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Uncertainties in the debate on the environmental impact of lithium brine extraction in the Salar de Atacama, Chile

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ABSTRACT

The global energy transition has dramatically increased the demand for raw materials, including lithium. The largest global reserves of lithium are situated in the salt flats of the Atacama Desert in Chile and the current boom is expected to result in an increase in production. Local communities and environmental NGOs fear a destabilisation of the vulnerable ecosystem of the salt flat. However, the mining companies present scientific studies that refute such claims. In this interdisciplinary research paper, this contradiction in the impact debate is further analysed and interpreted through a literature study and interviews with representatives of different stakeholders on location. What is observed is an unbalanced and possibly incomplete field of knowledge production, with a different role of the involved stakeholders. The state takes a passive position when it comes to monitor compliance of existing environmental legislation and lets the initiative for area and impact studies to the other stakeholders. This leaves the companies in a dominant position with their historical access to research equipment, technological knowhow and data. The communities lack the capacity to match the position of the companies and seem hesitant towards interacting with external researchers. In order to resolve this impasse and understand the long-term effect of large-scale lithium mining in the region, what is urgently needed is more independent research, ideally with a more proactive role of the state.

1. Introduction

The global energy transition has dramatically increased the demand for raw materials, as clean energy technologies require large amounts of metals such as copper, nickel, graphite and lithium (World Bank, 2020). The International Energy Agency (IEA) estimates that the world will see its mineral demand quadruple between 2020 and 2040 if it wants to achieve the Paris Agreement goal of staying "well below 2 °C global temperature rise" (IEA, 2021). This resource intensity of the energy transition will intensify environmental and social tensions in regions of extraction.

Chile finds itself in a central position in this modern day 'gold rush', as it possesses over half of the world's lithium reserves (ECLAC, 2023). Lithium plays a key role in clean energy technologies as its physical characteristics make it an important component of batteries for electric vehicles and electricity grids. As a result, the demand for lithium is expected to increase by up to a factor forty by 2040 compared to 2020 (IEA, 2021). Once the world leader in lithium production, Chile is now the second producer of lithium behind Australia, accounting for around a quarter of global production (ECLAC, 2023). All Chilean lithium is extracted from the Salar de Atacama (Atacama Salt Flat) in the north of Chile by two private companies: Chilean Sociedad Química y Minera (SQM) and Albemarle from the US. While the government, investors and the mining companies eye to expand operations and production to meet global demand, others fear a degradation of the vulnerable ecosystems and the further marginalisation of local communities.

In this paper we look at the debate on the environmental impact of lithium mining in Chile and the power dynamics when it comes to knowledge production. We argue that the field of knowledge production is both unbalanced and possibly incomplete. The political and scientific dominance of corporate actors distorts the debate on environmental impact. Independent scientific research is scarce and public control depends on corporate data and self-monitoring. As other stakeholders, such as local communities, NGOs and even state agencies lack the capacity for additional research, important and alternative perspectives might be absent in this debate. As a result, uncertainties around the short-term and long-term environmental impact of lithium mining in Chile remain insufficiently addressed.

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This paper is the result of an interdisciplinary research project funded by the ENLENS research priority area at the University of Amsterdam that united researchers across faculties to work on economic, environmental, technological, social, political and business aspects of the energy system and transition. During a visit to Chile in the beginning of 2023, a mixed group of ten early career and established social and earth scientists, including the authors of this paper, spent between 2 and 8 weeks on the Atacama Salt Flat and in Santiago. During this period, we conducted around thirty semi-structured interviews with representatives from the lithium companies, the state, academia, local communities, activists and artists. The visit also involved fifteen field excursions in the region, including observations on the geology, geomorphology, hydrology, and land use and land cover in the Salar de Atacama, and a visit to the lithium extraction sites of Albemarle. The results of the field research were locally presented at the UN Economic Commission for Latin America and the Caribbean (ECLAC) and the Dutch embassy in Santiago, and three Chilean universities (Universidad Catolica del Norte, Antofagasta; Universidad de O'Higgins, Rancagua; Universidad de Santiago de Chile, Santiago).

In the remainder of this paper we first introduce the Salar de Atacama, its unique ecosystem and the socio-ecological interdependencies of the region. We then discuss controversies around alleged environmental impact of the lithium extraction, and the methodological challenges in this respect. We conclude by proposing a series of suggestions to move beyond the current impasse.

