Science of the Total Environment 920 (2024) 170954

Contents lists available at ScienceDirect

Science of the Total Environment

journal homepage: www.elsevier.com/locate/scitotenv

When another one bites the dust: Environmental impact of global copper demand on local communities in the Atacama mining hotspot as registered by tree rings

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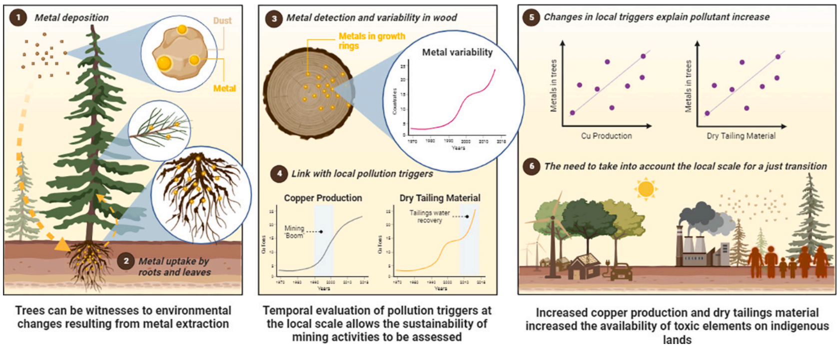
HIGHLIGHTS

- Tree-rings reveal the temporal distribution of metal(loid)s in an area historically affected by mining activities.
- During the 1990s, there was increased exposure to metal(loid)s on these indigenous lands.
- The recovery of water from tailings dams may lead to increased metal(loid)s emissions from dry sediments.
- The energy transition scenario could lead to an increase in the availability of metal(loid)s in local environments.

GRAPICAL ABSTRACT



ARTICLE INFO

Editor: Elena Paoletti

ABSTRACT

Assessing the impact of mining activity on the availability of environmental pollutants is crucial for informing health policies in anticipation of future production scenarios of critical minerals essential for the transition to a

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[1] Deceased 19 November 2023.

https://doi.org/10.1016/j.scitotenv.2024.170954
Received 23 December 2023; Received in revised form 2 February 2024; Accepted 11 February 2024

Keywords:
Environmental monitoring
Mining emissions
Tailings management
Indigenous communities
Historical pollution

net-zero carbon society. However, temporal and spatial monitoring is often sparse, and measurements may not extend far enough back in time. In this study, we utilize variations of chemical elements contained in tree-rings collected in local villages from an area heavily affected by copper mining in the Atacama Desert since the early 20th century to evaluate the temporal distribution of pollutants and their relationship with local drivers. By combining time-varying data on local drivers, such as copper production and the dry tailings deposit area, we show how the surge in copper production during the 1990s, fueled by trade liberalization and increased international demand, led to a significant increment in the availability of metal(loid)s related to mining activities on indigenous lands. Our findings suggest that the environmental legislation in Chile may be underestimating the environmental impact of tailing dams in neighboring populations, affecting the well-being of Indigenous Peoples from the Atacama mining hotspot region. We argue that future changes in production rates driven by international demand could have negative repercussions on the environment and local communities. Therefore, mining emissions and the management of tailing dams should be carefully considered to anticipate their potential negative effects on human and ecosystem health.

1. Introduction

Chile is a dominant player in the global copper market, serving as the largest producer of this essential mineral crucial for the energy transition. In 2022, Chile accounted for 27 % of the international demand for copper, producing approximately 200,000 tons and holding 21 % of world's reserves (U.S. Geological Survey, 2023). Looking ahead, the significance of Chile's role is expected to intensify. This projection aligns with the anticipated surge in copper-dependent low-carbon energy and the electrification of transportation technologies in the coming years (Schipper et al., 2018). Given the current scenario of the energy transition needed to achieve the Paris Agreement goal of limiting warming to 2 °C, it is expected that copper production will need to increase by >350 % to meet the estimated demand of 29 million tons by 2050 (World Bank, 2020). The history of copper production in Chile has witnessed fluctuations since the early 20th century, primarily due to international demand, with a remarkable surge during the 1990s. This significant increase was propelled by the opening of the Chilean economy to the global market, following a neoliberal economic model imposed by the civil-military dictatorship (Lagos, 1997). The massive influx of foreign investments that led to the establishment of new mining operations and an increased demand for state-owned production resulted in a phenomenal upswing in copper production and export rates during the 1990s (Fig. 1). Most of the copper mining in Chile is located in the Atacama Desert, within or adjacent to Indigenous Peoples' protected lands (Fig. 2). While the mining industry has been a key driver of economic growth for Chile (Lagos and Blanco, 2010), concerns have been raised regarding the potential environmental and health risk that

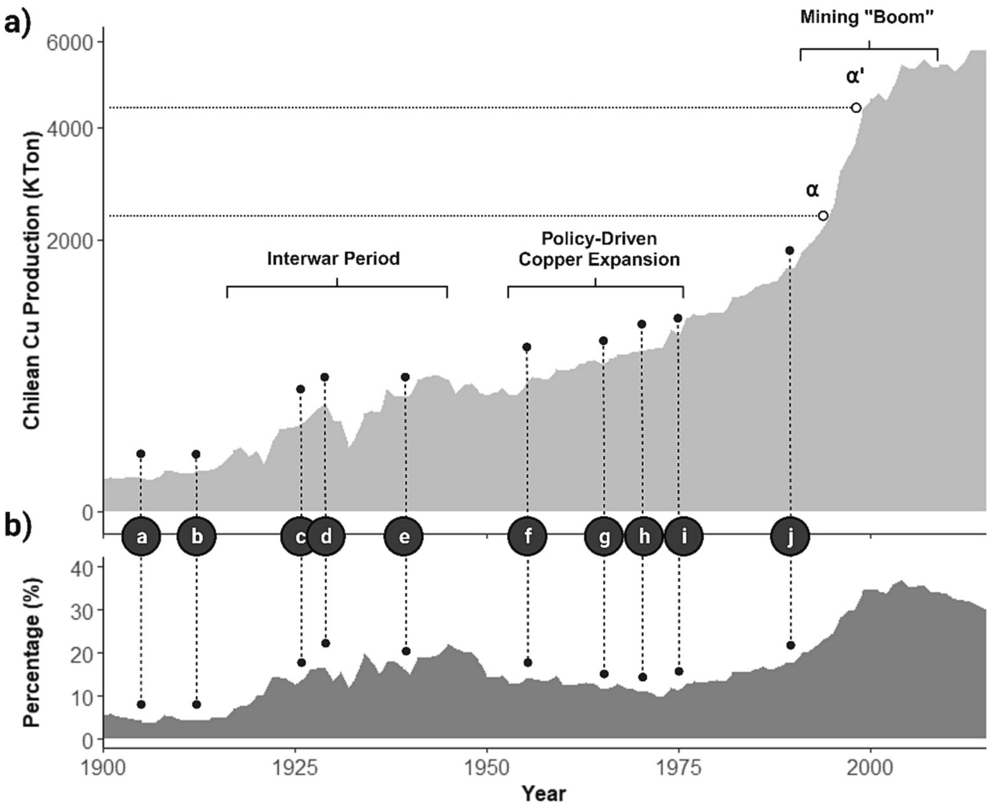

Fig. 1. (a) Chilean copper production spanning the period 1900 to 2015. (b) Variability of the Chilean copper production as a percentage of the global demand. A pronounced surge in demand for Chilean copper is linked to mid-20th-century global conflicts (World Wars) and economic downturns. A similar situation unfolded in the early 1990s, marked by an unprecedented increment of >2000 Ktons in just six years (from 2055 ktons in 1993 (α) to 4391.2 ktons in 1999 (α')), accompanied by a notable increase in its global market share from 21.7 % to 34.4 %. The circles accompanied by letters denote significant events: a) 1904: Introduction of the Flotation Process; b) 1914: World War I; c) 1927: Establishment of the Mining Credit Bank; d) 1929: The Great Depression; e) 1939: World War II; f) 1955: Foundation of CODELCO; g) 1966: The 'Chilenization' of copper; h) 1971: Nationalization of 'Gran Minería'; i) 1973: Implementation of a new privatization strategy for copper; j) 1990: The 'Mining Boom'. Details of the events mentioned in Collier and Sater (2004).

the transition to clean energy could pose to Indigenous communities (Zanetta-Colombo et al., 2022). As the global demand for copper and other conductive elements continues to rise to contribute to the ambitious zero-emission targets, it becomes crucial to analyze and understand the temporal dynamics of contaminants derived from mining activity in Chilean extractive territories within a long-term perspective. This presents a challenge given the limited and sporadic monitoring, which impedes a comprehensive analysis and severely constrains the historical perspective. Therefore, there is a need to enhance the available data on polluting emissions and their temporal patterns across the country.

