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# The socio-cultural implications of glacier retreat demand further attention: a case study from Cerro El Plomo in Santiago, Chile

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Glaciers provide vital meltwater to rivers and mountain ecosystems and hold profound significance for societies worldwide. Their retreat due to climate change has been well documented, however, research has overlooked the socio-cultural dimensions of their retreat, particularly in the Chilean Andes. We use the case of the retreating glaciers of Cerro El Plomo near Santiago, Chile to call for more collaborative studies between glaciologists, anthropologists, and local communities. The Cerro El Plomo glaciers are arguably the most visible and socio-culturally significant in the Santiago region. Satellite imagery analysis and prior studies show that the total area of Cerro El Plomo glaciers has decreased by  $17\% \pm 6\%$  since 2000 and their mass balance has become increasingly more negative, particularly after the onset of the Central Andes megadrought in 2010. The mountain's hanging glacier has retreated up the steep bedrock, with many areas of the glacier tongue thinning by 10–20 m from 2017–2019. A literature review indicates that glacier retreat disrupts and may reconfigure long-standing relationships that local groups have with them. These include Andean Indigenous and *mestizo* peoples for whom glaciers hold deep cosmological significance as part of the Cerro El Plomo *apu* (sacred protector); mountain guides and *arrieros* (traditional herdsman or muleteers) whose social identities and livelihoods are tied to them; and *santiaguinos* (Santiago residents) who view them as emblems of the landscape and derive from them a sense of place. The retreat of these glaciers presents not only a water security risk, but also important socio-cultural implications that deserve further study.

## KEYWORDS

glacier retreat, climate change impacts, socio-cultural implications, central Chile, Andes, multi-disciplinary collaboration

## 1 Introduction

Despite growing attention, research on the implications of glacier retreat on diverse human societies remains limited (Gagné et al., 2014; Carey et al., 2017). Existing studies on the human dimensions of glacier changes tend to focus on their implications for hydropower, agriculture, drinking water, food security, and tourism (e.g., Kaser et al., 2010; Jackson, 2015; Carrivick and Tweed, 2016; Mark and Fernández, 2017; Huss et al., 2017). Yet glaciers also hold deep cultural and cosmological significance for many societies, a relationship that is being disrupted by rapid deglaciation under climate change (Jackson, 2015;

Carey et al., 2021). Scholarship has documented this relationship with glaciers in mountain regions across the world, including in the Andean Cordillera Blanca of Peru and Volcán Cotacachi in Ecuador (Gagné et al., 2014; Allison, 2015). Research in anthropology and Indigenous studies have found that glaciers, as “icons of the landscape” (Gagné et al., 2014, p. 795) and “charismatic entities” (Dannevig and Rusdal, 2023, p. 1678), are a focal point in how communities make sense of the world and their place in it, creating “a sense of loss when these change” (Orlove, 2009, p. 26).

In the Andes, diverse Indigenous communities see glaciers as ancestors and sacred beings (Lushwala, 2023). These communities maintain close cosmological and socio-cultural relationships with glaciers through ceremonies, pilgrimages, origin stories, daily routines, and artistry (Carey, 2010; Gagné et al., 2014; Moens, 2020; Magnani, 2021). Glacier retreat has prompted mountain communities to remake and reinterpret their relationships to glaciers, challenging how they understand themselves and the world (Carey, 2010; Allison, 2015). For example, in the Peruvian Cordillera Blanca, Indigenous leaders describe glacier retreat as a spiritual crisis where their reciprocal relationship of presenting offerings to assure adequate water supplies has been disrupted (Paerregaard, 2020). Other community leaders share that snow and glacier loss are signs that the power of the *apus*, mountain sacred protectors, has reduced (Carey et al., 2017). Neighboring communities believe that “the mountains would die” if the glaciers disappeared (Motschmann et al., 2020). Facing profound loss, these communities and others across the Andes are finding ways to grieve, cope, and adapt to the changes that glacier retreat presents to their worldviews, cultural practice, and social relations (Orlove et al., 2008; Motschmann et al., 2020; De la Cadena et al., 2015). For example, in light of the disappearance of Chacaltaya glacier in Bolivia and Cotacachi glacier in Ecuador, local communities have preserved their significance through climate change education tourism and continued artistic representations (Rhoades et al., 2008; Kaenzig et al., 2016). Central Chile, however, remains notably less studied on this topic compared to other regions in Chile and the Andes. Glacier research in central Chile has examined the physical retreat of glaciers over recent decades (Malmros et al., 2016; Dussaillant et al., 2019; Fariás-Barahona et al., 2019), implications of glacier loss for water resources (Burger et al., 2019; Ayala et al., 2020), glacial hazards (Iribarren Anaconda et al., 2015; Iribarren Anaconda et al., 2018a; Wilson et al., 2018), and political and legal avenues to protect glaciers from mining and industrial activity (Iribarren Anaconda et al., 2018b; Gramsch et al., 2020; Yunis et al., 2023). How local communities relate to glaciers in central Chile and how they experience their disappearance, however, remain largely unexplored (Burgos, 2025).

