledge by using data collection methods that give them a voice, legitimizing the place and role of situated knowledge in the same way as that of experts (Callon et al., 2001). Favouring an approach where the "problems [are] identified by the stakeholders themselves" (Collignon, 2005) is in itself a form of ethical commitment.

Characteristics of the sample surveyed

The present reflection on socio-spatial representations and the perception of air pollution risk is the outcome of the social survey conducted among residents of the Chacabuco province between 2019 and 2022 (Le Goff, 2024). The interviews were initially conducted as part of a study about the perception of water-related risks in the territory. During these discussions, residents spontaneously voiced their concerns about local air quality. Having acquired sufficient data, we decided to incorporate them into a new relevant study on air quality in this area. Two different qualitative research data collection tools were used: semi-structured interviews and cognitive maps. In total 30 interviews and 19 maps were conducted with representatives of rural drinking water committees, farmers, mining companies and residents of Tiltil and northern Colina localities. As non-statistical qualitative research, the sample of participants was not intended to be representative of the population, but to reflect a diversity of viewpoints. Semi-structured interviews were conducted with key people in the study areas, using a non-probabilistic sampling technique of the cooperative or snowball type, in which each person suggests other contacts who seem interesting for the study. The first people contacted were representatives of social organisations or users of state programmes registered with the province's municipalities. In all, 30 people were interviewed, including 19 men and 11 women, 9 of whom were involved in farming. Place and time of residence were used as selection criteria. Among them were 28 residents and 2 non-resident mine representatives, and the average length of residence was 40 years (between 4 and 70 years). Half of the respondents were in the 60-69 age bracket, 6 in the 40-49 age bracket, 6 in the 50-59 age bracket and 3 in the 70-79 age bracket. The respondents lived in the following areas: Montenegro (2), Rungue (1), Tiltil center (1), Polpaico (3), Punta Peuco (1), Santa Matilde (4), Huertos Familiaires (3), Huechún (2), El Colorado (3), Quilapilún (3), El Canelo (1) and Casas de Chacabuco (4).

Social data collection

The interview data collected in 2019 and 2020 were then used to determine the future sampling sites, and those conducted in 2022 were used to consolidate the analysis of risk perception of local air quality. During the semi-structured interviews, we asked residents if they perceived any pollution risks in their environment if they did not mention it offhand. In the majority of cases, we used a cartographic support to complement the interview in order to collect socio-spatial representations linked to pollution risks. We then spatially classified the anonymous maps according to participants' areas of residence. The interviews were recorded and transcribed. The discourses and cognitive maps were then analysed separately using the thematic analysis method (Paillé & Mucchielli, 2016). Each theme corresponds to social representations that are frequently recurrent in their discourse. To ensure that they are relevant and representative, the corpus collected was subjected to analytical questioning. On the one hand, we examined the following questions in the discourses: what perceptions do residents have of air quality in their living environment? On what do they base these perceptions? Do they feel exposed to the risk of air pollution? On the other hand, we asked the following questions of the cognitive maps: what sources of air pollution do they identify and where are they located? Which populated areas would be affected?

From cognitive maps to air pollution data collection

The protocol had to be adapted to the context of the Covid-19 pandemic. Given the restrictions on group meetings long in force in Chile, the participatory methodology initially planned was replaced by research into the relationship to risks on an individual scale. Cognitive mapping appeared to be an interesting tool for accessing the spatial dimension of representations and perceptions. Cognitive maps support our data collection on air pollution by helping to precisely locate residential areas perceived to be exposed to the risk of air pollution, potential sources of pollutant emissions and the trajectories of observed dust clouds. Their analysis also highlighted an area of greatest concern, dubbed the "triangle of uncertainty" because of its location between three major industrial sites (see Results' Section "Risk of air pollution perceived in the vicinity of tailings ponds"). The identification of these different elements guided us in determining where to set up our measurement sites and in interpreting the results of the air quality data collection.

Biomonitoring of air quality using *T. bergeri*

Selection and preparation of the T. bergeri plants for the experiment

T. bergeri are common in gardens in central Chile, where they are known locally as *"claveles del aire"*. As it was impossible to obtain them from local greenhouses, some local women were kind enough to donate specimens taken from their gardens. The need for a large number of plants to cover the five monitoring sites for two years led us to use several sampling sites for the control sites: one in the province of Chacabuco (Santiago Metropolitan Region, (33°22'54.31"S, 70°92'49.43"W) in 2020 and two in the province of Petorca (Valparaiso Region; 32°13'8.53"S, 70°48'50.18"W and 32°10'16.06"S, 70°46'29.57"W, about 140 km north of the area) in 2021. These rural locations were considered to not be polluted and had no potential contamination sources in their vicinity. Epiphyte plants were all collected from the same parent plant. As these epiphyte plants had been growing in a control site in the Chacabuco province for several years, a meticulous washing procedure was applied before starting the exposure experiment, which entailed washing their leaves three times in deionized water slightly acidified (pH = 4) by HNO3 to remove dust and all the potential adsorbed particles. The efficiency of three rinses was checked by elemental concentration determination in control plants. Plants from the same parent plant were then exposed in manufactured nylon mesh bags in the five different sites of interest (Fig. 1). Exposed plants correspond to stems without any flowers.

Experimental set-up of T. bergeri

Two long-term experimental set-ups were conducted successively in the Chacabuco area.

For the first experiment, plants were collected from a rural area in the Chacabuco province. In January 2020, they were exposed for one year. Three nylon mesh bags containing one *T. bergeri* each, corresponding to approximately 30 g of fresh matter, were installed at the five sites. One *T. bergeri* from the same parent plant was kept as a control for this experiment, and then directly analyzed (see Section "Analysis of the leaf tissue of *T. bergeri*"). Plants of similar size were used to make the bags and were secured on trees or wooden posts at a height of 1.7 m. At each site, one plant was collected approximately every four months: in May 2020, August 2020, and January 2021, to follow the deposition of airborne particles over a full year. As this experiment started just before the COVID-19 pandemic, plant collection was performed as regularly as logistically possible while complying with travel restrictions. Most of the plant collection was carried out by local residents in coordination with the research team. After harvesting, plants were stored in paper bags. They were dried at 45°C for 48-72h in the laboratory in Toulouse, later ground in an agate mortar with liquid $N_{2,}$ dried again if necessary, and stored in polyethylene vials before being analysed.

A second experiment was deployed in March 2021: *T. bergeri* from the mountain area in Petorca province were exposed in the same five sites of interest for seven months from March until the end of October 2021. This second experiment aimed to validate the first one and obtain more data, over a new year. The same procedure was respected for plant collection, control check and preparation before analyses.

It should be noted that after exposure, the plants were not washed because both deposition on the leaves and potential uptake and accumulation through the shoots are considered in this study.

Analysis of the leaf tissue of T. bergeri

Surface morphology, trichome conformation and chemical composition (potential presence of metal(loid)s) of exposed *T. bergeri* were firstly analyzed using scanning electron microscopy with energy dispersive X-ray spectroscopy (SEM-EDX). Measurements were carried out using a Vega 4 LMU (TESCAN®) instrument (in the GET laboratory), on the most contaminated plant (*Santa Matilde - Oct 2021, seven months of exposure*). Technically, before observation, epiphyte plants were dried and fixed on a carbon substrate without any further preparation before analysis. The apparatus was operated in partial vacuum mode (~20 Pa) at 25 kV.

Study of atmospheric fallout using Owen gauges

Experimental set-up

To determine the dry and wet atmospheric fallout in the global area, three devices for collecting deposited dust known as Owen gauges, were installed in El Colorado, Polpaico and Santa Matilde sites. These three sites permit a closer look at the "triangle of uncertainty" described by Le Goff (2024) in this area. These devices allowed better characterization of atmospheric particulate matter, as reported by Blondet et al. (2019), Navel et al. (2015) and Schreck et al. (2012). They are explained in the context of passive atmospheric deposition collection devices in Amodio et al. (2014). The Owen gauges were collected after seven months of exposure, *i.e.* in August 2020 and October 2021. Unfortunately, the Polpaico gauge broke following an intense rainfall event in August 2020, leaving only two gauges (El Colorado and Santa Matilde) for the experiments.

Mineralogy of the atmospheric fallout samples

Particle mineralogy was analyzed in a water/ethanol medium by X-Ray diffraction (XRD) using a D2 Phaser diffractometer from Bruker® in the GET laboratory. Analyses were interpreted using the diffract_EVA® software.