Tree-rings represent one of the most conspicuous proxies used to monitor past climate and environmental variability and changes (Hughes et al., 2011). Given that tree growth is determined by the interactions of chemico-physical and biological factors that can be registered in tree-rings, this proxy can be used to assess temporal environmental variations related to chemical anomalies and determine metal(loid)s availability in soil and air over time. These anomalies serve as indicators of deviations from anticipated or baseline environmental conditions, allowing us to elucidate periods marked by heightened metal(loid) deposition or other noteworthy environmental shifts (Binda et al., 2021; Burken et al., 2011a). Trees can act as a historical repository of pollution, storing various pollutants, including metal(loid)s, within their annual growth rings and offering environmental records beyond the time period of instrumental records or in areas where such data are not available. This provides a unique perspective on the study of environmental changes at the local scale, offering distinct advantages over other paleoecological methods commonly employed for regional and global-scale assessments (such as ice core and lake sediments) to asses pollution and unravel the impacts of mining on ecosystems (Balouet et al., 2012; Dobrzańska et al., 2021; Rocha et al., 2020; Watmough and Hutchinson, 2003). Dendrochemical analyses can provide records at an annual resolution, allowing for the identification of short-term fluctuations and long-term trends of pollution (Burken et al., 2011b; Padilla and Anderson, 2002).

This study aims to evaluate the temporal variability of metal(loid)s in two indigenous villages in the Atacama Desert using dendrochemical analysis. Additionally, we seek to understand the relationship between this variability, copper production, and the presence of dry sediments in the nearest tailing dam. We utilize Micro X-ray Fluorescence (μXRF) to measure a total of 23 chemical elements and their variations in tree-rings over the last ~50 years. This rapid and non-destructive technique has been successfully employed in other dendrochemical studies to determine pollution (Balouet et al., 2012; Latimer et al., 1996; MacDonald et al., 2011; Rocha et al., 2020). The targeted chemical elements encompasses both geogenic (naturally occurring) and mining-associated elements previously reported in the literature. We hypothesize that the rise in local copper production and the expansion of the dry area within the tailing dam will increase the presence of metal(loid)s within the tree rings of the indigenous villages. This is because an increase in mining dust emissions will be transported to and impact the indigenous communities. By unraveling these intricate connections and comprehending

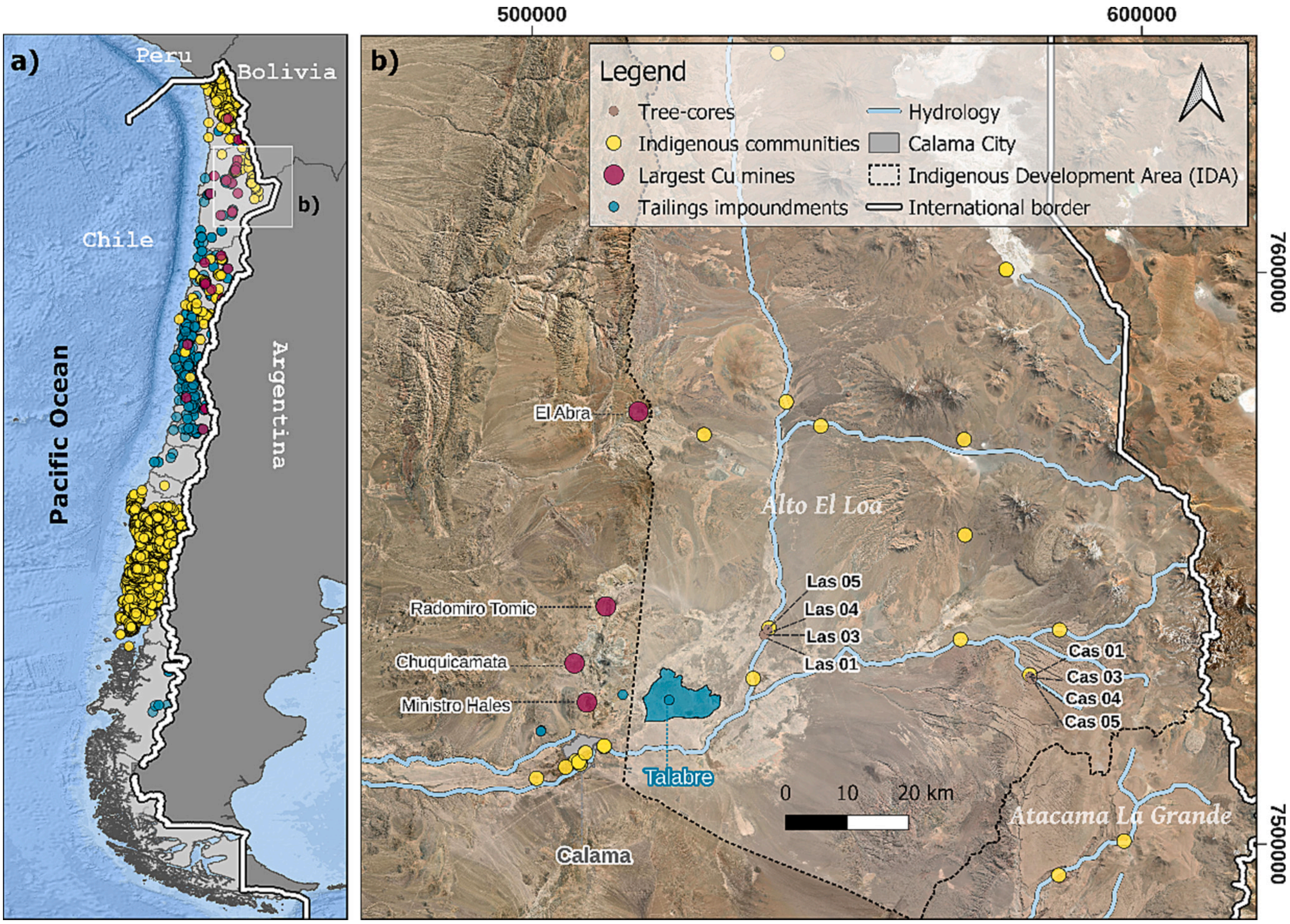

Fig. 2. Location of major copper mines, tailing impoundments, and indigenous communities at: (a) national, and (b) local (Alto El Loa region) scales. (a) Illustrate the nationwide distribution of major copper mines, tailing impoundments, and indigenous communities, respectively. Pink dots denote copper mine locations, light-blue dots and polygons in (b) represents tailing impoundment sites, and yellow dots indicates indigenous community locations. In panel (b) one can note that the Talabre tailings impoundment area is larger than Calama city, the major urban center close to the mining complex (depicted as a grey polygon).

the enduring repercussions of mining activities at the local scale, our study, based on a case in the globally significant mining hotspot of the Atacama Desert, offers valuable insights that transcend regional boundaries. The findings contribute essential considerations for improving mining practices in Chile and globally, especially in extractive territories in the Global South.