A particularly striking gap is the lack of research on the societal implications of glacier retreat on Cerro El Plomo [33.236°S, 70.214°W, 5,424 m above sea level (m a.s.l.)], a glaciated Andean mountain towering above Santiago, Chile’s capital (See Figures 1A–C). The peak is one of the most visible in the Metropolitan Region (Villar, 2021). Likely a function of its prominence, Cerro El Plomo and its glaciers hold deep and ancient socio-cultural significance for Indigenous, *mestizo*, and non-Indigenous peoples who live in the Maipo River Valley (Orrego Silva et al., 2021). The peak and its glaciers are featured in music, literature, and art, and is an increasingly popular destination

for mountaineering and tourism (Laborde, 2004). Cerro El Plomo is one of the sacred guardian *apu* mountains in the Andes where the Incans practiced human sacrifice ceremonies (Fernández Droguett and Berríos, 2023). In recent decades, mountain guides have reported that the glaciers of Cerro El Plomo are melting so quickly that some believe Cerro El Plomo Glacier, the hanging or *colgante* glacier visible from across the Santiago region, may disappear within the decade. In 2024, several news outlets reported that Cerro El Plomo Glacier was melting at such an alarming rate that its moraines were destabilizing and surrounding permafrost was thawing (Villegas, 2024; Daza and Villegas, 2024; El, 2024; France 24, 2024).