2. The Salar de Atacama

All lithium in Chile is extracted from the Salar de Atacama, a salt flat at the foot of the Andes, 1500 km north of Santiago, the capital of Chile. The Salar stretches roughly 80 km north to south and 40 km east to west, making it the third largest salt flat in the world after the Salar de Uyuni and Salinas Grandes just across the border in Bolivia and Argentina.

The Salar de Atacama is an intermontane basin, and part of a succession of north-south trending ranges and basins, formed during Neogene uplift and the development of the Andean volcanic arc within the central Andean Altiplano (Alonso et al., 1991; Cabello, 2021). In this closed hydrological system (an endorheic basin), playa conditions have existed for approximately 15 Ma (Alonso et al., 1991). The accumulation of evaporite deposits started around 6–10 Ma, and is dominated by halite minerals (Corenthal et al., 2016; Marazuela et al., 2019a). The current basin floor has an estimated surface area of 2900 km^2, and a salt flat nucleus area of 1700 km^2 (Fig. 1). The volume of the halite deposits exceeds >1800 km^3, in which lithium brine (~5000 ppm), potassium,

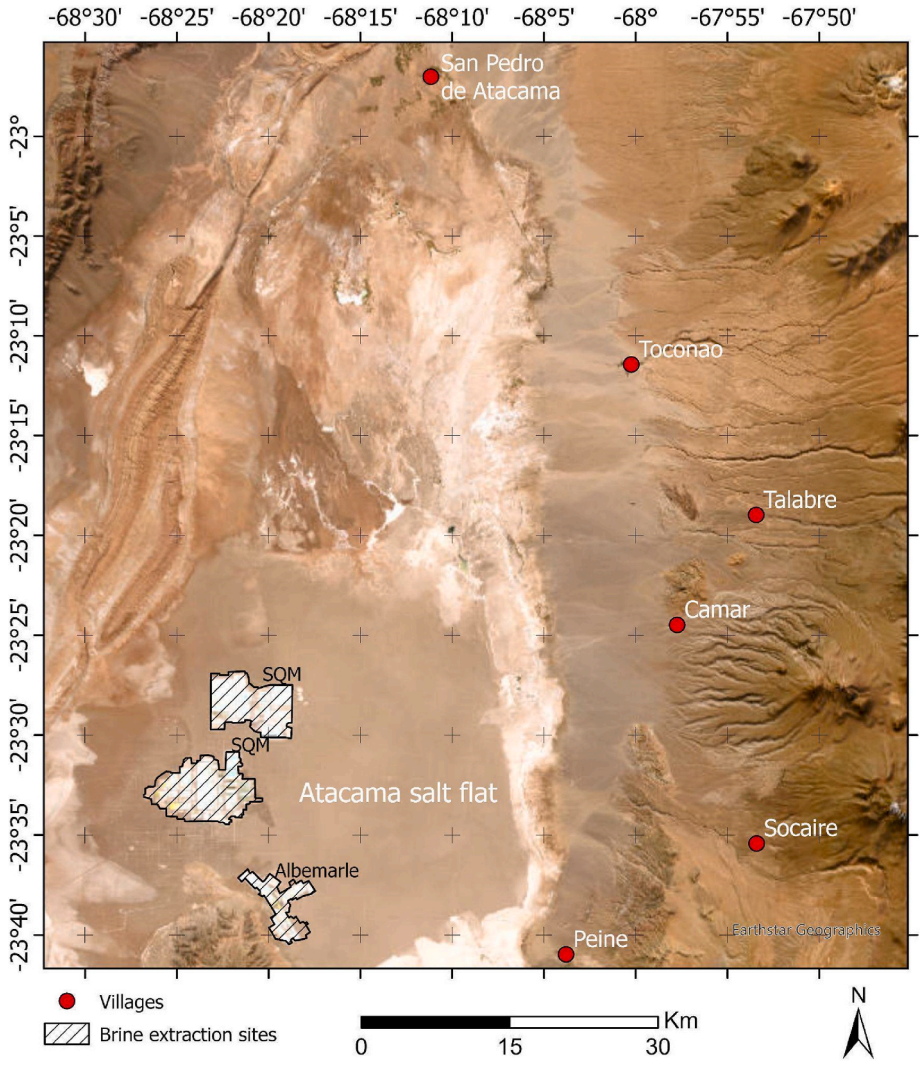

Fig. 1. Location of the brine extraction sites (SQM and Albemarle) in the Salar de Atacama, Chile. The white reflecting N–S trending zone (mixing zone) marks the transition between the Atacama salt flat in the west, and alluvial fans to the east. East of the villages Toconao, Camar, and Peine, volcanic rocks and outcropping basement dominate the image (Marazuela et al., 2019a). The figure is constructed using backdrop photos available in ArcGIS Pro 3.1 (ESRI, 2023). The brine extraction sites of SQM and Albemarle have been digitised on-screen.