2. Materials and methods

2.1. Sample location

The present study focuses on the Alto El Loa Indigenous Development Area (IDA) in the Antofagasta Region of northern Chile, where large-scale copper mining has been ongoing since the early 1900s in the core of the Chilean copper mining hotspot region. Previous research has revealed significant socio-environmental conflicts between the mining industry and local communities, especially in terms of contradictory social disruptive relationships (Calderón-Seguel and Prieto, 2023), water use an allocation (Prieto et al., 2022), and emissions of metal(loid)s (Zanetta-Colombo et al., 2022). We chose two study sites, incorporating the villages of Lasana and Caspana, situated 10 km and 50 km east, respectively, and downwind from the mining complex, comprising mines and the Talabre tailing dam. These locations, along with the local mines, tailing dam, and the city of Calama, are illustrated in Fig. 2.

2.2. Sample collection

We sampled a total of eight tree individuals of *Cupressus macrocarpa* (Muñoz et al., 2019) in the Alto El Loa area; four in the village of Lasana and four in the village of Caspana (~10 km and ~ 50 km from the Talabre tailings impoundment, respectively). For each individual, we extracted two samples of increment cores perpendicular to each other at breast height (1.3 m) using a 10 mm diameter increment borer made of hardened steel (HAGLÖF SWEDEN®, Forestry Suppliers, Inc., Jackson, MS). The collected samples were placed inside plastic straws to preserve them during transportation to the laboratory and were subsequently air-dried before processing. Fig. 2b shows the location of the samples in the context of Alto El Loa. *Cupressus macrocarpa* is a species introduced as an ornamental tree across Chile, and in the Alto El Loa area where planting programs led by the Chilean Forest Service (CONAF) took place during the 1970s. We selected this tree species because it had previously been used successfully in dendrochemical studies to determine the temporal variability of metal(loid) pollution in industrial areas of central Chile (Muñoz et al., 2019).

2.3. Laboratory analysis

Thin laths, each 1.2 mm in thickness, were cut out from each of the increment cores using a high precision twin-bladed saw (DendroCut, Walesch Electronic, Switzerland). Subsequently, the laths were x-rayed in an Itrax Multiscanner (Cox Analytical Systems, Sweden) at the DendroGreif tree-ring laboratory at the University of Greifswald, Germany. The Multiscanner, equipped with a 1.9 kW Cr-tube operated at 30KV and 50 mA, as used for this purpose. The annual rings of each sample were counted, visually cross-dated, and the calendar year of each ring was assigned from the most recent ring according to the year in which radial growth started. Crossdating accuracy was verified using statistical parameters provided by the dplR package (Bunn, 2008), statistics from the different chronologies are presented in Table S1. Then, thin laths of the tree-ring samples were exposed to the high intensity X-ray beam for 10 s at each measurement point, advancing in radial direction in 50 μm steps. The X-ray fluorescence energy excited on the samples was continuously recorded by a silicon drift chamber detector (SDD). Simultaneously, transmitted X-rays were captured by a digital camera to produce a radiographic greyscale image. Peaks in the continuous XRF spectrum were assigned to specific elements using the Q-spec software (Cox Analytical system, Sweden), resulting in relative concentrations (countrates of fluorescent photons) for pre-defined elements for every analyzed point. The selected elements included Al, As, Ba, Ca, Cd, Cl, Cu, Fe, K, Mg, Mo, Nb, Ni, P, Pb, S, Sb, Si, Sn, Ti, V, and Zn. To account for the matrix effect of changing wood densities, all values were divided by the coherent scatter (Scharnweber et al., 2015, 2023). The radiographic images were then used to assign the element-specific countrates of every measurement point to each annual rings. For this purpose, the annual ring boundaries were defined on the radiographic image using WinDendro (Regent Instruments, Canada), and the pixel-based output of the element's measurements were used to produce a countrate value of each chemical element for each annual ring. Mean, maximum and minimum annual time series of the elemental countrates were obtained.

2.4. Data analysis

2.4.1. Dendrochemical data

The mean annual countrate values from each tree were averaged among the trees at each study site to create element-specific site chronologies of each chemical element in the Lasana and Caspana villages. These chronologies of chemical elements covered the period 1970 to 2018 and 1970 to 2017 in the villages of Lasana and Caspana, respectively. These periods at each site ensured that at least two trees covered the corresponding years, as depicted in Fig. S1. The suitability of the chemical element chronologies for factor analysis was assessed using the Kaiser-Meyer-Olkin (KMO) factorial adequacy test. The KMO Measure of Sampling Adequacy (MSA) serves as a metric to evaluate the extent to which underlying factors could contribute to the variance in the variables. Elevated KMO values ($MSA > 0.5$) suggest that conducting a factor analysis with the data is advantageous. Conversely, if the value falls below 0.5, the results might not provide meaningful insights (Kaiser, 1974). We employed a Principal Component Analysis (PCA) approach to reduce the dimensionality of the elements chronologies dataset and identify the main underlying patterns of temporal variability. This statistical technique enabled the extraction of key components that accounted for most of the variance in the original data, providing a simplified representation of the complex temporal relationships between variables. We utilized the non-parametric Mann-Kendall test to identify the components exhibiting significant temporal trends.

2.4.2. Local pollution triggers

In this study we identify local pollution triggers based on previous research that assessed the influence of emission from mining operations, including open-pit mining, and the Talabre tailings impoundment (66 km^2), on the spatial distribution of metal(loid) concentrations in settled dust in the Alto El Loa (Zanetta-Colombo et al., 2022). These drivers significantly affect the spatial distribution of metal(loid)s in the Alto El Loa region and are mentioned below.

[1] Variability of copper production at the local scale: We assumed that higher copper production would correspond to increased dust emissions due to larger volumes of soil movement and corresponding industrial emissions. Based on this, we collected data on copper production from operations within the Alto El Loa mining region, including Chuquicamata, Ministro Hales, Radomiro Tomic, and El Abra. The production data, measured in thousands of tons (ktons), were obtained from The Chilean Copper Commission (COCHILCO) official data covering the period from 1960 to present (COCHILCO, 2023). By summing the annual production levels for the specified mining operations, we developed the variable representing copper production in Alto El Loa denoted as AEL.

[2] Variability of (dry) sediments in the Talabre tailings impoundment: This factor is associated with the fluctuation in the extent of the area of dry sediments within the Talabre tailings

impoundment, emerging as a noteworthy contribution to local pollution. Upon discharge, the tailing exhibit a composition comprising 45.1 wt% solids and 54.9 wt% water (Smuda et al., 2014). Due to the high solar radiation, extremely low surface humidity, and drainage, the tailings experience substantial evaporation, leading to unsaturated vadose zones and exposing dry sediments that can be transported by winds up to 50 km (Zanetta-Colombo et al., 2022). To characterize the temporal variability in the Talabre tailings' dry sediments, we employed a series of processes. First, a Principal Component Analysis (PCA) was conducted on multispectral satellite imagery to enhance the identification of tailings sediments and establish appropriate annual boundaries (Fig. 3). The PCA method, widely used in remote sensing for various purposes such as mineral mapping and tailings sand separation, allowed us to reduce the number of correlated spectral bands to a few uncorrelated ones, emphasizing the highest spectral contrast in bright, similar surfaces (Hao et al., 2019; Lillesand et al., 2008; Mazhari et al., 2017). To detect the area of dry material on the surface of the Talabre tailing dam, the Normalized Difference Water Index (NDWI) (McFeeters, 1996) was calculated as an annual mean for every year (one image per month) between 1985 and 2019 (see Table 1). The NDWI, based on Landsat data, uses spectral reflectance in the Near-infrared Band (NIR) and the Green Band (G) to assess the presence of water content. Utilizing a threshold ($>$0.015) for wet tailings obtained from Hao et al. (2019), the NDWI allowed us to discern dry sediments on the tailing dam's surface. The temporal variables obtained from these analyses for the Talabre tailings impoundment include the area of the tailings impoundment (TA), the area of dry sediments within the tailings (DTA), and the percentage of dry sediments concerning the total impoundment area (DTA %).