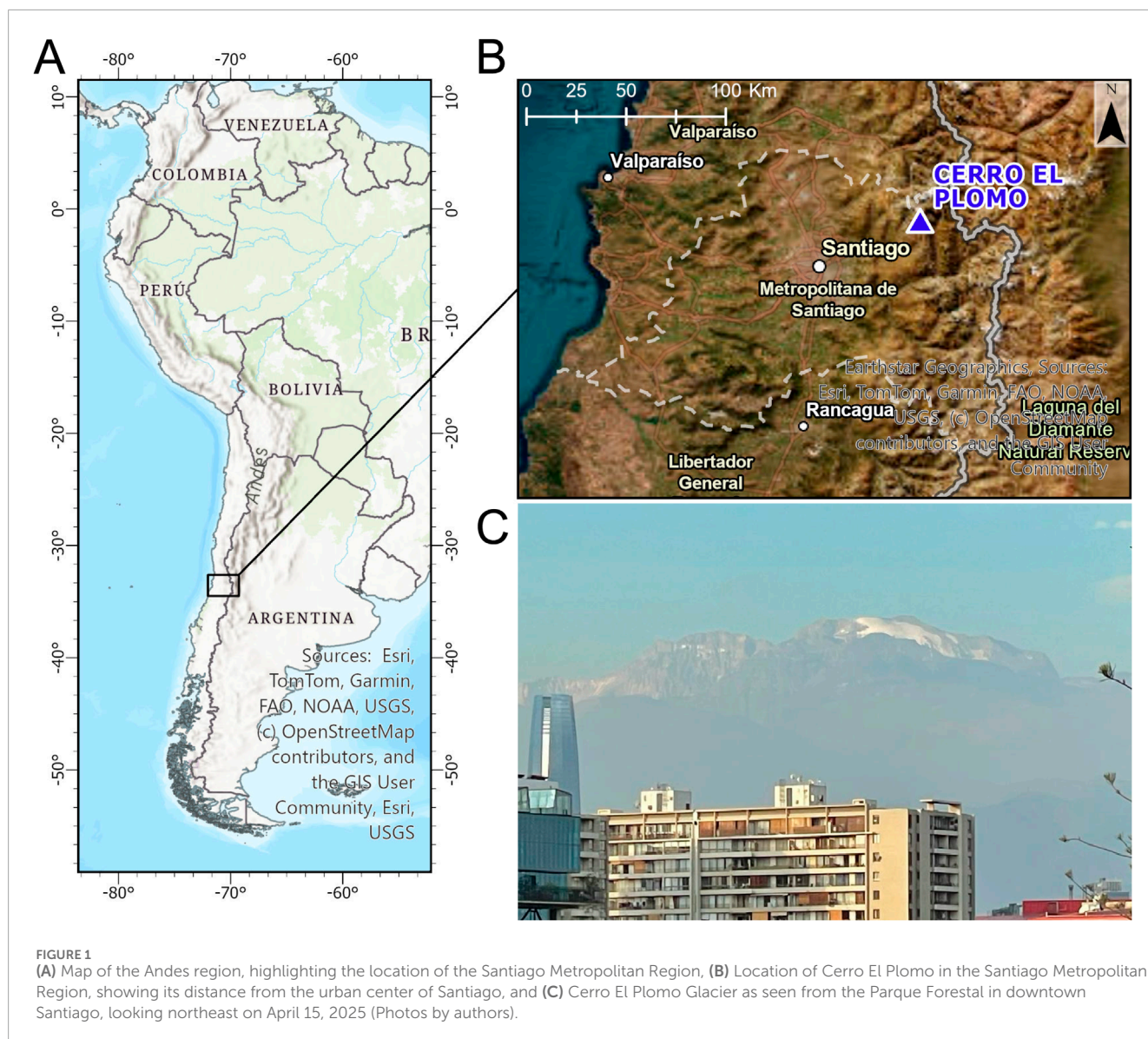
In this perspective article, our goal is to highlight this urgent and understudied issue to facilitate further socio-cryospheric research on the physical dimensions and socio-cultural implications of the retreat of Cerro El Plomo’s glaciers. We define socio-cultural implications here as changes in cultural practices, social relations, identity, cosmologies, and ways of life due to the environmental disruption of glacier retreat. First, we describe the major physical changes undergone by the Cerro El Plomo glaciers and ground-truth those remotely-sensed observations with personal insights from local mountain guides and *arrieros* (traditional herdsmen or muleteers). Second, we evaluate local academic and grey literature (i.e., non-indexed government and non-governmental publications) on the observed and potential socio-cultural implications of the glacier’s retreat. We organize these insights in terms of the local groups that the literature identifies as having a connection to these glaciers: (1) Andean Indigenous and mestizo peoples in the region who have a cosmological relationship with the glaciers, (2) mountain guides and *arrieros* whose livelihoods and identities are tied to the glaciers, and, more broadly, (3) *santiaguinos*, people living in the Santiago region, who see the glaciers as an emblem of the landscape and derive from them a sense of place.

## 2 Socio-cryospheric analysis

### 2.1 Physical changes of Cerro El Plomo glaciers

Several glaciers can be found on the slopes of Cerro El Plomo and the neighboring peaks. Meltwater from these glaciers drains to the Mapocho and Olivares rivers, which are both tributaries to the Maipo River. This glacier melt contributes crucial streamflow in the summer months (December through May), supporting Santiago’s drinking water supply, ecosystems, and the agriculture, energy, and mining industries in the metropolitan region (McCarthy et al., 2022; Alvarez-Garretón et al., 2024).