boron, gypsum, and other minerals, released by chemical weathering of surrounding rocks, and secondary mineral formation, occur (Corenthal et al., 2016; Meixner et al., 2022). In zones of high subsidence, a thickness >1.5 km of halite, interbedded with ignimbrites, is reached (Jordan et al., 2007). Godfrey and Álvarez-Amado (2020) suggest that lithium enrichment is related to the leaching of ignimbrites and other volcanic rocks, and to volcanic activity in interaction with groundwater, that drives enriched lithium solutes upwards from a subsurface magmatic body. This is in line with findings of Cabello (2021), who mentions that volcanic rocks are the major sources for the evaporites. Over time, coarse-grained permeable sediments have created alluvial fans on the transition between the salt flat and the Andean Mountains (Fig. 1). Occasionally, such sediments could reach the mixing zone and the salt flat during flash flood events. Geologic evidence from the halite deposit suggests that the basin has received significant water inflow over at least 7 Ma (Corenthal et al., 2016), suggesting lithium brine formation at least over that time span. This largely coincides with Munk et al. (2016), who propose that the accumulation and concentration of brines likely occurred in the past 10 million years.

The ecosystem of the Salar de Atacama is spread across desert, wetland and *altiplano* habitats, and includes the important *Reserva Nacional Los Flamencos* national park and the world-famous *El Tatio* geothermal geyser field. The wetlands and playa lakes sustain a rich biodiversity, including guanacos, vicuñas and llamas, three types of flamingos, migratory (water) birds, lizards, bats, foxes, various types of rodents and the ostrich-like rhea, some which are unique to this ecosystem (Gajardo and Redón, 2019). Additionally, the extreme conditions on the salt flat are important for studying microbial life that developed over the past million years, which could explain the earliest stages of evolution on earth (Dunai et al., 2020).

The hydrogeological balance of the ecosystem is highly vulnerable, due to the minimal rainfall in the Atacama desert, on average only 15 mm per year (Liu et al., 2019), in combination with high evaporation rates. Of key importance for the surface presence and quality of water is the so-called 'mixing zone' (Marazuela et al., 2019a), situated at the eastern borders of the salt flat (Fig. 1). Here fresh surface runoff from the Andean mountain slopes and saline groundwater aquifer are mixed. At the surface this delicate balance between surface and groundwater recharge is expressed in wetlands and playa lakes. The mixing zone is currently under threat, and several studies report that the Salar suffers an increasing water deficit as the outflow exceeds the recharge capacity (e.g., Bustos-Gallardo et al., 2021; Jerez et al., 2021; Kaunda, 2020). This water deficit and the subsequent water stress form an important background to understand the socio-environmental tensions in the region.

A handful of towns is located at the eastern border of the salt flat at the foot of the Andean mountains on the alluvial fans, close to the mixing zone, local wells and little streams (Fig. 1). The region is home to approximately 11,000 people most of which live in San Pedro de Atacama, a small town of single storey mudbrick houses and dusty sand roads (Fig. 2). The majority of the people in the region are indigenous *Likanantay* or *Atacameño,* who have been living in this region for thousands of years in small agro-pastoralist communities (Babidge and Bolados, 2018). In recent years, the region has become one of the most popular tourist destinations in Chile which unique landscapes attract over 100 thousand visitors per year (Babidge, 2016). The majority of the people combine wage labour in tourism or the mining industry with small-scale farming of corn, alfalfa, quinoa and desert herbs. In addition, small herds of llamas, alpacas, goats, sheep and donkeys are kept for subsistence or commercial purposes (Sepúlveda Rivera et al., 2015). The experience of generations living in the extreme conditions of the Salar has resulted in well-adapted socio-hydrological systems. The towns possess century-old irrigation systems of widely branched canals and have representative local water boards to manage and distribute the water between the different households (Babidge and Bolados, 2018). The Atacameño culture is heir to an Andean cosmovision that considers nature, people and spirits as part of a unitarian and harmonious *pacha.* As a result, beyond a scarce and vital resource for survival, water also has an important symbolic value and it forms a central element in the social, political and cultural organisation of the towns and communities.