2.4.3. *Relationship between local pollution triggers and metal(loid) availability in the environment*

We employed three pivotal analytical approaches to scrutinize the intricate relationships among metal(loid)s availability, local mining influence, and environmental changes. Spearman correlation analysis was initially applied to unveil broad associations between metal(loid)s availability in study areas and local pollution factors (Spearman, 1904). Subsequently, we implemented moving correlations using the rollapply function from the zoo package (Zeileis and Grothendieck, 2005) with a window size of 10 years to systematically identify critical periods within the analyzed timeframe. This selection of a 10-year window aligns with our objective of capturing both long-term trends and potential cycles in metal(loid)s availability, especially those influenced by environmental changes and local mining activities. Finally, regime shift detection analyses were conducted to pinpoint pivotal junctures where alterations in mining activity could influence corresponding changes in metal(loid)s availability (Rodionov, 2015).

Table 1
Satellite data used to characterize the Talabre tailings impoundment.

Data	Temporal range
Landsat 5 TM	1985–2011
Landsat 7 ETM+	2012
Landsat 8 OLI	2013–2019

Through these analyses, we aimed to comprehensively determine the relationship between local pollution drivers and environmental changes driven by metal(loid) pollution, contributing to a long-term evaluation of mining activities on the local pollution of neighboring villages. All figures were generated using the ggplot2 package in R Studio (version 2022.07.0) (Wickham, 2016).

3. Results

3.1. *Temporal patterns of chemical elements presence*

Fourteen and sixteen chemical elements from the Lasana (Al, Ca, Cd, Cl, Fe, K, Mg, Nb, Ni, Pb, Sb, Sn, Ti, and Zn) and Caspana (Ca, Cd, Cl, Cu, Fe, K, Mo, Nb, Ni, P, S, Sb, Si, Sn, V, and Zn) villages, respectively, passed the KMO test (KMO $>$ 0.5) and were subjected to Principal Component Analysis (Table S2 and Fig. 4a). For the study period (1970–2017), in the village of Lasana the first principal component (PC1-Las) explained 41 % of the common variance between elements, and in Caspana PC1 (PC1-Cas) explained 37 % of the variation. Strong and moderate loadings were observed for the elements Cd, K, Cl, Fe, Sn, Ca, and Sb in PC1, indicating their significant contribution to the main temporal mode of variation in both villages. Most of these elements are linked to pollution resulting from mining activities (Csavina et al., 2012) and demonstrated a pronounced increasing trend since the late 1980's (Mann-Kendall score of 832 for PC1-Las and 829 for PC1-Cas, p-value $<$ 0.001) (Fig. 4b). Additional details on the KMO factorial adequacy test, PCA, Mann-Kendall test, and other obtained components can be found in Tables S2, S3, and S4 in the Supplementary material.

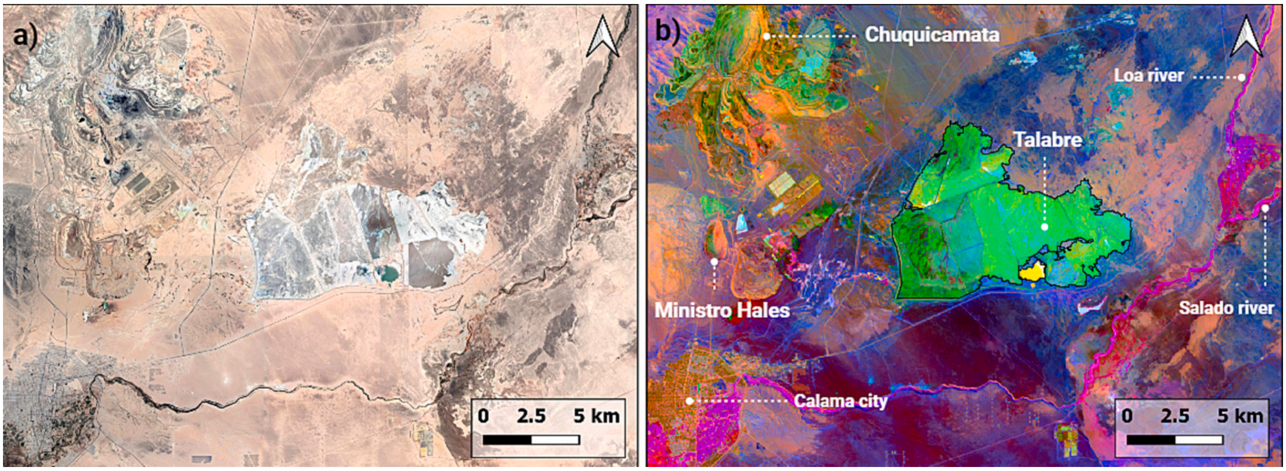

Fig. 3. Landsat 8 OLI image of year 2019 showing the Talabre tailing dam at the right and the Chuquicamata and Ministro Hales cooper mines. (a) true colour image, and (b) PCA bands 3-2-1 and expert-based delimitation of the tailing dam.