In recent decades, glaciers in the Maipo River basin have experienced large area reductions and negative glacier mass balance, particularly since the onset of the Central Andes Megadrought in 2010 (Malmros et al., 2016; Masiokas et al., 2020; Dussaillant et al., 2019; Fariás-Barahona et al., 2020). Dussaillant et al. (2019) estimated that the annual mass balance of glaciers in the Maipo River basin changed from  $+0.10 \pm 0.22$  m w. e.  $a^{-1}$  in the period 2001–2008 to  $-0.25 \pm 0.20$  m w. e.  $a^{-1}$  in the period 2009–2017. Caro et al. (2021) reported that the total glacier area across the Central Andes (30–37°S) reduced by 39% in the period 1980–2019. Here, we calculate the area changes of Cerro El Plomo’s three



largest debris-free glaciers (Esmeralda, Los Castaños, and Cerro El Plomo) between 2000 and 2025 using satellite imagery and Chilean national inventories. Then, we assess their mass balance across different subperiods from 2000 to 2022, based on data from four previous studies (Braun et al., 2019; Farías-Barahona et al., 2020; Hugonnet et al., 2021). Technical details are provided in the Supplementary Sections 1, 2. Changes in the area of Cerro El Plomo glaciers are assessed by comparing glacier outlines in the summer of 2025 with those in 2000, which were mapped in the Chilean National Glacier Inventory of 2014 (DGA, 2014). We drew the 2025 glacier outlines in Google Earth using an ©Airbus satellite image from February 2025 and using the 2019 glacier outlines from the Chilean National Glacier Inventory of 2022 (DGA, 2022) as a reference.

Over the 25-year period, Cerro El Plomo glaciers have lost  $1.40 \pm 0.51 \text{ km}^2$  ( $-17\% \pm 6\%$ ) (Figure 2A; Supplementary Table S2), with individual area losses of  $-4 \pm 10\%$  (Los Castaños),  $-16\% \pm 8\%$  (Esmeralda) and  $-29\% \pm 14\%$  (Cerro El Plomo). The reductions in glacier area appear to be linked to loss at the upper glacier

boundaries and frontal retreat, particularly of Cerro El Plomo Glacier, where a proglacial lake has formed in the last decade (Supplementary Figure S1). Satellite imagery reveals an expansion of debris-covered areas on the tongues of Cerro El Plomo and Esmeralda glaciers since 2014 (Supplementary Figure S1).

The mass balance of Cerro El Plomo's glaciers was assessed using the elevation changes datasets provided by Braun et al. (2019), Farías-Barahona et al. (2020) and Hugonnet et al. (2021) (Supplementary Section 2), and their corresponding glacier outlines (Supplementary Table S3). The analyzed datasets indicate that the mass balance of Cerro El Plomo glaciers varied from near-neutral before the year 2000 to increasingly negative, especially since the beginning of the Central Andes Megadrought (Figures 2B,C; Supplementary Table S3). For example, results of Hugonnet et al. (2021) for Cerro El Plomo Glacier show that the annual mass balance varied from  $-0.09 \pm 0.25 \text{ m w. e. a}^{-1}$  in 2000–2010 to  $-0.32 \pm 0.27 \text{ m w. e. a}^{-1}$  in 2010–2020. For the latest analyzed period (2017–2022), the dataset of LEGOS & OMP (2025) results in annual