Metal(loid) concentration determination in plants and atmospheric fallout

For the determination of total metal(loid) concentrations in *T. bergeri*, 0.100 g of dry matter were digested using a mixture of 8 ml of bi-distilled HNO_3 and 2 ml HF (suprapure quality). Acid mineralization was conducted using a CEM® Mars 6 microwave using iPrep vessels with the "plant tissue" setting. The heating program consisted of a 30 min ramp until 200°C followed by a holding time of 10 min prior to a cooling period (Calas et al., 2024). For atmospheric fallout, 0.050 g of dry deposits were digested using the same acid mixture.

Afterwards, all solutions were completely evaporated at 70°C on a hotplate and the dry residue was resuspended in HNO_3 0.37N before analysis. Metal(loid) concentrations in diluted solutions (HNO_3 0.37N) were determined using Inductively Coupled Plasma-Mass Spectrometry (ICP-MS; iCAP Q Thermo Scientific®, from the ICP-MS Service of the Midi-Pyrénées Observatory in Toulouse and from the ICP-MS AETE-ISO platform of OSU OREME, at the University of Montpellier). Each batch of samples included acid blank and certified reference material: SRM 1515 Apple leaves from the National Institute of Standards and Technology (NIST, USA) for *T. bergeri* samples, and SRM 1648a Urban particulate matter (NIST, USA) for atmospheric deposits. Details on the quality of acid mineralisation and the instrumental analyses are given in Table SI-1. Mineralisation recoveries were calculated using NIST SRM 1515 and 1664a standards. For instrumental analyses, the limits of detection (LOD) and quantification (LOQ) were calculated as the average plus 3 times and 10 times, respectively, the standard deviation (SD) of the concentrations in the HNO_3 blanks. SRLS-6 standard (river water certified reference material for trace metals and 31 other constituents) and EPOND standard (multi-element standard solution) were used for the ICP-MS analyses. Recoveries are expressed as the ratio of the measured to certified concentrations. Relative standard deviations (RSD %) were < 5 %, and relative standard deviation on blank replicates were$<$ 10 %. All certified elements presented satisfactory recoveries, in the 85–104 % range (see Table SI-1).

Environmental and health risk assessment

Environmental risk assessment from T. bergeri experiments

An assessment of the **environmental status** of the different sites monitored by **epiphyte plants** was performed by the calculation of enrichment factors (EF) of *T. bergeri* in the different elements. For the epiphyte plants, enrichment factors for each element were calculated by comparison to the estimated average concentrations registered for the Upper Earth's crust, as generally performed in the literature and first described by Taylor and McClennan (1985). We used this reference as it was commonly used for environmental studies focused on mining sites (Blondet et al., 2019; Kasongo et al., 2024; Zhou et al., 2024) even if it is possible that the geochemical background of this part of Chile may be naturally higher. The upper crust values of the eight elements used in the EF calculations were 1.52, 550, 85, 25, 542.13, 44, 17 and 71 mg·kg^{-1} respectively for As, Ba, Cr, Cu, Mn, Ni, Pb and Zn. Titanium (Ti) was chosen as an invariant for normalization in this context. The ICP-MS recoveries (measured with EPOND standard) were excellent for this element (98 %, Table SI-1), chosen to avoid any interference with the re-suspended soil. The formula of EF calculations is expressed in Eq. (1):

$$EF_{(Metal(loid))} = \frac{C_i/C_{Ti}\,sample}{C_{Ti}/C_{Ti}\,uppercrust} \quad (1)$$

where Ci is the measured metal(loid) concentration, and C_{Ti} is the Ti concentration, respectively in the *T. bergeri* sample or in the upper Earth's crust (Blondet et al., 2019). Enrichment factors up to 10 indicate pedo-geochemical origin of elements whereas higher values of EFs indicate anthropogenic sources (Esmaeilirad et al., 2020; Pellegrini et al., 2014).

Moreover, the pollution load index (PLI) was also used to quantify the potential environmental risks involved, and to study the relative contribution of the different toxic metal(loid)s found in samples of *T. bergeri*. The PLI was firstly proposed by Tomlinson et al. (1980) and recently used by Chen et al. (2022) and Calas et al. (2024). This pollution index reflects the contribution of metal(loid)s to regional pollution as well as its temporal and spatial changes (Chen et al., 2022). According to Tomlinson et al. (1980), the formula for calculating PLI is expressed in Eqs. (2) and (3):

$$P_i = \frac{Ci}{C_n^i} \quad (2)$$

$$PLI = \sqrt[n]{\pi_i^n P_i} \quad (3)$$

where Pi is the single-factor pollution index, Ci is the measured metal(loid) concentration in the *T. bergeri* sample, and C^i_n is the measured metal(loid) concentration in *T. bergeri* used as control in the experiment. As explained by Chen et al. (2022), the PLI values are then ranked in four levels from I to IV, indicating no (PLI <1), mild (1 = PLI <2), moderate (2 = PLI <3), and severe pollution (PLI ≥3), respectively. Only the elements with EF values over 10 were selected for this PLI calculation.

Inhalation bioaccessibility assays of the fallout samples

Inhalation bioaccessibility assays were conducted at Eurecat's facilities (Manresa, Spain), following the method described by Kastury et al. (2017) and Kim et al. (2014). These were carried out for As, Cr, Cd, Pb, and Sb, which exhibit proven toxicity for the inhalation pathway (Balali-Mood et al., 2021). Furthermore, these five metal(loid)s are classified as chemicals of major public health concern since June 2020, as shown recently on the WHO website.[3] For the determination of the inhalation bioaccessibility, the atmospheric fallout samples collected in the two sites (El Colorado and Santa Matilde) were dried at 25 °C for 24 h and sieved at 20 µm. A Phagolysosomal Simulant Fluid (PSF) solution was prepared by combining 142.0 mg sodium phosphate dibasic anhydrous (Na_2HPO_4), 6650.0 mg sodium chloride (NaCl), 71.0 mg sodium sulphate anhydrous (Na_2SO_4), 29.0 mg calcium chloride dihydrate ($CaCl_2$-$2H_2O$), 450.0 mg glycine ($C_2H_5NO_2$), 4084.6 mg potassium hydrogen phthalate ($C_8H_5KO_4$) and 50 mg of alkylbenzyldimethyl ammonium chloride (ABDC) with deionised water in a final volume of 1.00 L, as reported by Stefaniak et al. (2005). The pH of the PSF solution was

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[3] https://www.who.int/news-room/photo-story/photo-story-detail/10-chemicals-of-public-health-concern

stabilized at 4.5 ± 0.1. An aliquot of 0.05 g of the sample was added to 5 mL of PSF (solid liquid ratio of 1/100) and placed on an agitator at 170 rpm at 37 °C for 24 h. The experiment was performed in triplicate. The solution was then filtered through a 0.45 µm nylon filter and metal(loid) concentrations measured by an inductively coupled plasma mass spectrometer (ICP-MS, Agilent 7500cx). The Bioaccessible Fraction (BAF) was calculated as the ratio of the dissolved metal(loid) concentration in the PSF-extracted solution over the total metal(loid) concentration in the sample.

Health risk assessment

Health risk assessment calculations were performed on the total and bioaccessible metal(loid) contents obtained from the dust samples collected each year in both El Colorado and Santa Matilde sites. The metal(loid) concentration in atmospheric fallout ($C_{\text{total air}}$, in mg·m^{-3}) was calculated considering the total metal(loid) content measured in the airborne particles (C_{sample}, in mg·kg^{-1}) and an estimation of the concentration of air particles in the atmosphere of the studied region of Chacabuco ($C_{\text{particles}}$, in mg·m^{-3}; considered to be 70 µg·m^{-3} for the city of Santiago according to Valdés (2011) and Trewhela et al. (2019)), (Eq. 4):

$$C_{\text{total air}} = C_{\text{sample}} \times C_{\text{particles}} \tag{4}$$

For risk assessment, the bioaccessible concentration of metal(loid)s in air particles ($C_{\text{bioaccessible air}}$, in mg·m^{-3}) was calculated following the Eq. 5 :

$$C_{\text{bioaccessible air}} = C_{\text{sample}} \times \text{ BAF } \times C_{\text{particles}} \tag{5}$$

where BAF is the bioaccessible fraction calculated as pollutant content released into the PSF fluid over the total metal content.

Risk assessment was determined using the US EPA methodology (US EPA, 2009). For each metal(loid), Exposure Concentration for assessing cancer risk (EC_{CR}) was estimated using Eq. 6 whereas Exposure Concentration for assessing the hazard quotient (EC_{HQ}) was estimated using Eq. 7, as previously reported in Blondet et al. (2019):

$$EC_{CR} = \frac{C_{air} \times ET \times EF \times ED}{T_{CR} \times \frac{365d}{year} \times 24h/day} \tag{6}$$

$$EC_{HQ} = \frac{C_{air} \times ET \times EF \times ED}{T_{HQ} \times \frac{365d}{year} \times 24h/day} \tag{7}$$

where C_{air} is the concentration of the chemicals of concern in the air (in mg·m^{-3}), ET is Exposure Time (in h per day), EF is Exposure Frequency (in days per year), ED is Exposure Duration (in years), and T is average Time considered for CR or HR (in years). Exposure parameters considered for the different scenarios are included in Table SI-2.