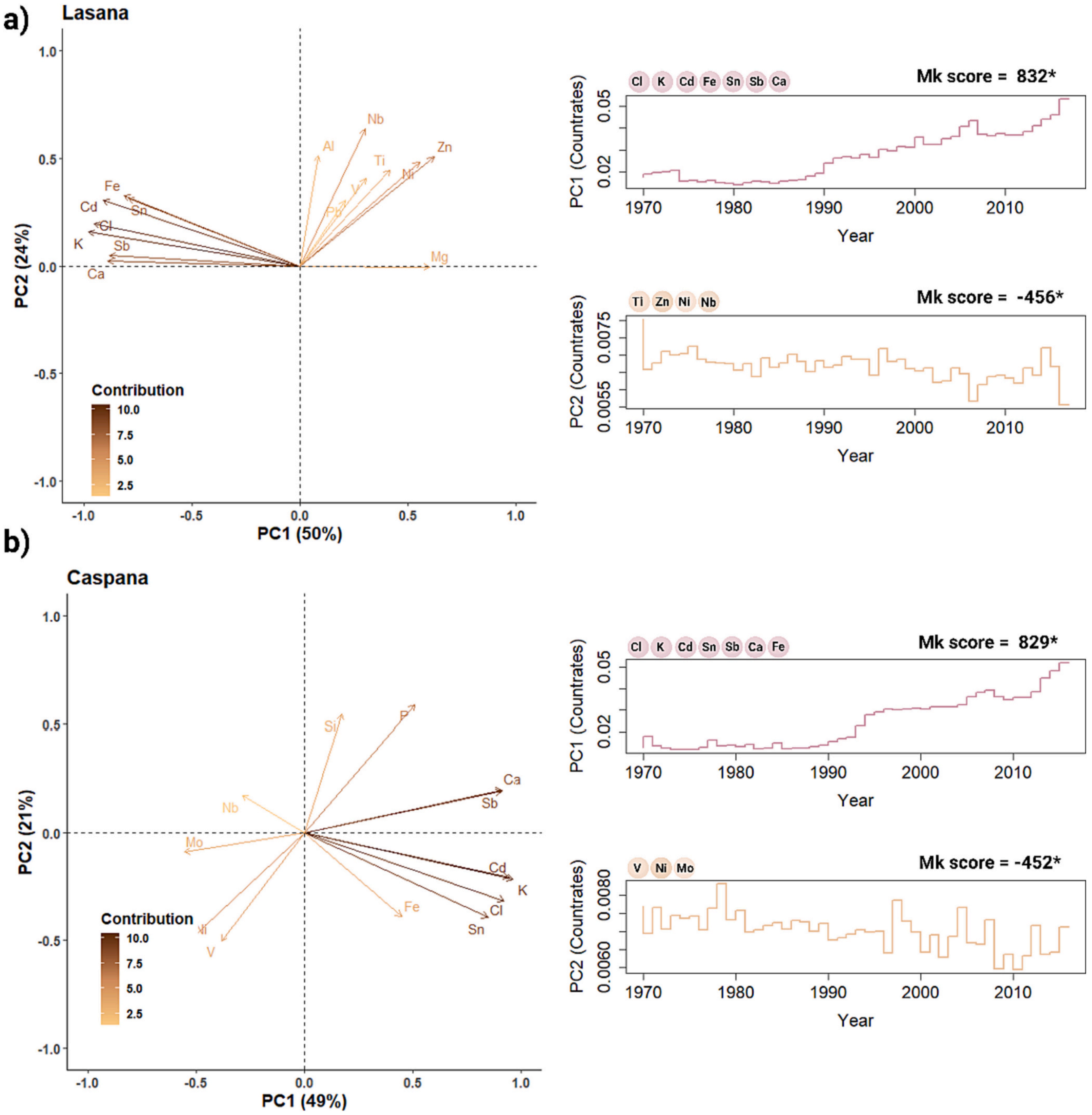

Fig. 4. Principal component analysis (PCA) of the temporal availability of polluting elements in the (a) Lasana and (b) Caspana villages contained in the tree-ring samples during the period 1970 and 2018 (right panel), and the respective time series of the main modes of variability (left panel). The Mann-Kendall test result is indicated in the time series (Mk Scores, *p-values < 0.01).

3.2. Relationships between local potential drivers and metal(loid)s

3.2.1. Correlation analysis

The correlation analysis in Fig. 5 highlighted positive and statistically significant relationships among most variable pairs. Specifically, AEL demonstrated a noteworthy positive correlation ($r = 0.6$, $p < 0.001$) with both TA and DTA throughout the study period ($r = 0.56$, $p < 0.01$). Furthermore, robust positive correlations were observed between AEL and PC1-Las ($r = 0.6$, $p < 0.001$) and PC1-Cas ($r = 0.6$, $p < 0.001$). Notably, there were even more pronounced positive correlations between DTA and PC1-Las ($r = 0.96$, $p < 0.001$) and PC1-Cas ($r = 0.95$, $p < 0.001$).

3.2.2. Moving correlations

Moving correlations between variables revealed a dynamic association pattern over time (Fig. 6). During the 1990s mining boom period, strong and positive correlations were observed between AEL and PC1-Las and PC1-Cas. However, during the mid-2000s, this correlation decreased and became inverse. Similarly, the moving correlations between DTA and PC1-Las and PC1-Cas exhibited a positive association during the mining boom period. The connection between DTA and PC1-Las, as well as PC1-Cas, began to diminish in the early 2010s. Notably, there was a more recent positive association between these variables from the mid-2000s to the early 2010s. This differed from the relationship observed between AEL and PC1-Las and PC1-Cas during the

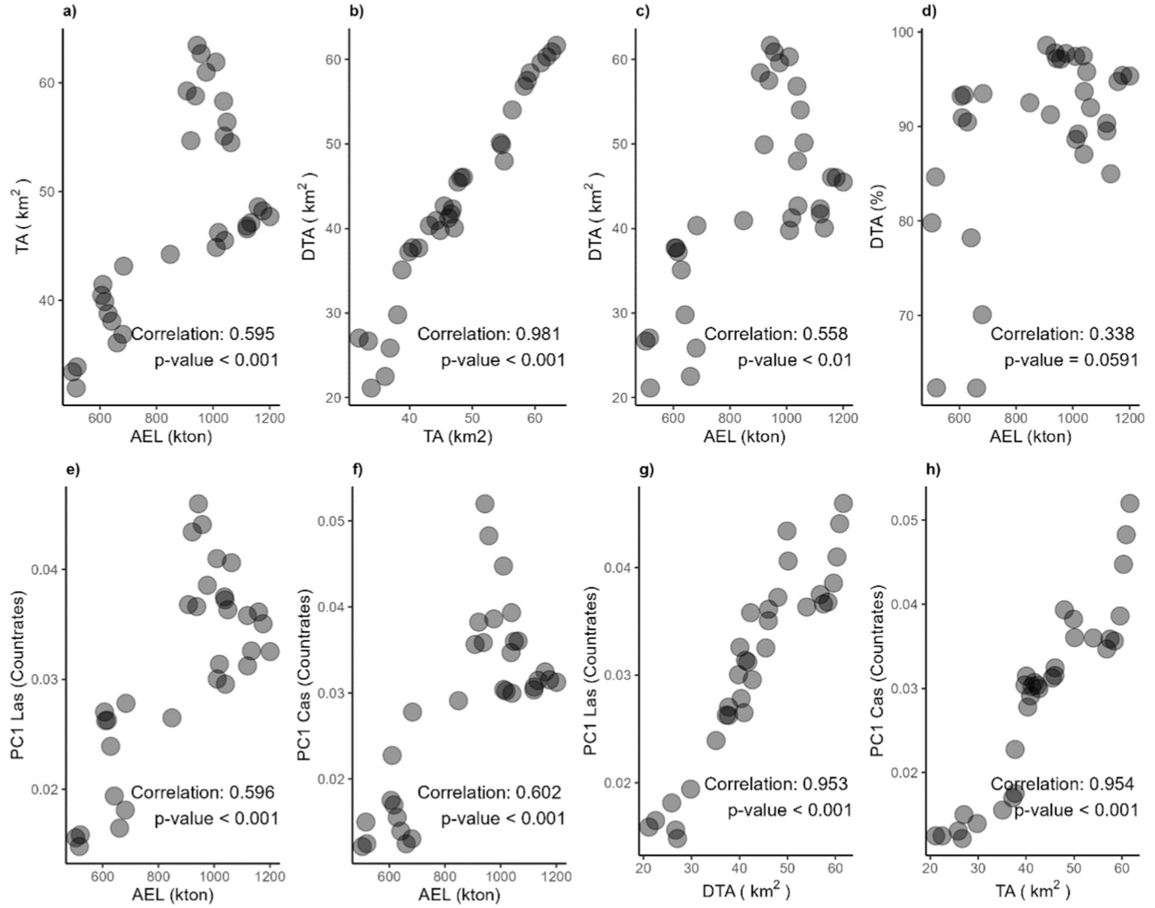

Fig. 5. Correlation Analysis between local potential drivers and metal(loid) levels in the study area between 1985 and 2017. PC1-Las and PC1-Cas corresponds to the corresponding principal components indicated in Fig. 3, AEL (kton) corresponds to copper production at Alto El Loa, TA (Km2) corresponds to the area of the Talabre tailings dam (Fig. 2), and DTA (Km2) corresponds to the area of the Talabre tailings dam with dry sediments. The chosen time period aligns with the availability of satellite imagery, as detailed in Section 2.3 of the Methods.

same period.

3.2.3. Regime shifts

Our analysis suggests four regime shifts (Fig. 7a) in copper production (AEL). The first three shifts (1, 2, and 3) attest for abrupt increases in copper production during the mid-1970 decade, 1989, and 1997, respectively. Whereas the fourth shift (4) suggests a significant transition during the early 2010s marked by a decline and stabilization in copper production.