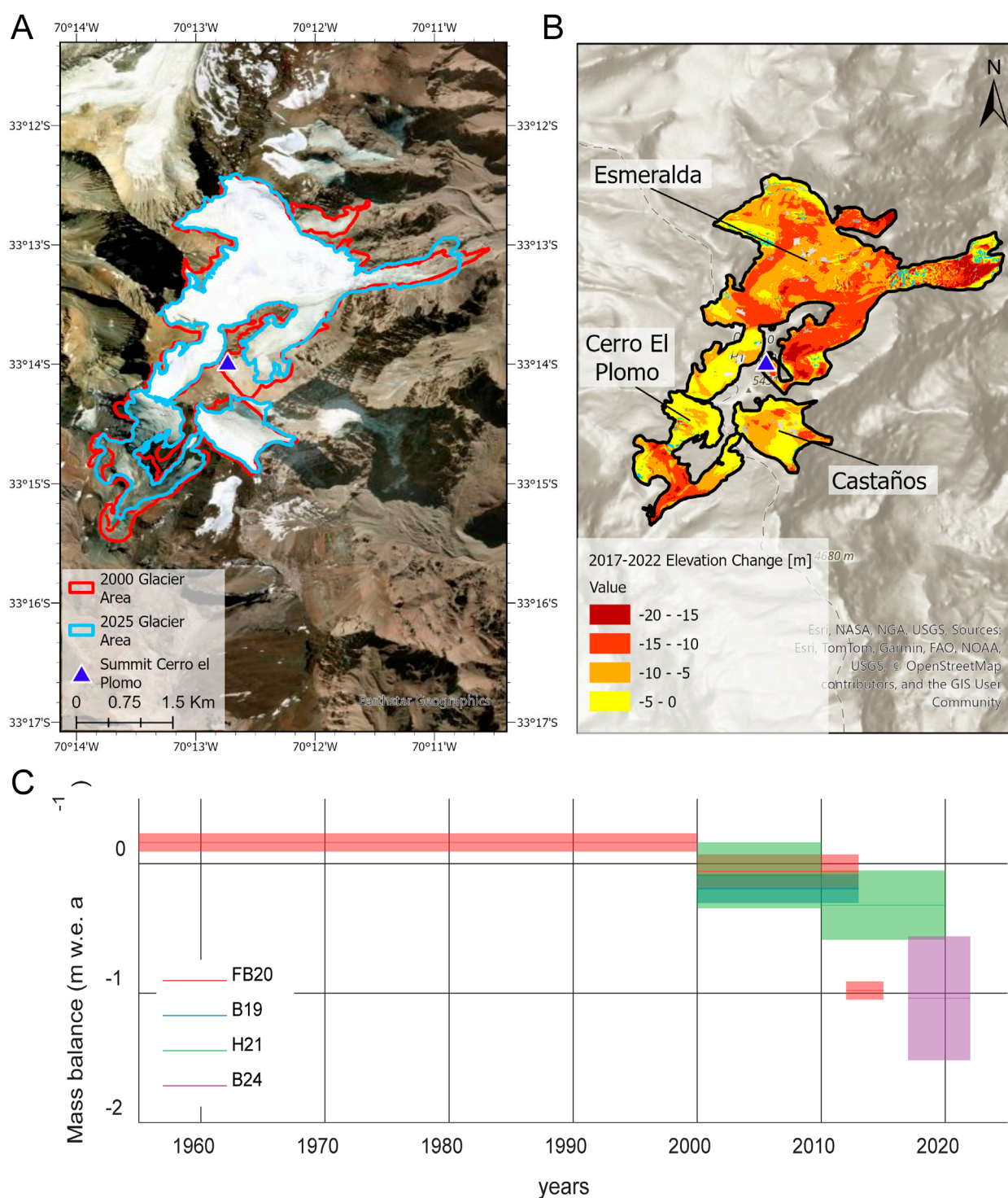


FIGURE 2

(A) Glacier area change from 2000 (DGA, 2014) to 2025 (outlines derived from a ©Airbus satellite image, 2025), overlaying Maxar (2024) basemap, and (B) Elevation changes of the study glaciers from 2017 to 2022 as extracted from the Pleiades Glacier Observatory (PGO) (LEGOS & OMP, 2025). The glacier outlines correspond to the year 2019 (DGA, 2022). (C) Cerro El Plomo Glacier annual mass balance estimated in the studies of Farias-Barahona et al. (2020) (FB20), Braun et al. (2019) (B19), Hugonnet et al. (2021) (H21) and LEGOS & OMP, 2025 for different periods since 1955. Shaded areas show the uncertainty associated with each dataset. See the Supplementary Material for methodological details.

mass balances of  $-1.04 \pm 0.48$  m w. e.  $a^{-1}$ ,  $-1.40 \pm 0.39$  m w. e.  $a^{-1}$  and  $-0.90 \pm 0.51$  m w. e.  $a^{-1}$  for Cerro El Plomo, Esmeralda and Los Castaños glaciers, respectively.