A long-term exposure scenario was considered (Table SI-2), i.e. a child becoming an adult in the same area (corresponding to 6 years as a child followed by 26 years as an adult living in the same place). Cancer risk (R) and hazard quotient (HI) were estimated for each metal using Eq. 8 and Eq.9, respectively, considering toxicity values (IUR, CIR, and sCIR) from the literature (see Tables SI-2 and SI-3 for more details).

$$R = IUR \times EC_{CR} \tag{8}$$

$$HI = \frac{EC_{HQ}}{CIR} or \frac{EC_{HQ}}{sCIR} \tag{9}$$

where IUR stands for Inhalation Unit Risk (in µg·m^{-3}) CIR for Chronic Inhalation Reference Concentration (in mg·m^{-3}), and sCIR for Subchronic Inhalation Reference Concentration (mg·m^{-3}). Total cancer risk R and total hazard quotient HI were estimated by summing the individual risks and quotients calculated for each metal(loid) involved in this study. Non-acceptable risk was considered when either total cancer risk was over 1E^{-5} or total hazard quotient was above 1, as defined in the Agency for Toxic Substances and Disease Registry (ATSDR, 2023) and US EPA (2023).

Results

The perception of air pollution risk

A concern for air quality from local industries context

Interview analyses (all listed in Tables SI-4 and SI-5) show that residents of Chacabuco province identified two problematic areas for air quality: 1/ the northwest of the province, corresponding to the localities of Montenegro and Rungue in the north of the

Tiltil municipality (Figure 1) and 2/ the north-east of the province, from the north of the municipality of Colina to the south-east of the municipality of Tiltil (Figure 1). In the first area, the effluents from the regional household waste dump (KDM®), the pig farm (Porkland®) and the sewage sludge treatment plant are reported to cause headaches, nausea and a reduced quality of life for local residents (interviews of Montenegro and Rungue inhabitants). The second area contains two tailing ponds that may emit fine particles into the air: the Ovejería tailing pond of the Codelco® national copper mining company (INDH, 2024; Tapia et al., 2020, 2024) containing mostly Si, S, Fe, Al, Ca, Mg, K, Na and Mn at a pH of 6.3, as shown in Tapia et al. (2017), and the Las Tórtolas tailing pond of Anglo American® from a copper mine high up in the surrounding mountains (Consejo Minero, 2024; INDH, 2024 and Figure 1). Since we aimed to study the presence of metal(loid)s in the atmosphere and their potential impacts by inhalation on local residents, our work was concentrated on this second area.

In the north-east of the province, we distinguished two different points of view with regard to air quality. On the one hand, some residents do not perceive any risks associated with air quality and some even claim that it is better or at least equal to Santiago 35 km to the south (Table SI-4-1). On the other hand, the majority of people surveyed insist on the existence of "disturbance phenomena brought by local wind patterns" impacting air quality (Table SI-4-2, 3, 4, 6, 7, 8, 9, 11, 12, 13, 14). Moreover, there is a context of suspicion linked to the local over-representation of harmful industries (Table SI-4-4, 5, 10, 13). Despite the reassuring rhetoric of companies, there is a state of vigilance and mistrust on the part of local populations concerned about the presence of harmful industries close to their living environment (Le Goff et al., 2022).

Among the three categories of residents surveyed, it was almost exclusively residents who expressed concerns about air quality, identifying suspended dust or feeling exposed to air pollution. Farmers feel less or not exposed to air quality problems. For their part, the representatives of the Anglo American® company interviewed warned us against the perceptions of the inhabitants who would fantasize about the situation (Table SI-4-25). They claim to be a modern "21st century" mining industry controlled by permanent studies of their production sites (Table SI-4-26). According to them, the distrust of the inhabitants towards the mines is not related to a lack of transparency, but due to poor communication on their part and on the disperse and difficult access to existing data, reinforced by a digital divide among the rural and elderly populations of the north of the province of Chacabuco (Table SI-4-27). Despite our research, and in the intervening time, we have not uncovered any recent information on the air quality around the Las Tórtolas site, nor has the company responded to our request in this regard.

Risk of air pollution perceived in the vicinity of tailings ponds

Almost all of the 19 cognitive maps created (17 out of 19, Figures SI-1 and 2) refer to the risk of pollution, as expressed in Table SI-5. The only two maps that do not mention it correspond to inhabitants from the locality of Casas de Chacabuco ("CC" in Figure 1). Geographical location and distance from the above-mentioned industries seem to be two factors that reduce the feeling of being exposed to pollution. According to these maps, the localities most exposed to the risk of pollution are those of Huechún, Santa Matilde and Huertos Familiares (Tables SI-6 and SI-7), located inside the perimeter of the two mining settling basins and the cement factory,[4] in the heart of the "triangle of uncertainty" (Le Goff, 2024) as presented in Figure SI-2. Figure 2 proposes a schematic representation of the perception of inhabitants' exposure to a risk of atmospheric or water pollution based on their cognitive maps. The center of gravity of the area perceived as exposed by the pollution risk has moved in space towards the areas of residence of the people interviewed (Figure 2), and varies according to the type of pollution mentioned (Figure 2 and Tables SI-4 and SI-5). Air pollution seems to concern the northeast of the studied territory whereas water pollution focuses on southwest areas, while

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[4] The estimated surface area of these three industrial sites based on Google Earth satellite imagery in 2023 is as follows: Cerro Blanco's cement factory (Cemento Polpaico®): 1,047 ha; Las Tórtolas' mine tailing pond (Anglo American®): 1,112 ha; and Ovejería'smine tailing pond (Codelco®): 1,185 ha.

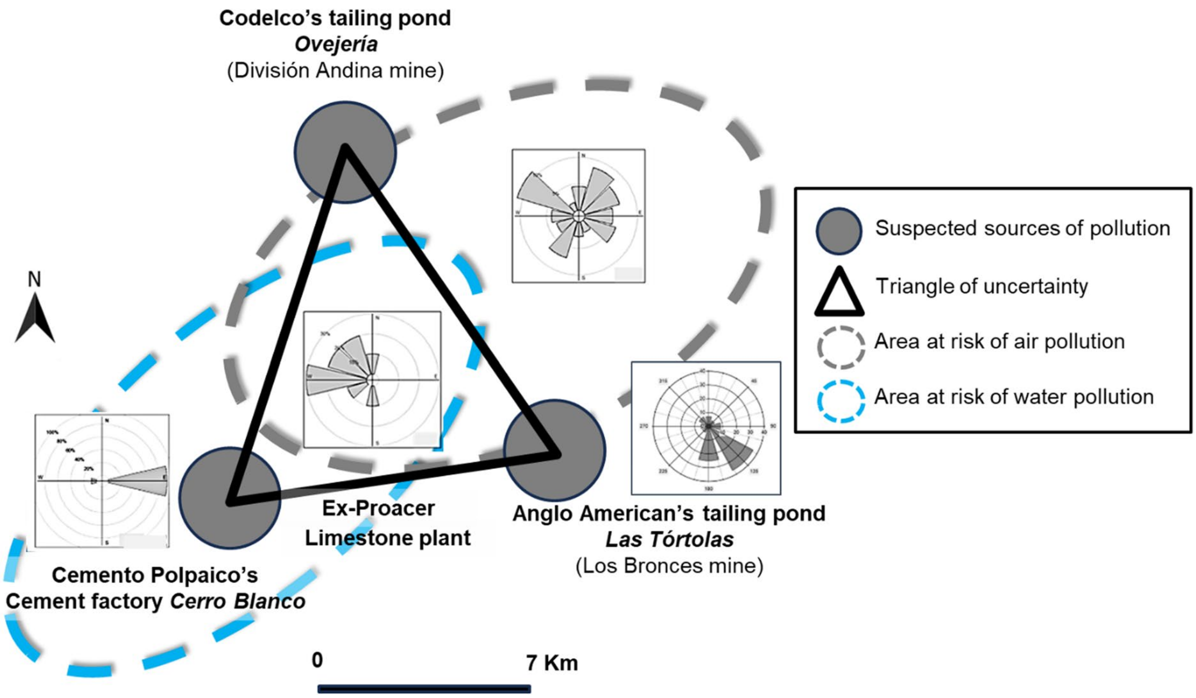


Fig. 2 Synthesis of spatial distribution of the suspected risk of exposure to air and/or water pollution according to the cognitive maps designed by the inhabitants of Chacabuco province, as well as wind roses built for the different locations, suggesting potential air contamination dispersion

the area located inside the triangle of exposure, between industrial sites, is affected by both (Figure 2). The mining and extractive companies are frequently cited in the identification of air pollution sources (Table SI-4-9, 12). The tailing ponds of the Codelco® and Anglo American® mining companies are of particular concern to the local communities: respectively 15 and 14 inhabitants out of 19 have identified them as the main sources of air pollution (Table SI-7). Lastly, analysis of socio-spatial representations shows that the locality of residence shapes their perception of air quality.