Regime shifts in features of the Talabre tailing impoundment (TA, DTA, and DTA %) (Fig. 7b,c,d, respectively) were closely linked to the mining boom of the 1990s. That is, the first of these occurred only few years after its implementation. Still, subsequent shifts appear influenced by factors extending beyond cooper production trends, potentially attributable to changes in tailings management practices. Notably, around the mid-2000, a second regime shift was observed in DTA and TA, followed by another significant shift in early 2010 that affected all tailings-related variables.

At local scale, two regimen shifts in metal(loid) availability are observed at Lasana (PC1-Las, Fig. 8a) and Caspana (PC1-Cas, Fig. 8b). The first matches to the regime shift in AEL during the 1990s mining boom. Whereas the second occurs around the late 1990s aligned with the notable surge in copper production, representing the most substantial increase during the study period.

Although not statistically identified as regime shifts, changes observed in TA, DTA, and DTA% (Fig. 8a) had an evident effect on PC1-Las trends from the mid-2000s onward. The second regime shift of TA (2004) and DTA (2003) occurred just a few years before a steep increase in PC1-Las. Similarly, the third regime shift in the Talabre tailings-related variables during the early 2010s preceded a sustained rise in PC1-Las, which continued positively until the study period's end.

Similar patterns emerged in PC1-Cas, reflecting the regional influence of the local pollution drivers (AEL, TA, DTA, and DTA%) (Fig. 8b). However, some differences were introduced by spatial factors, such as the distance between emission sources and PC1-Cas (50 km away from the open pits and Talabre tailings). The regime shifts of 1992 and 2000 in PC1-Cas were also reflected in PC1-Las but with a slight temporal lag. The effect of tailings-related variables on the mid-2000 trend in PC1-Cas were less pronounced than in PC1-Las.

4. Discussion

Here, we provide further insights into the factors that have accounted for the pollution trajectory of the Atacama mining hotspot by developing a novel environmental proxy. In this vein, we demonstrate that dendrochemical records -i.e., tree-rings- represent a valuable environmental proxy for tracking metal(loid) deposition in areas lacking long-term monitoring networks.

By examining correlations and regime shifts in copper production and tailings changes we can see these are important triggers that explain the observed increase in metal(loid) levels in the neighboring villages. These results highlight the implications of the intensification of mining both at the local and national levels. The utilization of tree rings as environmental indicators provides a unique perspective for

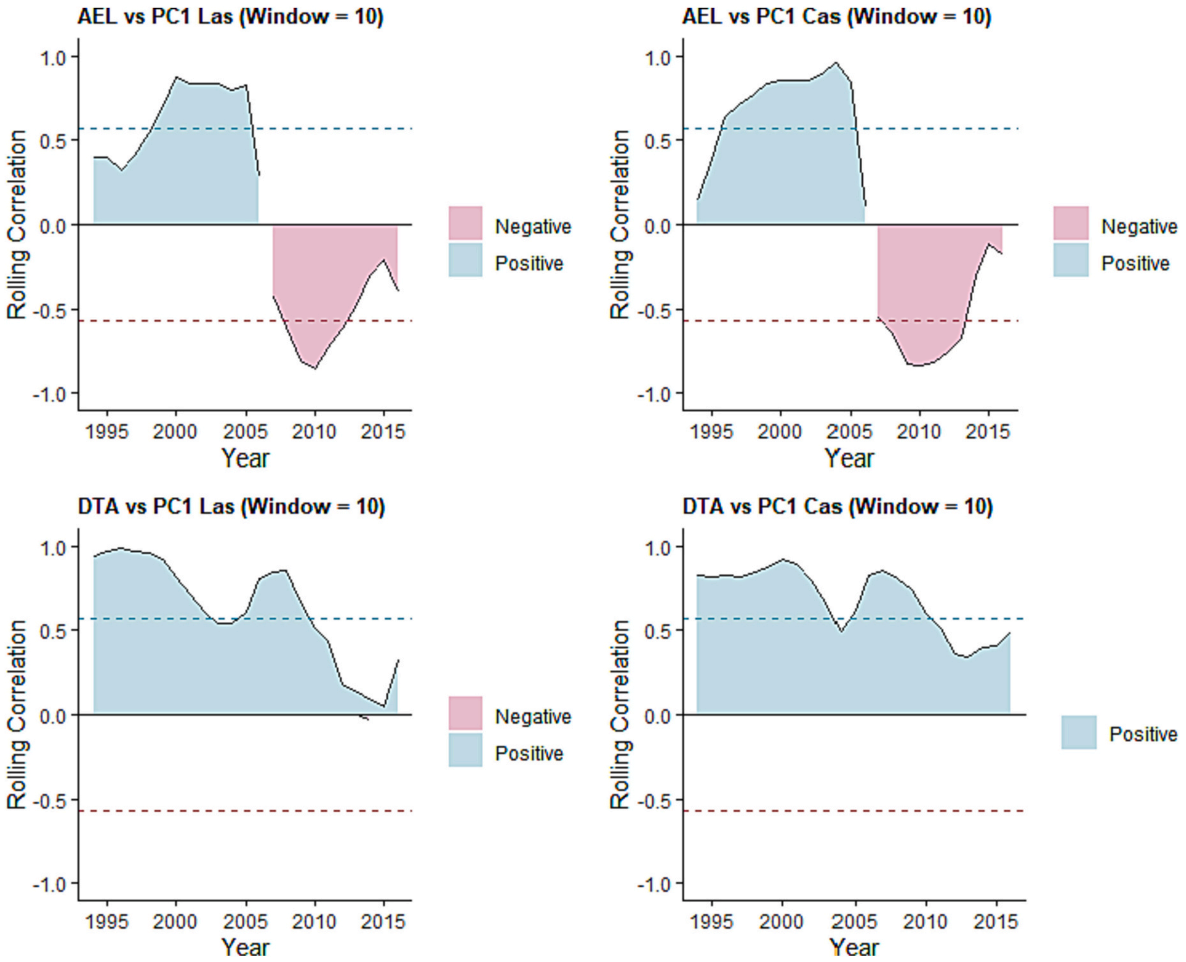

Fig. 6. Moving correlations (10 years window) between local potential drivers (copper production at Alto El Loa "AEL" and the area of the Talabre tailings dam "DTA") and metal levels in the Lasana (PC1-Las) and Caspana (PC1-Cas) villages, registered by tree-rings and during the period 1985 to 2018. Values above and below the dotted horizontal lines indicates significant positive and negative correlations (α = 0.05).

understanding the long-term impacts of mining activities on surrounding ecosystems and communities.

4.1. *Significance of local drivers and periods*

The results emphasize the crucial role of abrupt changes in local drivers, particularly copper production levels and the availability of dry tailing materials, in influencing local pollution. These drivers significantly contribute to metal(loid) concentrations observed in the tree rings from the Lasana and Caspana villages. Two notable periods emerge: (1) a substantial and sustained increase in metal(loid) deposition during the 1990s (Fig. 8) aligned with the intensified mining activities in the region (Fig. 7a) and the surge in global demand (Fig. 1), and (2) the impact of potential alterations in tailings management from the mid-2000s onwards resulting in abrupt changes in the overall trend of metal(loid) deposition (Fig. 8). These temporal associations strengthen the link between local mining operations and metal(loid) pollution, providing important insight into the long-term impacts of mining activities and the importance of understanding these dynamic relationships for effective environmental management and sustainable regional mining practices. Crucially, the mining boom of the 1990s, evident in Chile, had far-reaching implications beyond the national sphere. Since 1985, over 90 states in the Global South have revised their mining laws to attract foreign investment and catalyze rapid growth in mining operations. This trend is especially prominent in mineral-rich regions within emerging markets (Bridge, 2004). This broader global context strongly suggests that the scale and intensity of environmental impacts linked to mineral extraction may have undergone substantial growth in other strategic investment regions, echoing the observed patterns presented in this study.