Future glacier changes in the Southern Andes for the 21st century project a continuation of current retreat and mass loss (Rounce et al., 2023). The morphology of Cerro El Plomo



glacier is characterized by very steep terrain and is thus more subject to sudden collapses, particularly when unusually large volumes of meltwater access the glacier bed. Such collapses have been observed in recent years in the nearby regions of the Andes mountains (Falaschi et al., 2019) and around the world (Kääb et al., 2021; Bondesan and Francese, 2023). Monitoring and attention to the future evolution and mass loss of Cerro El Plomo Glacier is important given its morphology and future regional projections.

These remotely-sensed findings corroborate *in-situ* insights from mountain guides and *arrieros* shared with news outlets on the glaciers' area loss and negative mass balance. In February 2024, mountaineers and guides witnessed unusually high summer temperatures, high melt flow, and moraine landslides, sinkholes and destabilization, leading local organizations to change a section of the trail's historic route below Cerro El Plomo Glacier to avoid these hazards (Meyers, 2024). Speaking to Reuters, mountain guide Rusbel Vidal said that starting for the first time in 2022, crampons were no longer needed to summit (Villegas, 2024). Francisco Gallardo, an *arriero* who has worked for the last nearly 50 years supporting mountaineers and whose family has worked on Cerro El Plomo for generations said that the mountain "is crumbling" as "rising temperatures due to climate change have caused the glacier to retreat and the permafrost to melt ...new lakes have formed and disappeared, landslides have injured climbers, and huge sinkholes have opened up, blocking the old path to the summit" (Daza and Villegas, 2024). He shares that "every year it's changing more. Every year we are seeing more sadness ...I calculate ten years more and goodbye" (Daza and Villegas, 2024). Indeed, the conventional wisdom among local mountain guides is that Cerro El Plomo Glacier will disappear in the next ten years based on the rate of glacial loss that they have observed in recent decades (Balthasar 2024, personal communication, 2 February 2024).

## 2.2 Socio-cultural significance of the Cerro El Plomo glaciers

Academic literature on other Andean settings, as explored earlier, indicates that the rapid retreat of a glacier as iconic and storied as Cerro El Plomo has major socio-cultural implications for the people living near it. Published literature underscores that Cerro El Plomo is a sacred site to which Andean Indigenous groups have historical and ongoing cosmological ties to. It is important to note that the suppression of Indigenous groups in central Chile, first by Spanish colonization and later by the Chilean state, led to the erasure of Indigenous peoples, cosmologies, and cultural practices in the Maipo River Basin (Fernandez Droguett, 2019). Even still, ten percent (approx. 718,000) of the Santiago Region's population self-identify as Indigenous, according to the most recent census data available (INE, 2018). In recent decades, urban Indigenous groups in Santiago have begun reclaiming ceremonies, revitalizing language, and reestablishing these relationships in the modern urban context (Brablec, 2019; Brablec, 2022; Casagrande and Barton, 2023). Cerro El Plomo and its glaciers appear to be an anchor in this process, although the specific ways in which these groups perceive and relate to these glaciers and understand their retreat deserves further study. In this section, we present what is

captured in the literature on this relationship despite this context of erasure.

Cerro El Plomo and its glaciers are a guardian high mountain, an *apu*, that grounds the Andean Indigenous cosmovision into the modern urban space of Santiago (Fernández Droguett, 2018). The mountain's height, rising prominently above the central valley, is interpreted by Incas and by many Andean Indigenous peoples, such as the Mapuche, Aymara, and Quechua peoples, who are the most represented groups in the region, as providing Cerro El Plomo with a close relationship to the heavens and *Inti* (Father Sun) (Fernández Droguett, 2019). For Indigenous peoples across the Andes, an *apu* is a sacred place of connection and interaction between the cosmos and Earth, between the earthly and spirit worlds, and thus is a powerful place for ceremony and rituals (Fernández Droguett and Berrios, 2023).