3. Contradictions in the debate on environmental impact

On the salt flats of South America lithium is extracted from brine, extremely saline groundwater. The brine is pumped up in large quantities (around 200 million litres per day by both companies) and left to evaporate in a sequence of ponds in order to increase the natural lithium concentration. Brine consists of around 70% water and 95% of this water

Fig. 2. San Pedro de Atacama with the active Licancabur volcano in the background (Photo by lead author).

is lost to evaporation in the production process (Liu et al., 2019). In the context of the precarious water balance in the region that was discussed above, this water-intensive production process has increased concerns around hydrological disruption in both media (e.g. El Mercurio de Calama, 2017) and scientific studies (e.g. Bustos-Gallardo et al., 2021; Jerez et al., 2021; Liu et al., 2019). Liu et al. (2019) report significant environmental effects of brine extraction, including the degradation of surface vegetation, elevating daytime surface temperatures and decreasing soil moisture levels. Other studies address the negative effects on groundwater levels, aquifers and the wider hydro-system (Kaunda, 2020), a distortion of the biodiversity of the wetland ecosystems (Gutierrez et al., 2022), and increasing drought periods and desertification (Izquierdo et al., 2015). In addition to these scientific publications, local communities and environmental NGOs have produced reports (e.g. Jerez, 2018; Romero et al., 2019; Walter et al., 2021) and documentaries (e.g. Fundación Tantí, 2021; OPSAL, 2019) that address the effects of brine extraction on a vulnerable ecosystem with a high ecological, cultural and symbolic importance. These concerns have increased with the prediction that production might increase significantly over the coming years (ECLAC, 2023).

The lithium companies on the other hand contest these claims and concerns regarding the hydrological and ecological impact of brine extraction. First of all, they point out that brine should not be confused with freshwater. The brine under the salt flat is ten times saltier than seawater and cannot be used for human or agricultural consumption (e.g. Albemarle, 2022: 42; SQM, 2023). Secondly, the companies argue that the pumping stations and evaporation ponds are located on the remote southern edge of the Salar, 40 km from the closest town Peine and 80 km from San Pedro de Atacama (Fig. 1). The companies refer to Marazuela et al. (2019a,b) who argue that groundwater levels have fallen as a result of brine extraction, with up to 8 meter in some places, but that this only occurs in areas close to the pumping stations, far from the mixing zone and population centres. In the words of a sustainability report by Albemarle (2020: 56):

> Low permeability sediments around the saline interphase minimise the effects of brine extraction. Data from our hydrogeological model confirm that brine pumping does not affect the upstream groundwater levels or the size of the lagoons.

Although the companies are aware of the vulnerable ecosystem and sensitive social context, they see no scientific evidence that would indicate a need to limit or refrain from expanding production. The situation is presented as a case of 'hard science' versus 'local sentiments'. Indeed, most of the scientific studies that do argue that there is environmental impact from brine extraction, generally observe a correlation between increased lithium mining and increased environmental degradation, but do not find a causal effect. For example Liu et al. (2019: 154) conclude that lithium production on the Salar *"may be* one of the important environmental stressors to the overall health of the local environment*"* (our emphasis). The mentioned NGO reports (e.g. Jerez, 2018; Romero et al., 2019; Walter et al., 2021) do address important issues around environmental impact and human rights, but often lack scientific details and rigour.

Altogether, the debate on the environmental impact of lithium mining on the Salar de Atacama is divided into two narratives that hardly converse with one another. This is also a reality we encountered on location, where different interviewees on either side of the divide would reiterate the same list of arguments, without much reaction or interaction between the two.

4. Contested knowledge production

At present, it is unknown whether large-scale brine extraction has had an effect on the wider ecosystem of the Salar de Atacama. In the literature and on location we observed that there is no full and openly available scientific understanding of the subsurface hydrological dynamics in the region. Although there is no lack of documentation from actors with a direct stake in the conflict, from critical documentaries and reports to corporate sustainability reports, scientific studies into the environmental dynamics of the region are scarce. Important gaps remain in scientific knowledge on both recharge and discharge dynamics of the groundwater systems, as the actual water flows are largely unknown and the evaporation process is poorly quantified (e.g., Babidge, 2018). These knowledge gaps could be interpreted as an absence of impact as long as it has not been irrefutably proven. In contrast, local communities and environmental NGOs insist that more extensive and independent hydrological studies, impact assessment and extraction monitoring must be implemented and made public before continuing or even expanding brine extraction. They argue that even in the case of a stable production rate, it remains unknown how the hydrological system will react in the long run. To complicate the scenario, there are other potential causes to the current hydrological deficit: from the (historical) freshwater consumption of neighbouring copper mines, to a local population that has doubled in size between 2002 and 2017, the rapid expansion of tourism over the same period, and climate change. All in all, the result is a highly complex, contested and under-studied research field.