The importance of perceived wind corridors to explain atmospheric pollution exposure

The perception of atmospheric contamination risk is based on the sensory experience of residents (Table SI-4-5), mainly visual experiences (white dust, yellow clouds, industrial infrastructures). The most common manifestation is the formation of sporadic dust whirls reported by many residents of northeastern Chacabuco province (Table SI-4-6, 7, 8). According to them, these phenomena are relatively recent, seasonal and local, depend on wind corridors and mostly occur in summer. The surface of the tailing ponds (see Figure 1) dries out and the northwest wind that dominates during this time of the year (as also reported by the wind roses of Santa Matilde/Huertos Familiares and El Colorado, Figure SI-3) transports dust to the northeastern sector of the province. In winter, this phenomenon does not occur due to less sunlight, lower temperatures and more humidity (and less evaporation), keeping the dust more compact (Table SI-4-8). Finally, the reported feeling of "being exposed to" or "polluted by" this resuspended dust depends on wind corridors and prevailing winds that change with the seasons (Table SI-4-6, 7, 8). Inhabitants suggest that dust from the surface of Las Tórtolas tailing pond (Table SI-4-6) (Figure 1) affects the surroundings (Table SI-4-9), while suspended particles from the Ovejería tailing pond pass above Huechún (Table SI-4-13) and Quilapilún before settling in Santa Matilde, El Colorado and Casas de Chacabuco (Table SI-4-6, 7, 10, 13 and Figure 1 for more location details). For more information about these two tailing ponds, see Cacciuttolo et al. (2022). Mining activities tend to overshadow air pollution potentially generated by agricultural activities, but few inhabitants (Table SI-4-18, 19) mention the use of agricultural phytosanitary products that are known to be sprayed on grape and walnut crops, both destined for export.

Perceptions about the potential health impact of inhaling industrial dust

Some residents express concerns regarding the inhalation of dust resuspended from tailing ponds (Table SI-4-21, 22, 23, 24). Many of them believe that annual episodes of dust resuspension affect their health, particularly in terms of the respiratory system, while a few people think the dust is harmless. In the residents' discourse (Table SI-4-20), the fine particles of waste from the tons of material processed to extract copper are clearly considered as harmful, in particular because of their content of metals and metalloids. They qualify the degree of danger of Las Tórtolas basin (Anglo American®) as more damaging to them (Table SI-4-15, 16, 17). Anglo American® processes copper in the valley, while Codelco® deals with it upstream in the Cordillera at the El Saladillo mining camp and, as a result, the components present in the basins are different. Moreover, residents believe that the silica emanating from Cemento Polpaico® (cement plant, see Figure 1 for localisation) affects the Huertos Familiares and Santa Matilde localities (Table SI-4-9, 10, 13). They are concerned about the future impact of industrial activities on their health and are looking for answers to their doubts.

Results of biomonitoring experiments

Meteorological data

Results of weather data are reported in Figure SI-3 and Figure 2, as a summary. A rainier period corresponding to a cumulative rainfall of 139.6, and 145.5 mm in Polpaico and Santa Matilda respectively was observed during the austral winter, especially in June-July 2020 for the first experiment. 52.6, 66.2 and 90.8 mm of rain in total was recorded in Polpaico, Santa Matilda and El Colorado respectively in the second experiment in 2021, in May-June and August-September. The different sites show a similar rainfall profile (Figure SI-3). However, wind roses reported different behaviours between sites: in Polpaico, the predominant wind direction was easterly in both 2020 and 2021, whereas in Santa Matilde/Huertos Familiares and El Colorado, the predominant monthly wind data showed respectively that the westerly and north-west directions were the most intense in 2021. The lack of data in 2020 meant that the main wind direction and speed in 2020 was inconclusive for these two locations. But minute averaged data from the Chilean Meteorological Office at Peldehue Ad, east of Las Tórtolas for 2020 and for March to October 2021 showed predominant south and southeasterly winds (Figure SI-3 and Figure 2).

Metal(loid) concentrations accumulated in T. bergeri

The total concentrations of metal(loid)s in **epiphyte plants** (deposited and uptaken) are shown in Figure 3 (A for 2020 and B for 2021). Only 8 elements are reported in Figure 3, corresponding to the most concentrated or those of interest in terms of environmental or health impacts with regards to air quality standard regulations (As, Ni and Pb). They can also be considered as useful markers of pollution sources such as industrial and mining activities (As, Cu, Pb and Zn), vehicle emissions (Cr, Cu), fuel oil combustion (Ba, Cr and Ni) and agricultural inputs (Cu, Mn, Ni and Zn), as reported by Esmaeilirad et al. (2020).

For the first experiment, there is no strong kinetic deposition nor accumulation of metal(loid)s in plant tissues, except for some elements (Cu, Mn, Pb, Zn) in Santa Matilde and Polpaico sites. High metal(loid) concentrations are measured in plants exposed in the Santa Matilde site, in comparison to the controls, especially for As, Cr and Zn, but also for Cu and Pb to a lesser extent (Figure 3A). A seasonal effect has also been identified, particularly for As and Mn, with a drop in metal(loid) concentrations during austral winter (August 2020, Figure 3A). Concentrations of As, Cu, Mn, Pb and Zn rise during the austral summer, as evidenced by the "January 2021" sample.

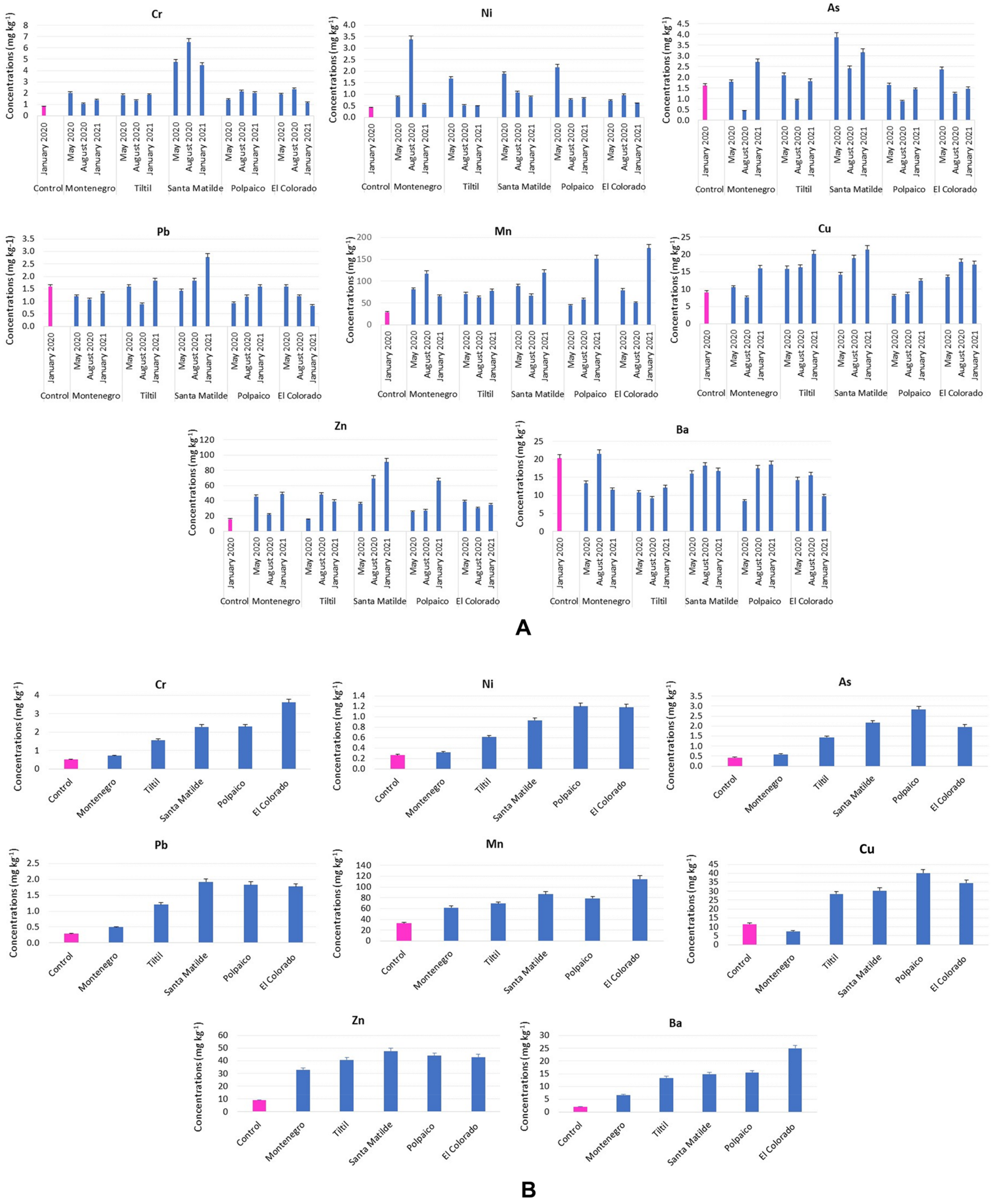


Fig. 3 Main metal(loid) concentrations (mg kg^{-1}) in *Tillandsia bergeri* exposed in the 5 sites of interest in the Chacabuco province, during the year 2020 (A) and for 7 months in 2021, from March to October 2021 (B)