In the Andean cosmovision, the city of Santiago, which was built upon an Indigenous settlement at the modern-day Plaza de Armas, is located in a system of sacred geography through *ceques*, invisible lines, that linked to the Cerro El Plomo and its *huacas*, sacred protector hills (Fernandez Droguett, 2019). The *huacas* associated with the *apu* of Cerro El Plomo include Cerro Blanco (*Wechuraba*), Cerro Santa Lucía (*Huelén*), Cerro Chena (home to a *Pucará*, Incan fort), and possibly Sierra de Ramón, which contains an Incan hilltop shrine that faces Cerro El Plomo (Tapia and Opazo, 2017; Silva et al., 2017; Fernández Droguett, 2018).

Today, Andean Indigenous and *mestizo* peoples in the Santiago region continue to cultivate their cosmological connection to the *apu* of El Plomo, including through regular ceremonies at Cerro Blanco and outside of the Museum of Natural History (Fernández Droguett, 2018). Since 2009, the National Indianista Coordinator (CONACIN) has hosted a ceremony on the winter solstice festival *Inti Raymi* outside of the museum to honor *El Niño del Plomo*, son of Cerro El Plomo (Fernández Droguett and Berrios, 2023). *El Niño del Plomo* refers to an eight or nine-year-old Incan mummified child who was disinterred from the ruins of an Incan *ushnu* (ceremonial structure) near the summit of Cerro El Plomo in 1954 by prospectors and now is held in the museum (Durán Serrano, 2005). Archeologists and Indigenous leaders understand *El Niño del Plomo* to have been the center of an Incan sacrifice ritual called *Capacocha* to the Incan sun god *Tata Inti* to pray for a good harvest (Krakl and González, 1957; Mostny, 1959; Horne and Kawasaki, 1984; Ceruti, 2001; Vitry, 2008; Fernández Droguett, 2018; Amaro et al., 2022). The *Inti Raymi* ceremony of song and dance to honor *El Niño del Plomo* has served as an important cultural practice to cultivate and reaffirm an urban Indigenous Andean identity in Santiago (Gundermann Kröll and González Cortez, 2009; Fernández Droguett and Berrios, 2023). Highlighting this relationship, Cecilia Vicuña's famous 2006 performance piece "Quipu menstrual (la sangre de los glaciares)," "Menstrual Quipu (the blood of glaciers)," honors the sacredness of Cerro El Plomo's glaciers in Andean Indigenous cosmologies and protests mining activity and climate change that threaten them (Vicuña, 2006; Vicuña and Jorquera, 2017; Witkowski, 2019; Cortese et al., 2019). The piece, most recently shown in Santiago for World Glacier Day 2025, captures her journey carrying 28 red *quipu* (wool strands), representing an umbilical cord, menstruation, and the lifeline between humans and glaciers, from Santiago to Cerro El

Plomo's glaciers as the city's water and life source (Witkowski, 2019; MNBA, 2023; MNBA, 2025).

More broadly, diverse groups who live in the Santiago region see these glaciers as a part of their sense of place and social identity. The snow-capped Andes cordillera is described by residents and writers as an "imposing and majestic" (Núñez et al., 2017, p. 3) "icon" of the region's landscape (Miño and Austin, 2022, p. 304). This landscape is crowned by Cerro El Plomo's glaciers that "overlook" the region as the "main protagonist of Santiago's skyline" (Guendelman, 2018, p.1). Writer Miguel Laborde describes *santiaguino* social identity as "we, the inhabitants of the Metropolitan Region, step on glacial sediments and drink snow water ...the mountain ranges are the structure of our space" (Laborde, 2004, p. 67). Cerro El Plomo and its glaciers are likewise depicted in film and folk arts as part of the central Chilean Andes cordillera to depict social identity and belonging. For example, Patricio Guzman's documentary "The Cordillera of Dreams" (2019) explains that the glaciated cordillera of central Chile is a pillar of national identity and history. He argues that the peaks visible from Santiago, including Cerro El Plomo, provide inspiration, a sense of being witnessed, and communal belonging to something greater. The glaciated and snow-capped peaks of the Andes are a common motif to represent the national landscape in *arpilleras*, handmade yarn tapestries in Chilean folk arts that depict everyday activities and cultural and political themes (Witkowski, 2019) (See Supplementary Figure S2).