There are several aspects that contribute to this contested knowledge production. A first factor that is important to analyse further is the research monopoly of the lithium companies. Scientific research has consistently been carried out by the companies in the Salar de Atacama since the discovery of lithium in the area in the 1960s. As such, almost all equipment, access to measurement stations, research technology and, subsequently, most data are owned by the companies. This is a reality that we also faced in the field, where it was practically impossible to obtain information, measurements or raw data from non-corporate sources. These data are not independent and there is a risk that certain aspects remain underrepresented if this is the only source. Publicly funded research or research led by communities or an environmental NGO might ask different questions, use different approaches and, possibly, shed light on different aspects of the question of impact.

To some extent, the companies do attempt to include the communities in the impact assessment. SQM shares monitoring data online (SQM, 2023b), while Albemarle organises joint monitoring missions together with representatives of the communities. However, this inclusion and transparency of research practice does not fundamentally alter the power relations in this respect. Moreover, due to the technical language of the studies and reports produced for the companies, these documents are often inaccessible to civil society. In addition, as part of their lease contracts with the state, the companies contribute to the establishment of research and development centres. Recently two of such research centres have been created, with a third in process (ECLAC, 2023). These centres organise events, provide training and publish publications on issues like the circular economy in mining and electromobility in Chile. The underlying question of the effect of brine extraction on the environment is not part of their agenda.

Local communities have taken some initiative too. Recently, the *Consejo de Pueblos Atacameños* (Council of Atacameño People, CPA) that represents most of the communities around the Salar has set up an environmental department. Its first reports still have to be published, but a key task is monitoring and analysing the environmental impact of lithium mining in the region. Such community-led impact measurement remains complicated due to a lack of sufficient funding, equipment, and scientific infrastructure like laboratories and qualified technicians and scientists. All in all, the companies remain in a dominant position when it comes to knowledge production.

A second aspect that complicates a more independent research agenda concerns difficulties on the social level. Since the 1990s, indigenous land rights have increasingly been recognized in Chile and the communities have authority over parts of the Salar (Dorn and Gundermann, 2022). During our fieldwork we learned that local indigenous communities are very hesitant to grant outsiders permission to visit certain areas or take samples. Our requests were largely ignored or

denied, and we were told it might take months if not years to get the right permits. In order to do scientific research, it is essential to construct serious and long lasting connections to establish contact and trust. Absence of permits obviously affects research, it complicates access to interviewees and inhibits sampling and certain types of field inventory.

The hesitating position from the side of the communities should be understood in context. It is partly the result of historical and ongoing neglect of the north of the country, the marginalisation of its indigenous population and the experience that outsiders, be it from Santiago or abroad, historically have come for the mineral wealth in the region. Additionally, the reluctant attitude by the communities can be understood as an expression of empowerment and ownership over their land that suddenly became the focal point of national and international interest. Lastly, there is a general fatigue among the overburdened communities, which might explain their reservations. Next to the surge of mass tourism, the region is visited by representatives of the lithium companies (from engineers to consultants and social workers), environmental NGOs, ministry representatives, political activists from Santiago and, on top of that, groups of (inter)national researchers that all want something from its inhabitants.

In contrast, the companies were easier to approach. They offered us the services of their PR department, access to data and provided a private tour on their operational site. In this way, the companies not only possess most of the research hardware and technical know-how, as was mentioned above, but also have the capacity to present their narrative effectively. Independent scientific research that is done in the region has to be very careful navigating this unequal field of information provision. The openness of the companies does have its limits, as they did not allow for sampling around their operations. Although they provided us with datasets, the data was often either prepared or sent in lengthy documents. It raises questions on how objectively these data could be interpreted.