For the second experiment, the inter-site disparities show that the plants exposed in Santa Matilde, Polpaico and especially El Colorado exhibited the highest metal(loid) concentrations (Figure 3B). Concentrations vary according to the considered element, but are still very high compared to controls. These results, combined with EF calculations (*see later*), enabled us to select As, Cu, Mn and Zn for PLI calculations.

Atmospheric deposits on the leaf structure of the plant

The SEM-EDX observations (Figure SI-4) show the general morphology and the trichome's structure of *Tillandsia bergeri* exposed during seven months in the Santa Matilde location (Figure SI-4A&B). Particles of various sizes with a homogenous distribution were observed on the plant surface (Figure SI-4A). Most of the EDX spectra exhibit the presence of Si and O, suggesting the deposition of quartz (SiO_2), but also the presence of Fe, Cu (Figure SI-4C) and sometimes Mn and Cr (*observations not shown*).

Results of the study of atmospheric fallouts from Owen gauges

Atmospheric fallout composition and mineralogy

Mean metal(loid) concentrations in atmospheric fallout from **Owen gauges** of the El Colorado and Santa Matilde sites are presented in Table 1A.

Results show that, among the 8 studied elements, metal(loid) concentrations measured in Owen gauge deposits were highest at the Santa Matilde site, except for Cu and Mn. The highest concentrations were determined for Mn (713.3 mg kg^{-1} in El Colorado) and for Zn (574.8 mg kg^{-1} in Santa Matilde).

Mineralogy of particles analyzed by XRD are reported in Table 1B. Results show that, apart from the main minerals (quartz, feldspars and clays) commonly found in volcanic Andean soils, two different arsenate minerals have been identified. In Santa Matilde, atmospheric fallout mineralogy has revealed the presence of scorodite, typical in former mining waste storage areas. By contrast, pharmacolite, a mineral releasing As through oxidative dissolution of the surface earth system, was found in abundance in El Colorado (Table 1B).

Table 1 Characterization of atmospheric fallouts from Owen gauges, for the two studied sites of El Colorado and Santa Matilde: (A) mean metal(loid) concentrations (expressed in $mg \cdot kg^{-1}$) and (B) mineral composition of atmospheric fallouts, determined by X-ray diffraction (XRD)

A	Studied site	Mean metal(loid) concentrations over the experimental periods ($mg \cdot kg^{-1}$)							
		As	Ba	Cr	Cu	Mn	Ni	Pb	Zn
	El Colorado	16.35	169.00	26.64	331.45	713.30	10.42	18.15	306.78
	Santa Matilde	91.76	177.10	204.32	259.98	496.90	22.17	29.58	574.84

B	Mineralogy of atmospheric fallouts from Owen gauge's samples (XRD)					
	Santa Matilde			El Colorado		
	Identified mineral	Formula	Occurrence	Identified mineral	Formula	Occurrence
	Albite	$NaAlSi_3O_8$	+ + +	Sylvite	KCl	+ + +
	Anorthite	$CaAl_2Si_2O_8$	+ + +	Quartz	SiO_2	+ +
	Quartz	SiO_2	+ +	Albite	$NaAlSi_3O_8$	+ +
	Scorodite	**$FeAsO_4 \cdot 2H_2O$**	**+ +**	Anorthite	$CaAl_2Si_20_8$	+ +
	Perovskite	$CaTiO_3$	Suspected	**Pharmacolite**	**$CaHAsO_4H_2O$**	**+ +**
	Vesuvianite	$Ca_{10}(Mg,Fe)_2Al_4(SiO_4)_5(Si_2O_7)_2(OH,F)_4$	Suspected	Muscovite	$KAl_2[(OH,F)_2 \vert AlSi_3O_{10}]$	+
				Clinochlore	$Mg_5Al(AlSi_3O_{10})(OH)_8$	+

Notes: Minerals are classified in the Table according to their probability of occurrence in the analyzed samples. Minerals in bold characters are the main arsenic phases

Metal(loid) bioaccessibility by inhalation from atmospheric fallout

Results of mean metal(loid) bioaccessibility by inhalation for El Colorado and Santa Matilde for 2020 and 2021 are reported in Table 2. Among the selected metal(loid)s, Zn, Sb and As were the most bioaccessible elements (Table 2). Their bioaccessible fraction (BAF) reached 32.0, 25.2 and 25.1 % for Zn, Sb and As respectively. The other investigated metal(loid)

Table 2 Bioaccessibility by inhalation for 6 investigated metal(loid)s at the 2 locations (El Colorado and Santa Matilde) from Owen gauges, in the 2020 and 2021 experiments

BAF (Inhalation Bioaccessible Fraction, the average metal released to the PSF fluid over the total metal content), expressed in %						
	Zn	Pb	As	Cu	Cr	Sb
El Colorado 2020	30.3	2.0	25.1	5.5	1.5	25.2
El Colorado 2021	8.9	ND	17.1	8.3	1.9	ND
Santa Matilde 2020	32.0	2.2	15.8	3.7	0.7	17.8
Santa Matilde 2021	14.8	1.1	19.4	3.5	0 5	ND

Notes: ND = Not Determined; Mn was not determined in this BAF study

Table 3 Enrichment factors of 8 elements of interest (As, Ba, Cr, Cu, Mn, Ni, Pb and Zn) in *Tillandsia bergeri* from the 5 investigated sites in the Chacabuco province (Metropolitan region) in Chile: Montenegro, Tiltil, Santa Matilde, Polpaico and El Colorado

Enrichment factors (EF)								
Year 2020	As	Ba	Cr	Cu	Mn	Ni	Pb	Zn
January–May 2020 (4 months)								
Montenegro	9.75		1.22	4.99	8.20	0.91		**35.74**
Tiltil	**37.62**		1.40	**31.79**	8.91	3.33		
Santa Matilde	**56.69**		1.74	7.70	4.12	1.25		**10.61**
Polpaico	2.05		0.58	0.00	2.35	3.26		**10.86**
El Colorado	**19.17**		0.49	6.74	3.56	0.26		**12.32**
January–August 2020 (7 months)								
Montenegro		0.23	0.30		**16.16**	6.64		8.40
Tiltil			0.44	**19.28**	4.15	0.15		**30.22**
Santa Matilde	**12.95**		1.63	9.54	1.70	0.37	0.35	**18.29**
Polpaico			0.44		1.49	0.22		4.40
El Colorado			0.47	9.01	1.00	0.31		5.17
January 2020–January 2021 (12 months)								
Montenegro	4.55		0.39	**14.02**	2.82	0.05	0.45	**10.28**
Tiltil	**103.56**		4.33	**49.70**	**16.74**	1.07	6.95	**105.82**
Santa Matilde	**56.70**		0.55	**21.53**	5.15	0.26		**35.43**
Polpaico			0.55	5.08	8.70	0.35		**27.28**
El Colorado			0.68	**54.85**	**45.73**	0.69		**45.17**
Year 2021	As	Ba	Cr	Cu	Mn	Ni	Pb	Zn
March–October 2021 (7 months)								
Montenegro	8.61	0.69	0.20		4.43	0.10	0.99	**27.82**
Tiltil	**18.79**	0.58	0.34	**18.91**	1.89	0.22	1.50	**12.51**
Santa Matilde	**27.66**	0.55	0.50	**17.97**	2.38	0.36	2.28	**12.92**
Polpaico	**36.91**	0.56	0.48	**26.24**	1.96	0.49	2.07	**11.33**
El Colorado	**11.00**	0.45	0.39	9.94	1.63	0.22	0.94	5.15

Notes: from Taylor and McLennan (1985); normalization by titanium (Ti) as an invariant element; elements are classified by alphabetic order; values in bold character correspond to EF > 10 s showed very low bioaccessibility by inhalation, involving a low toxicity for humans, even if they were highly concentrated in the atmosphere. Unfortunately, Mn could not be determined due to experimental constraints although it was the most concentrated element in atmospheric fallout.