This relationship to the mountain and its glaciers extends into the mountaineering guides and *arrieros* who work on the mountain. Cerro El Plomo's geographic prominence, socio-cultural importance, and stunning glacial views draw mountaineers from across Chile and abroad. The increasingly busy trail to Cerro El Plomo's summit begins at the parking lot of the ski resorts La Parva or Valle Nevado and snakes approximately 35 km, gaining nearly 3,000 m to the peak. Mountaineering guides and their support teams of *arrieros* often instruct mountaineers and visitors to respect the mountain as a sacred *apu* guardian, including by asking the mountain for safe passage when arriving and not visiting or photographing the *ushnu* of *El Niño del Plomo* (see Supplementary Section 3 for further information). Underlining the newspaper quotes previously discussed, livelihoods in mountain guiding and tourism are threatened as climate change causes temperatures to rise, making the mountain less safe to climb. The reduced presence of snow and glaciers also limits tourism opportunities, and during summer heatwaves, temperatures become too high for safe hiking.

### 3 Discussion and conclusion

Cerro El Plomo glaciers have lost  $-17\% \pm 6\%$  of their area since 2000 and their mass balances have become increasingly negative. The *colgante* (hanging) Cerro El Plomo glacier has lost  $-29\% \pm 14\%$  of its area in that period, leading local mountain guides to hypothesize that the hanging Cerro El Plomo glacier may disappear within about 10 years. The retreat of Cerro El Plomo's glaciers impacts the mountain environment, increases local hazards, and threatens ecosystems and water security for downstream populations. It also may upend the socio-cultural relationships of various social groups in the region to the glaciers. We provide a

robust literature review, identifying three social groups: Indigenous and mestizo peoples, mountain guides and *arrieros*, and broader *santiaguinos* who have ongoing socio-cultural relationships with these specific glaciers. We and other researchers, however, have yet to collaborate and speak with these groups to hear with their consent and in their own words how they perceive and relate to these specific glaciers and how they are remaking their cultural practices, cosmologies, livelihoods, and social identities as they retreat. Towards this goal, we recommend a renewed attention on socio-cultural research, spanning the physical and human dimensions, to fill in gaps in socio-cryospheric research in central Chile.

Likewise, future research on the Cerro El Plomo glaciers under various climate scenarios is crucial for understanding when they might disappear. Attention to the hanging Cerro El Plomo glacier is particularly important as it is a focal point visible from across the Santiago region and imbued with various cultural and spiritual meanings (See Figure 1C). In studying these cultural dimensions in climate change impact and attribution studies, it is important to remember that culture is not static, but dynamic and evolving, and thus communities in the Santiago region who are coping with and adapting to a changing environment of retreating glaciers are doing so in this context. This suggests a need for collaborative work between glaciologists, anthropologists, and local communities to better understand the localized implications of glacier loss (Carey et al., 2021; Carey and Moulton, 2023).

### Data availability statement

The original contributions presented in the study are included in the article/Supplementary Material, further inquiries can be directed to the corresponding author.

### Author contributions

KA: Conceptualization, Data curation, Formal Analysis, Investigation, Methodology, Project administration, Visualization, Writing – original draft, Writing – review and editing. AA: Data curation, Formal Analysis, Investigation, Methodology, Validation, Writing – original draft, Writing – review and editing. MS: Formal Analysis, Investigation, Methodology, Visualization, Writing – original draft, Writing – review and editing, Validation.

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### Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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# Supplementary material

The Supplementary Material for this article can be found online at: <https://www.frontiersin.org/articles/10.3389/feart.2025.1564881/full#supplementary-material>

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