Another crucial factor to consider is the temporal lag in response between abrupt shifts in local pollution drivers and the observable signal of changes in tree rings (Fig. 8). This delayed response can be attributed to a sort of 'spatial latency of impact', wherein the transportation and deposition of metal(loid)s contribute to the observed delay in influence. Previous studies have identified temporal gaps between emissions and the actual uptake and incorporation of metal(loid)s in tree rings (Aznar et al., 2008; Fornasaro et al., 2023; Rocha et al., 2020). In our study, the detected abrupt changes in PC1-Las occur one year before those in PC1-Cas and two and three years after changes in AEL, respectively. This discrepancy in timing can be attributed to the proximity of PC1-Las to emission sources (~10 km), which is closer than PC1-Cas, located 50 km away (Fig. 2b). This spatial effect indicates that the distance from the emission source introduces a delay in the manifestation of environmental changes, contributing to the observed temporal discrepancy between the two locations (Aznar et al., 2008; Muñoz et al., 2019; Navrátil et al., 2017).

4.2. *Importance of evaluation of different emission sources*

Our study emphasizes the importance of evaluating multiple emission sources associated with mining activities. While regional-scale studies, such as the Illimani glacier in the Central Andes (Eichler et al., 2017) and Mount Johns in West Antarctic Ice Sheet (Schwanck

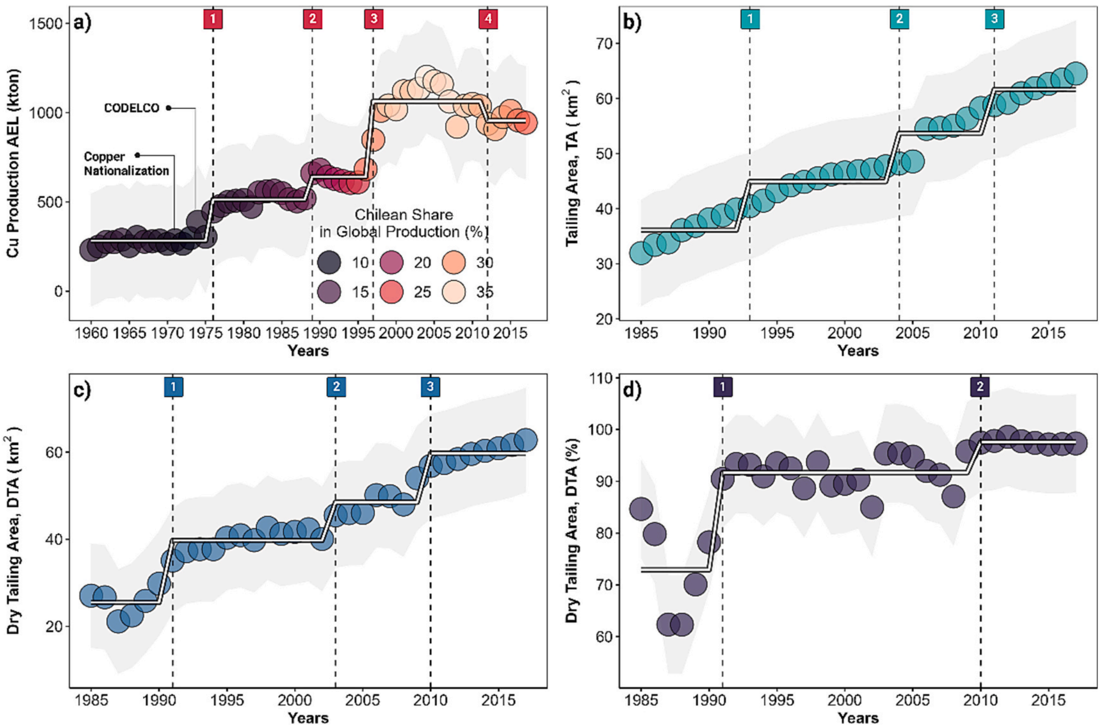

Fig. 7. Regime shifts in local pollution factors. Panel (a) represents AEL (Copper (Cu) production), panel (b) shows TA (Tailing Area), panel (c) displays DTA (Dry Tailing Area), and panel (d) exhibits DTA % (percentage of Dry Tailing Area in relation to the total area). The vertical dotted lines indicate significant regime shifts (Rodionov, 2015), with corresponding numbers listed at the top of the graph.

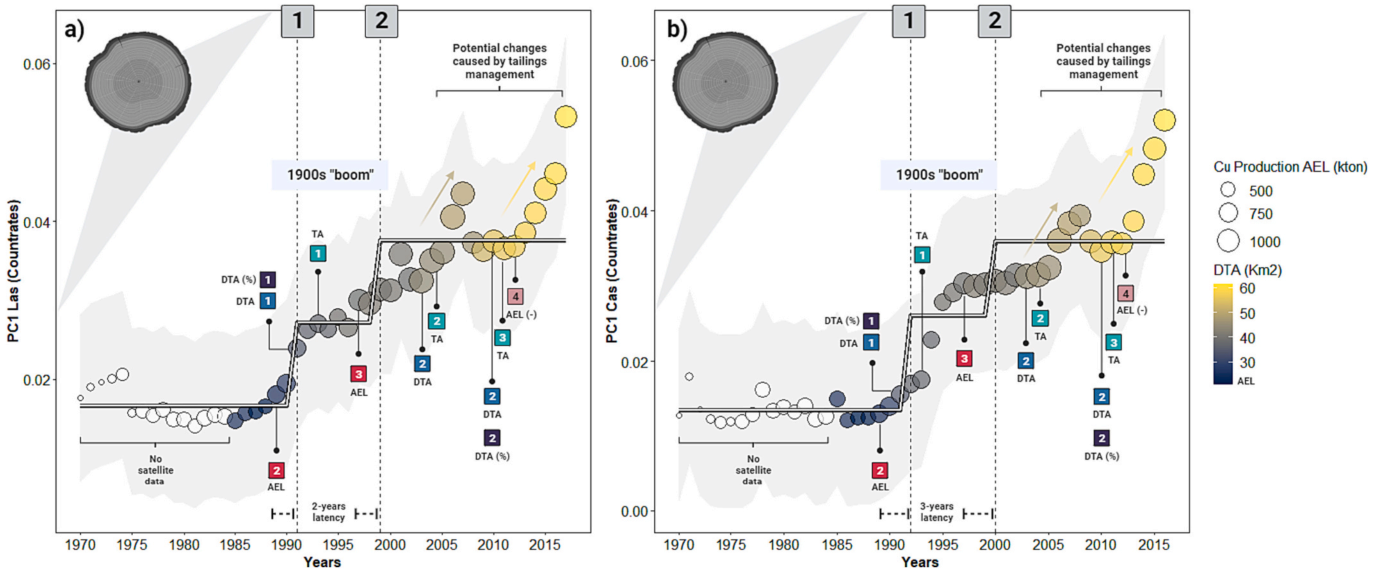

Fig. 8. Regime shifts in metal availability in the study area and its relationship with changes in local pollution drivers. Panel (a) represents PC1-Las (Lasana), and panel (b) shows PC1-Cas (Caspana). The vertical dotted lines indicates significant regime shifts (Rodionov, 2015), with corresponding numbers listed at the top of the graph (the most significant regime shifts are identified with colored circles). Regime shifts identified in the local pollution drivers in Fig. 7 are integrated into the analysis to establish their relationship with the observed changes in PC1-Las and PC1-Cas.

et al., 2016), primarily capture emissions from long-range sources like smelters with fine particle emissions, our analysis provides insight into the local-scale impacts of mining activities. The observed increases in metal(loid) levels in tree rings suggest that local sources, including the Talabre tailing dam and nearby mining operations, significantly contribute to environmental pollution. A partially similar trend has been identified in lake sediments at the local scale near our sampling sites (Cerda et al., 2019), hinting at a potential alignment between these two methods in capturing temporal contamination patterns. However, it is essential to recognize that various factors may influence each matrix differently, warranting careful consideration for comprehensive interpretations (Binda et al., 2021, and reference therein). Nevertheless, recent evidence in central Chile (Gayo et al., 2022) has indicated a degree of compatibility between the two methods.