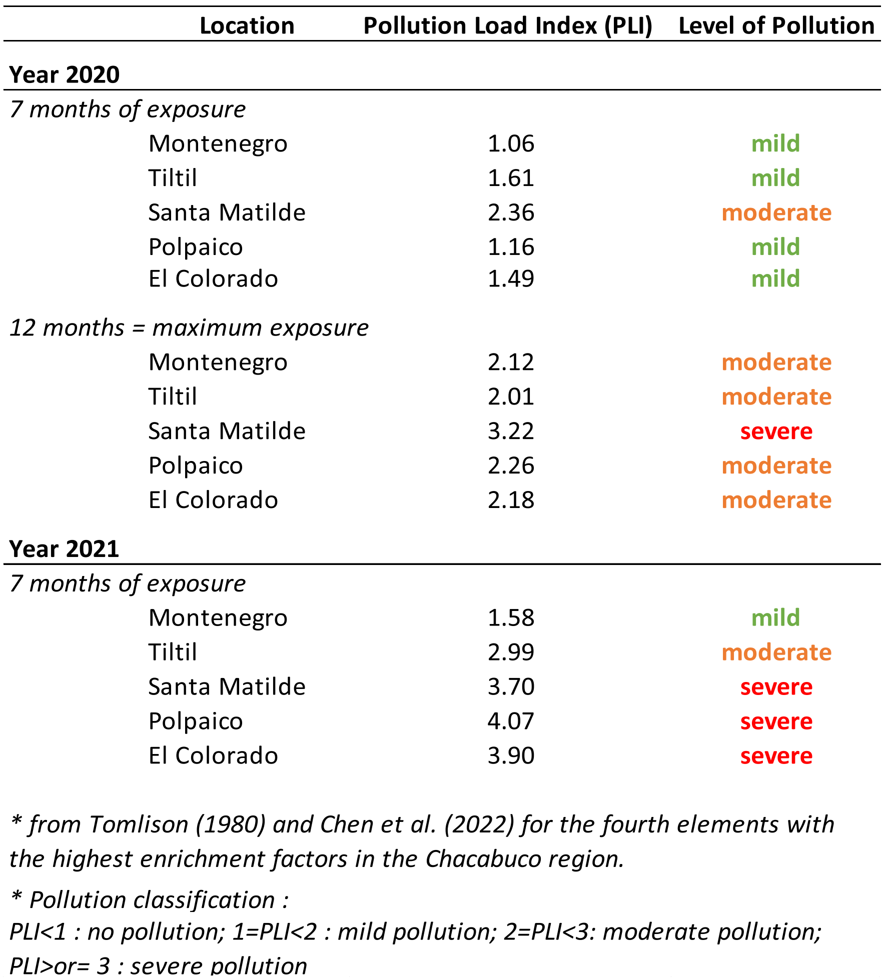
Environmental and health risk assessment

Environmental risk assessment from plants

Results of EF are presented in Table 3 for the different metal(loid)s, exposure times and locations. Table 3 shows non-significant enrichment in Ba, Cr, Ni and Pb (EF<10) in all the studied locations. By contrast, a moderated enrichment (EF>10) was clearly observed in Table 3 for Mn, especially for the longest time of exposure (twelve monthsy in 2020) for Tiltil and El Colorado, and for Cu in all sites in 2021. Arsenic and Zn showed the highest values of EF (> 10), in comparison to the Upper Earth's Crust reference, especially for Tiltil and Santa Matilde. For Zn, all the sites appeared as enriched to the same extent, considering crustal interpretation (Table 3). After studying these EF results reported in Table 3, only As, Cu, Mn and Zn were kept for PLI assessment.

Regarding PLI results (Table 4), values were calculated from *Tillandsia bergeri* data and for As, Cu, Mn and Zn for the five investigated sites in the Chacabuco province. Results show "mild pollution" after seven months of exposure at both sites in 2020 (except for Santa Matilde classified as having "moderate pollution"). When the exposure time was considered, the classification rose to "moderate pollution", except for Santa Matilde which was classified as having "severe pollution". In 2021, for seven months of

Table 4 Pollution Load Index (PLI) calculated from *Tillandsia bergeri* data for As, Cu, Mn and Zn, for the 5 investigated sites in the Chacabuco province (Metropolitan region) in Chile: Montenegro, Tiltil, Santa Matilde, Polpaico and El Colorado, in 2020 and 2021



	Location	Pollution Load Index (PLI)	Level of Pollution
Year 2020			
7 months of exposure			
	Montenegro	1.06	mild
	Tiltil	1.61	mild
	Santa Matilde	2.36	moderate
	Polpaico	1.16	mild
	El Colorado	1.49	mild
12 months = maximum exposure			
	Montenegro	2.12	moderate
	Tiltil	2.01	moderate
	Santa Matilde	3.22	severe
	Polpaico	2.26	moderate
	El Colorado	2.18	moderate
Year 2021			
7 months of exposure			
	Montenegro	1.58	mild
	Tiltil	2.99	moderate
	Santa Matilde	3.70	severe
	Polpaico	4.07	severe
	El Colorado	3.90	severe

** from Tomlison (1980) and Chen et al. (2022) for the fourth elements with the highest enrichment factors in the Chacabuco region.*

** Pollution classification :*
PLI<1 : no pollution; 1=PLI<2 : mild pollution; 2=PLI<3: moderate pollution; PLI>or= 3 : severe pollution

exposure, only Montenegro remains as “mild pollution” whereas the other sites fall under “moderate” (for Tiltil) to “severe pollution” (for Santa Matilde, Polpaico and El Colorado, median PLI values > 3).

Health risk assessment from atmospheric fallout

Results show acceptable health risks in all cases, for adults and children (Table SI-8). However, even if the total cancer risk and total hazard quotient were always below the non-acceptable thresholds (Table SI-8), arsenic appeared as the main contributor to risk, due to its high concentration in the atmosphere and its high bioaccessibility by inhalation. Zinc and antimony, which were seen as very bioaccessible, were not sufficiently concentrated in atmospheric fallout to generate a non-acceptable risk in the two investigated locations (Table SI-8). Moreover, Zn has no toxicological data reported for the inhalation pathway.

Comparing health and environmental risk assessments

Therefore, on one hand, we have results of health impacts from the fallout bioaccessibility analysis and ensuing hazard quotients and cancer risks and, on the other hand, the environmental risks from the plant experiments, that looks at enrichment and pollution loadings against background metalloid levels. Figure 4 combines the results of social representations and the perception of the risk of air pollution with the results of the chemical elements in the air. There is a clear relationship between risk perception and the measurements carried out to assess the risk of air pollution in the region. Health (H) and Environment (E) traffic light scales have been summarised at the different monitoring sites to see how these vary spatially and how they correlate with perceptions of contamination. This summary diagram shows that the area exposed to the risk of air pollution is more extensive than that perceived, including in particular the south-western part of the study area.

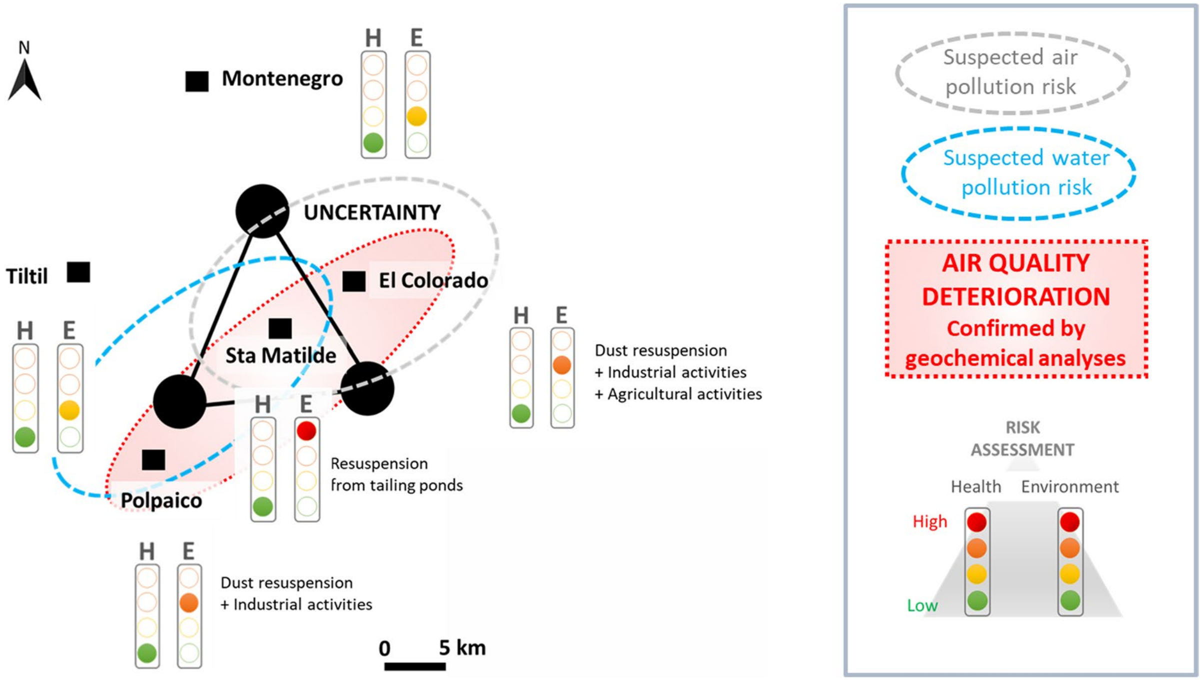


Fig. 4 Overview of environmental (E: for plant enrichment and PLI calculations) and health risks (H: for Owen gauge bioaccumulation and subsequent health risk calculations) in the Chacabuco province from geochemical data, and confrontation to human concerns (areas of suspected air or water pollution)