Lastly, what is urgently missing in this epistemological conflict, is a proactive and mediating role of state agencies that guarantee some level of independent research. This includes studies into the hydrological system, impact studies of large-scale brine extraction and active monitoring of actual extraction and water levels. This is not sufficiently happening at the moment and the state is not guaranteeing compliance with existing environmental laws. For example, the *Dirección General de Aguas* (DGA), Chile's central water regulation and monitoring agency, has only three inspectors in the whole area. The sentiment is well expressed by a leading chemist from the region in a local newspaper:

> If you want to understand the situation, you need to do a study of the hydrological balance. How much water gets into the Salar? How much water is there? Is there a deficit or not? The monitoring equipment belongs to SQM and Albemarle, they are private and therefore you do not have access to that information. For this reason, the state should invest in inspectors and in its own measurement systems. (El Mercurio de Calama, 2017, our translation).

More institutional sources such as the UN *Economic Commission for Latin America and the Caribbean* (ECLAC) also describe the role of the Chilean state as absent and characterised by ignorance and a lack of sufficient information to regulate, control and enforce its own policies (Poveda Bonilla, 2020; ECLAC, 2023). Representatives of Albemarle confirmed this image in interviews, sharing experiences where the state demands substantial environmental and legal documentation from the companies, but does not have the time or capacity to provide an appropriate response in time.

5. Conclusions and outlook

As has been discussed throughout this paper, whether large scale brine extraction has a negative impact on the hydrological dynamics and the wider ecosystem of the Salar de Atacama is a very complicated issue without a straightforward answer. The studies that claim that there is an impact fail to present causal relations between the brine pumping and hydrological alterations. Besides, there are other contextual and historical factors that could explain the hydrological deficit on the salt flat. The reverse conclusion however, that there is no effect from brine extraction, is also shortcoming. There are important research gaps and it remains under-researched what will be the effect of expanding extraction in the longer term. Independent research is on the one hand complicated by corporate dominance when it comes to access to equipment and data, and on the other by hesitant local communities. As a result, the current state of knowledge of the hydrological dynamics of the Salar de Atacama and the possible effect of brine extraction is incomplete.

A way to enhance this debate would be to support more community-led area, impact and monitoring studies. Such a democratisation of scientific research could contribute to more transparency and a wider scope of approaches to potential environmental impact. The CPA or other representative bodies of civil society could be funded better, provided with adequate access, equipment, laboratories and technical personnel. The question remains if it should be up to citizens to research possible environmental impact on their living environment. Instead of balancing "both sides", something that is difficult to achieve, what is really needed is a democratic and independent mediator, a role that is generally allocated to the central state. The state could play a much more proactive role in defining and safeguarding the conditions in which lithium mining takes place. Not necessarily as an active participant in the extraction itself, as proposed in the newly proposed lithium strategy of the Chilean government, but by defining and safeguarding the conditions in which lithium mining will take place. This would include funding and conducting independent research to map subsoil dynamics, water flows and the hydrological system. It also includes impact studies to map not only the effect of brine extraction, but also that of (historical) water consumption of copper mining, tourism and agriculture. Lastly, it means conducting serious control of compliance with environmental permits and laws, and intensive monitoring of actual extraction and water levels. It echoes what ECLAC states in their latest report on lithium mining in Latin America:

> … the public must have guaranteed access to timely and quality information, in a transparent and appropriate manner […] This type of information includes the freshwater and brine extraction rates in mining projects and other activities (tourism, agriculture, livestock, among others) through the comprehensive monitoring of salt flats (ECLAC, 2023: 33).

This recommendation goes beyond the particular case of Chile, stressing a general need for some form of independent democratic control in cases of extractive conflict. This necessity is even more pressing in times of resource fever such as the current lithium boom, when there is a very sudden increase of economic interest and, subsequently, levels of extraction, financial flows and unequal power relations.

Finally, the relevance of this debate on environmental impact is not merely epistemological, but has direct real world importance. Lithium is in high demand and will remain so for the foreseeable future. The companies operating the brine extraction aim to increase their production to be able to answer this demand. Their lease contracts will expire over the next years and they are eager to renew and increase their quota. The Chilean government has recently published a new national lithium strategy, aiming to play a more proactive role in the production of lithium. The current government wants to direct extractive profits to national development and is afraid to miss out on this historical chance. The local communities meanwhile are afraid that current and future extraction might irreparably affect their living environment and call for more caution. All in all, more than an abstract or theoretical exercise, this debate involves topics of extreme importance and its outcome will have direct tangible relevance for the region and the world.

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.

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