Moreover, the particle size of emissions would play a crucial role in the dispersion patterns of mining emissions. Regulatory measures implemented in the 1990s targeting smelters and fine particle emissions (Ministerio de Mineria, 1991) likely contributed to the decline in metal (loid)s concentrations in regional-scale studies (e.g. Illimani and Mount Johns). However, further investigation using atmospheric transport models considering particle size distribution, is warranted to strengthen this assumption and provide a more comprehensive understanding of emission dynamics.

4.3. Challenges and mitigation strategies for the future of mining in Chile

The common features observed in extractive territories on the national scale lead us to propose that environmental conditions in Alto El Loa region might offer insights into broader trends across various mining regions in Chile. The complex socio-environmental relationships between mining activities and local communities, along with the monitoring and regulatory deficiencies outlined in this case study, likely represent shared challenges at the industry and government level. Hence, it is imperative to understand the enduring environmental and health impacts of mining activities within the potentially affected territories. This is especially crucial in countries such as Chile and several others in the Global South, where the extraction of essential commodities for the energy transition is poised to play an increasingly critical role.

Looking ahead, the future of mining in Chile confronts challenges tied to heightened production and the resulting expansion of tailing areas. While implementing water recovery measures is imperative to address both climate-induced water scarcity and overuse, it inadvertently transforms dry materials into potential contaminants, putting neighboring communities and ecosystem at risk and exacerbating the environmental impact of mining. To mitigate these risks, comprehensive management strategies should be developed. In this context, Chile is currently contemplating the compulsory substitution of freshwater with seawater in certain industrial sectors, such as mining (Alvez et al., 2020). However, evidence has shown that in areas where water scarcity stems from improper water distribution (e.g., Dame et al., 2023), transitioning to the use of seawater may intensify pre-existing historical tensions instead of mitigating them (Fragkou and Budds, 2020).

Another critical aspect demanding attention is the enhancement of environmental monitoring practices. Chile's monitoring network is predominantly concentrated in urban areas, primarily focusing on short-lived pollutants like PM 2.5 and SO2 (Manzano et al., 2021). However, a notable gap exists in monitoring other crucial contaminants, particularly metal(loid)s. This limitation extends to both temporal variation and spatial patterns, hindering a comprehensive understanding of the environmental impacts of mining activities. To address this, there is an urgent need for an expanded and refined environmental monitoring framework that encompasses a broader spectrum of pollutants, such as metal(loid)s (Neaman et al., 2020). Such an initiative is paramount for effective mitigation strategies and sustainable mining practices in Chile.

Considering our findings reveal a rise in contaminant availability linked to increased mining activities (Fig. 8), a pertinent question arises: How might this heightened presence of contaminants in the environment impact the health of the local inhabitants? This exposure may yield unforeseen health implications. Current studies and monitoring efforts need to be more comprehensive in understanding the long-term impacts on public health. The potential health risk associated with increased exposure to metal(loid)s, as witnessed in Alto El Loa, raise critical questions about the unexplored health consequences. Are we inadvertently compromising the well-being of local communities in pursuit of regional and national economic development, perpetuating the concept of "Sacrifice Zones"? (Gayo et al., 2022; Juskus, 2023; Sanz and Rodríguez-Labajos, 2023; Valenzuela-Fuentes et al., 2021). As we focus on economic growth, are we paying attention to the imperative of safeguarding the health and prosperity of those who will inherit these mining territories? Despite that the link between elevate exposure to environmental pollutants and severe health conditions is well-established (Fraser, 2012; Horton et al., 2018), the need for more comprehensive studies and monitoring, specifically in mining-exposed population, leaves us with a crucial knowledge gap. As the global demand for new metals surges in the pursuit of the energy transition, it becomes imperative to ensure that this quest for development does not translate into a deterioration in both ecosystem and human health in local communities.

5. Concluding remarks

This study represents the first of its type to disentangle the intricate relationship between copper production in northern Chile and the availability of metal(loid)s in the environment, as observed through tree-ring analysis. While a significant link between these variables has been established, it is imperative to recognize the potential influences of other contributing factors. The findings suggest that controlling or reducing copper production may not necessarily lead to a proportional reduction in environmentally polluting metal(loid) levels. This is attributed to the emergence of alternative sources of metal(loid) emissions represented by tailing dams. Consequently, the dynamic nature of this relationship underscores the need for a comprehensive and integrated management approach. An integral facet of this approach involves implementing more rigorous measures for the treatment of tailings and their associated dry materials. Tailings are potentially significant contributors to metal(loid) dispersion in nearby communities. Therefore, a better management of the dry areas of tailing dams would be an effective management strategy that would prioritize the mitigation of metal(loid) emissions from these sources.

This study underscores the importance of steering industry practices through evidence-based decision-making. The well-being of the local population hinges on a balanced and scientifically informed approach to address the intricate interplay between mining activities and exposure to metal(loid)s. As we advance towards a global net-zero energy emission paradigm, a steadfast commitment to data-driven solutions will be pivotal in achieving a just transition. This commitment is crucial for safeguarding the health and livelihoods of the local communities, especially those from where cooper and other necessary minerals (e.g., lithium) are extracted. Only then can we ensure sustainable and equitable development, being mindful of the potential health impacts that might emerge when another one bites the dust.

CRediT authorship contribution statement

Nicolás C. Zanetta-Colombo: Writing – review & editing, Writing – original draft, Visualization, Investigation, Formal analysis, Data curation, Conceptualization. **Tobias Scharnweber:** Writing – review & editing, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Duncan A. Christie:** Writing – review & editing, Funding acquisition. **Carlos A. Manzano:** Writing – review & editing. **Mario Blersch:** Visualization, Formal analysis. **Eugenia M. Gayo:** Writing – review & editing. **Ariel A. Muñoz:** Writing – review & editing, Conceptualization. **Zoë L. Fleming:** Writing – review & editing. **Marcus Nüsser:** Writing – review & editing, Supervision, Resources.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

Acknowledgements

The authors express their gratitude to the indigenous communities of Alto El Loa, whose invaluable contributions made this research possible. Nicolás Zanetta-Colombo (NZC) is grateful to the Deutschen Akademischen Austauschdienstes (DAAD) which provided funding for the development of his Ph.D. thesis (Funding program "Research Grants – Doctoral Programs in Germany, 2020–21"). This work was partially supported by FONDAP 1523A0002 and ANID–Millennium Science Initiative Program NCN19_153. Our heartfelt thanks go to Soledad Perez who welcomed us into her home in the village of Lasana and permitted us to collect tree samples from her property, and Lourdes Flavià Forcada and José Castaño Ruiz (Murtra Santa María del Silencio) for their unwavering support in lodging during the sampling campaign. A special acknowledgment is extended to Isabella Aguilera Betti who facilitated the introduction of NZC to Tobias Scharnweber. The authors are indebted to Ulrich Möbius and Prof. Martin Wilmking from the Department of Landscape Ecology and Ecosystem Dynamics from University of Greifswald for their role in enabling the analysis of the collected samples. This work is dedicated to the memory of Tobias Scharnweber, a cherished colleague and friend whose untimely departure just before the submission of this article has deeply saddened us. To Tobias, his family, and everyone at *DendroGreif*.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.scitotenv.2024.170954.

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