Discussion

Long term monitoring of atmospheric composition with *T. bergeri*

The metal(loid) contents of exposed *T. bergeri* plants were always higher than in controls, but they were site dependent and strongly affected by external factors (such as meteorological events) during exposure. Despite being a different plant species, the concentrations of As, Ni, Pb, Cu, Mn, Cr, Zn and Ba measured in our plant tissues were of the same order as those reported by Calas et al. (2024) or Schreck et al. (2020), see Table SI-9 for more details. Moreover, our measured concentrations were higher than those expressed by Figueiredo et al. (2004) and Sánchez-Chardi (2016) in Latin America (Table SI-9). But our experiment was longer than those performed in Brazil and Paraguay (Table SI-9). For the same time of exposure, the epiphyte plants exposed in the Chacabuco area recorded a lower level of trace elements in their tissues, especially for As, Cd, Zn and Pb, than those exposed to the old waste storage site of "Avenque Tailing" in the former mining site of Cartagena-La Unión in Spain.

In terms of kinetics, a linear deposition was clearly observed for Cu, Mn, Pb and Zn in Santa Matilde and Polpaico sites (in the first experiment), but results were not so clear for the other elements and sites. This linear behavior was also observed by Parente et al. (2023) for Cu and Mn (Table SI-9). Schreck et al. (2016) reported an almost linear response for As, Cd, Hg, and Sn after five months of exposure as well as observing a global increase in Zn, Pb, As and Cd over twelve months of *T. usneoides* exposure. But some non-linear accumulations have also been noticed: Parente et al. (2023) observed a non-linear accumulation behaviour of As, Ni and Hg in *T. usneoides* as their concentrations were higher after 15 days than after 45 days of exposure. In the same way, Figueiredo et al. (2004) and Martínez-Carrillo et al. (2010) reported a maximal accumulation in *T. usneoides* after about two months of exposure. These processes seem to be common over time for the different plant species, and could certainly be related to the global concentrations in the atmosphere. They also could be due to a growth dilution effect or a specific metabolism occurring in plants for some elements, as previously suggested by Schreck et al. (2016). Moreover, the kinetics of metal(loid) concentrations measured in *T. bergeri* could be explained by a seasonal effect, especially related to the leaching process caused by rainfall on the plant surfaces. This phenomenon seems to occur during the austral winter, when cumulative rainfall is higher, and certainly responsible for the drop in metal(loid) concentrations recorded in *T. bergeri.* By contrast, concentrations of As, Cu, Mn, Pb and Zn rose during the austral summer, as evidenced by the "January 2021" samples (collected before the exceptional austral summer rainfall event that occurred at the end of this month), clearly in correlation with local residents' reports of pollution perception and the presence of whirlwinds (at the exposed sites of Santa Matilde and Huertos Familiares in particular) in this season. This observation also suggests that in the absence of rainfall, due to the current mega-drought and ongoing global warming, this area is faced with the serious threat of increasing resuspension (at the surface of tailing ponds) of sulfates and other associated metal(loid)s in the atmosphere. With increasing temperatures and drought, the metal(loid) contents in the atmosphere are therefore likely to increase in the future in this residential and agricultural area.

Air quality in the Chacabuco area

Air quality in a global and local context

Generally, local studies of atmospheric contamination in Chile focus on particulate matter (PM_{10} and $PM_{2,5}$) using expensive methods that provide a precise assessment of air quality. In our study, the analysis of wet and dry deposition (corresponding to the total suspended particles, TSP) collected by Owen gauges in two contrasting sites has brought some partial information that can be compared to other studies described in the literature. Indeed, the As concentrations (16.3 - 91.8 mg kg^{-1}) remain comparable to those obtained in former mining areas in Europe as reported in Spain by Blondet et al. (2019) and Navel et al. (2015) working in the old mine of Saint-Laurent le Minier and the Vis River valley in France. A high content in Mn is also clearly identified in the atmospheric fallout of Santa Matilde and El Colorado (respectively 496.9 and 713.3 mg kg^{-1}).

These values seem specific to this area according to the literature, and were previously mentioned in Chacabuco surface waters, and more precisely in the Rungue agricultural dam, by Tchernitchin (2006) but also Le Goff et al. (2022). The Cu concentrations (260.0 and 331.5 mg kg^{-1}, for Santa Matilde and El Colorado sites respectively appear to be significantly higher than those recorded in other impacted sites around the world, due to the naturally enriched geochemical background in Chile (Valdés Durán et al., 2022). Concentrations of Pb, Ni and Zn are however clearly lower than those reported in atmospheric fallout in mining areas in Europe (Blondet et al., 2019; Navel et al., 2015). Even if we only focused on the TSP in this study, all the measured concentrations are in accordance with data presented during the environmental monitoring committee of Colina[5] in January 2020 (personal communication of the head of community relationship of Anglo American®, 2020). This monitoring reported the existence of maximum levels for short periods during most years that exceed the Chilean 24 hours average standards (130 µg/m^3 for PM$_{10}$ and 50 µg/m^3 for PM$_{2.5}$) at 2 measurement points: Las Tórtolas tailing deposit and the road control to the SE of the deposit. This document also evidenced that PM$_{10}$ is dominant from September-November to March while PM$_{2.5}$ is usually dominant from March-May to July. Diaz (2013) measured PM in Las Tórtolas in January 2013 with a Dustmate hand held Particulate Matter instrument and showed highly varying PM$_{10}$ values reaching over 1000 µg/m^3 in the afternoons, whereas the PM$_{2.5}$ stayed low. However, the PM$_{2.5}$ peaks appear particularly concerning as these fine particles can penetrate deeply into the pulmonary alveoli and consequently affect human health (Goix et al., 2013; Tran et al., 2023).

Air quality and environmental impact

Results of PLI from the *T. bergeri* experiments concluded that atmospheric contamination exists in the Chacabuco area, increasing with the time of exposure in all the sites. In 2020, the atmospheric status after one year was qualified with “moderate pollution” in all sites (except for Santa Matilde classified with “severe pollution” in accordance with our previous results). In 2021, the classification became more severe with the El Colorado and Polpaico sites classified as having “severe pollution”, after only seven months of exposure. This observation could be explained by interannual variations, due to climatic conditions, but also due to the shutdown of several industries (including mining ones) during the lockdowns of the pandemic between March 2020 and March 2021 (Cámara de Diputados de Chile, 2020). These PLI values were higher than the PLI calculated by Chen et al. (2022), for whom “none” to “mild pollution” has been found in different sites of Wuhan and Yichang in China using pine needle bioindicators of air quality. Also the PLI calculated in the Orbiel valley in France by Calas et al. (2024) were lower (“moderate” for two exposed sites but “mild pollution” for urban and agricultural ones). Nevertheless, it is also important to point out that, in the case of the Chacabuco province, fewer elements have been selected for this risk analysis (with EF results), certainly explaining the higher gradation of pollution levels obtained.

Air quality and health risk

Calculations using the US EPA risk assessment had concluded that there was no risk for the local population, at all the sites investigated (Table SI-8). Yet, as mentioned in the WHO report (World Health Organization, 2022), there is no threshold below which no damage to health is observed for fine particle atmospheric pollution. High concentrations in metal(loid)s, particularly in the Santa Matilde area, could become of high concern as the health risk assessment reported a pulmonary bioaccessible fraction of about 20 % for As and Zn (Table 2), especially considering that the finest bioaccessible fraction of aerosols is the one that most affects human health (Goix et al., 2013). Moreover, it remains important to reiterate that health risk calculation could have been different if only the inhalable fraction (PM$_{10}$ and finer particles, as measured by authorities) had been considered in the risk assessment instead of the TSP, especially as the finest particulate matter (PM$_{2.5}$) in the ambient atmosphere that has been found to be strongly associated with adverse health effects (Park et al., 2018) whereas the TSP cannot be directly related to human health risks.

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[5] https://chile.angloamerican.com/~/media/Files/A/Anglo-American-Group-v5/Chile/medios/boletin-los-bronces/comunidad-cobre-octubre-2020.pdf

Identification of anthropogenic sources of metal(loid)s

Arsenic, Zn and Cu are the metal(loid)s showing the highest enrichment factors in *T. bergeri* in comparison to the Upper Earth's Crust reference (Taylor & McClennan, 1985), especially for Tiltil and Santa Matilde. These EF results should be nuanced because the pedogeochemical background in the Chacabuco area is naturally enriched in metal(loid)s, especially in Cu or As, as elsewhere in Chile because of the geochemical formations of the Andes Mountains (Tapia et al., 2018). But as reported by Pellegrini et al. (2014) or Esmaeilirad et al. (2020), EF >> 10 (as in Santa Matilde but also Tiltil to a lesser extent in our study) indicates atmospheric contamination due to anthropogenic sources (mining storage, industrial activities, traffic density…). The highest concentrations of metal(loid)s accumulated in exposed epiphyte plants (especially As, Cr and Zn) were observed in the location of Santa Matilde. The atmospheric fallout study confirmed this observation as the highest contents in metal(loid)s were systematically observed in Santa Matilde rather than in El Colorado (except for Cu and Mn). This observation could be certainly explained by the location of the Santa Matilde site, exactly between the two mine tailing ponds from porphyry copper mining (Fig. 1), and then highlights a potential atmospheric metal(loid) spread, with wind as the main dispersion factor. As observed by Zanetta-Colombo et al. (2022), characterizing metal concentrations in dust collected from roofs and windows of houses from the Alto El Loa area (North Chile), toxic elements (As, Sb, and Cd), potentially responsible for health risk, can be transported as particles from the tailings up to 50 km away. As recently suggested by Herrera et al. (2023) working in the Chacabuco area, a contribution of minerals related to the intrusive rocks was proposed, which would originate from the movement of fine particles by the wind from the tailing ponds to the ground, even if this contribution is considered as minor. Tchernitchin and Herrera (2006), also working on the Chacabuco and Polpaico area, attributed the atmospheric contamination to mining activities, and more precisely the resuspension of particulate matter, which contains high concentrations of sulfates and various metals in its composition, particularly Pb and Ni. Indeed, an increasing deposition mechanism also appears to be emerging for Cu and Pb at this site of Santa Matilde. The mining companies seem to be aware of this problem and are trying to reduce the phenomenon by incorporating new technologies to reduce dust emissions (Anglo American®, 2020). The fact that mining companies are running out of water too could partly explain why, under the combined effect of the megadrought and the impossibility of applying water to its mine tailings, the dust is increasingly mobilized by wind erosion.

For the second experiment, three locations evidenced the highest metal(loid) concentrations in *T. bergeri*. In addition to Santa Matilde, Polpaico and El Colorado highlight a potential influence of external sources of toxic metals, even if EF were relatively low in El Colorado. Although Si is a good marker of clay depositions (due to soil resuspension), its presence in Polpaico samples observed by SEM-EDX could be explained by the vicinity of the cement factory "Cemento Polpaico". The same observations have also been reported in Huertos Familiares, maybe due to the presence of the "Ceramica Santiago SA" plant in Batuco.

El Colorado is also concerned by contamination from agriculture since some elements (Cu, Ni, Zn, Mn) are known to be widely sprayed as agrochemicals (fungicides or fertilizers) for perennial crops (vineyards, orchards). Agricultural activities are reported to be responsible for pollution dispersion in Chile (Castillo et al., 2021), as elsewhere in the world (Ali et al., 2019). Then, even though Cu is widely extracted in all the Chilean territory, it can also come from agricultural issues as it is widely used as a fungicide (Castillo et al., 2021).

Moreover, the observations in *T. bergeri* were also in agreement with the results of Owen gauge's deposits analyses, suggesting different sources of metal(loid)s in the atmosphere according to each site. Indeed, metal(loid) concentrations (except for Cu and Mn, usually sprayed in agricultural areas) measured in Owen gauges were the highest in the Santa Matilde site, between the 2 tailing ponds. Moreover, their mineralogy also confirmed different sources of metallic pollution. The presence of scorodite in the Santa Matilde gauge could be attributed to potential widespread occurrence of arsenopyrite and arsenian pyrite (Blowes et al., 2014), from mine tailing's storage ponds. By contrast, pharmacolite is often observed in industrial areas when As-bearing water interacts with the underlying limestone substratum, which could be the case in El Colorado area (Zhu et al., 2022).

Confrontation between human concerns and geochemical data

The global analysis of the cognitive maps drawn by the inhabitants show that the risk of air pollution by resuspended particles was mainly identified in the northeast part of the Chacabuco province, framed by industrial and mining activities, while the risk of water pollution was more perceived in the southwest part (Figure 2). The study of social perception concluded that cohabitation with industries had led to a global and multidimensional degradation of the quality of the environment and the quality of life of local populations. The risk of pollution linked to the presence of nuisance-producing industries was regularly and clearly denounced by the inhabitants of the municipality of Tiltil, whose regional planning has transformed it into an environmental sacrifice zone (Jorge et al., 2020, Figure SI-4). Besides, the identification of harmful and polluting industries producing raw materials often destined for export or receiving residues from the entire Metropolitan region, this highlights the presence of socio-environmental inequalities, but also a feeling of injustice among the inhabitants (Jorge et al., 2020; Le Goff, 2024). There was an overlap, even a sectorization, of environmental quality issues, which supports the idea of a sacrifice zone as suggested by Paegelow et al. (2022), who had already highlighted a higher vulnerability of the province to water-related risks on the scale of the Santiago Metropolitan region and a major multi-criteria fragility of the municipality of Tiltil. Taking risk perception and social representations into account is therefore relevant for providing responses to populations, informing public policies and better anticipating and managing socio-environmental crises.

Therefore, by comparing the results of cognitive maps and geochemical data, we appear to have answered the main question of this study: Does the uncertainty about air quality felt by the local population translate into the existence of evident environmental and health risks? The answer is clearly “YES” as shown by the overlay of maps proposed as a general conclusion in Figure 4.

Conclusion

This innovative study has combined data from social sciences, through a series of semi-structured interviews and cognitive mapping, with two biomonitoring experiments and their geochemical analyses. The use of a new epiphyte plant species, i.e. *T. bergeri*, at five strategic sites of the Chacabuco province permitted an investigation of the long-term effects over several months. This biomonitoring tool could become extremely powerful, because it can create a new dynamic around participatory science. This study also highlighted the influence of abiotic factors as drivers of air composition and metal distribution from the identified sources. Even if the local health assessment after inhalation in this area evidenced no risk for the local population, the determination of enrichment factors as well as indexes of pollution have permitted a better description of the environmental status, which should be considered as degraded. With the added pressure from climate change that could involve more drought, resuspension of sulfate particles from the basins, or flash flood episodes on ultra-dried soils, as well as chronic exposure of inhabitants with long-term impacts, this evaluation needs to be considered of concern. Accordingly, our socio-environmental study of air quality in northern Chacabuco province validates and complements the identification of the province as an environmental sacrifice zone and brings new insights for its better management.

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Author's contributions ES, LLG, FB and AP were in charge of the study conceptualization. The methodology was designed by ES (for geochemical analyses), FB, LLG and AP (for social surveys) and performed by ES, LLG, CB, AC, AY, CB, MM and XML. The field study was performed by ES, LLG, FB and CB. The software gestion was done by LLG, AC, CB and AY. ES, LLG, ZLF, AY and AC were involved in data curation. Concerning writing, original draft preparation was performed by ES, ZLF, CB, AVR and LLG whereas all authors were involved in reviewing and editing. AP and ES were the two supervisors of the study, they assure with LLG and ZLF all the validation of the study and the manuscript revision.

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Data availability No datasets were generated or analysed during the current study.

Declarations

Conflict of interest The authors declare no competing interests.

Consent to Participate Informed consent was obtained from all individual participants included in the study.

Consent to Publish The authors affirm that they have collected consent from individuals (interviewed inhabitants from the Chacabuco province, Chile) to publish their data prior to submitting their paper to ESPR. Additional informed consent was obtained from all individual participants for whom identifying information is included in this article.

Ethical approval This is an observational study. The University of Toulouse (France) Research Ethics Committee has confirmed that no ethical approval is required.

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