



The impacts of environmental, social and governance (ESG) issues in achieving sustainable lithium supply in the Lithium Triangle

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Abstract

The electrification transition will intensify the demand for lithium. The endowment in the Lithium Triangle is significant, and the expectations for the global supply are high in terms of resources and sustainability. In this paper, we investigate the impact of environmental, social and governance (ESG) challenges to the future of sustainable lithium extraction. We undertook a qualitative analysis to prioritise the risks associated with these challenges and discussed their interlinkages. We argue that a sustainable perspective for lithium extraction in the region requires continuous and informed dialogue among government, industry and community stakeholders and participatory processes that reduce the asymmetries of power and knowledge. We provide a list of urgent mitigation actions that could assist the move towards sustainability. These include the following. First is expanding our understandings of the water cycle of lithium brines in this region. This should be underpinned by baseline data and ongoing monitoring at the watershed scale, capacity building to strengthen institutions, improved regulations and data infrastructures to promote data transparency and accessibility. Second is integrating biodiversity impacts within existing mining practices and procedures (e.g. Environmental Impact Assessments — EIA). We propose the strategic implementation of the mitigation hierarchy and IFC's Performance Standards to avoid, reduce and offset the risks of lithium extraction on ecosystem services and critically important biodiversity impacts. Third is strengthening social participatory processes that enable the local communities to become actors in decision-making and the ongoing management and monitoring of lithium projects. Fourth is establishing a framework to support a Strategic Environmental and Social Assessment (SESA) process specific to lithium with a regional approach in the Lithium Triangle.

Keywords Lithium brines · ESG challenges · Battery raw materials · Lithium Triangle · Social participation

Introduction

Lithium brine resources in the Lithium Triangle (Argentina, Bolivia, Chile) in South America are vast, and increasing production is an essential step towards achieving global decarbonisation targets. The decarbonisation agenda, together with the sustainable development goals (SDGs) (e.g. SDG12 on responsible consumption and production),

set high aspirations for the sustainable and responsible supply of raw materials. The time window for bringing lithium production to market is noticeably short. Projections suggest that lithium demand for clean energy technologies is growing faster than other major minerals, primarily due to the move towards electrification in transport. According to the International Energy Agency, lithium demand is expected to increase by over 40 times in the sustainable development scenario by 2040 compared to 2020 consumption (IEA 2021).

However, significant unquantified risks associated with the sustainable and responsible supply of lithium exist, requiring in-depth investigation and identification of impacts on the ability of markets to respond to global demand. One key obstacle is the poorly defined concept of sustainability in the case of lithium brines. Although attempts to explore the sustainability of lithium have been made which are discussed in the next section of this paper, the majority of them

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focus on macro-scale issues, for example the supply chain of lithium for electric mobility, rather than in situ challenges associated with the implications of lithium extraction at the local level. This is an important barrier to determining the factors that should be accounted for to ensure sustainable supply.

In this paper, we frame the sustainability of lithium brines extraction by investigating the associated environmental, governance and social (ESG) challenges. We discuss their interlinkages and the impact these often ‘hidden’ challenges may have on the future of lithium supply from South America. The argument proceeds in five stages. We begin with a succinct discussion on the definition of sustainability for the mining sector. Afterwards, we provide an overview of the salt flats in the Andean region, followed by a description of our methodology and approach. Next, the paper provides the most important insights in relation to the environmental, social and governance challenges. The final section focuses on a discussion of our results and recommendations that could contribute towards the alleviation of some of the most prominent challenges. Our analysis is based on extensive stakeholder engagement with actors and evidence gathering from all three countries in the Lithium Triangle.

The definition of sustainability and relevance to the mining sector

Lithium from the salt flats of South America represents an important mineral source for our decarbonisation technologies. However, concerns about the provision of raw materials and adherence to sustainability principles have emerged as demand is escalating. These concerns are provoking debate about the concept of sustainability and its environmental and societal dimensions.

Sustainability is a complex, dynamic and multidimensional concept. Since 1987 and the definition of sustainable development by the Brundtland Report (World Commission on Environment and Development 1987), there has been a variety of interpretations and approaches from various disciplines with different assumptions about the interconnection of environment, society and the economy (Elliot 1994, 2011; Howarth 1997), for instance, sustainability of natural resources and economic growth (Klaassen and Opschoor 1991; Meadows, Meadows et al. 2004; Turner 2008; Kandachar 2014), notions of intergenerational fairness (Woodward 2000; Hunt and Fund 2016), ecological equilibrium and resilience (Donohue et al. 2016; Kéfi et al. 2019) and ecosystems and economic development (McMichael et al. 2003; Barbier 2012; Harris 2013).

In 2015, the Sustainable Development Goals (SDGs) were adopted by 193 countries at the United Nations Summit. They represent an ambitious and broad framework for

tackling key issues around poverty, environmental degradation, economic development and inequality. The challenges of satisfying basic needs and the increasing pressure on natural resources by a growing global population (projected to increase to 10 billion people by 2100), rapid urbanisation (by 2050, more than two-thirds of the world population will live in urban areas) (Yillia 2016; Palanivel 2017) and climate change targets require reconciliation and balance between the different priorities of low-carbon transition, sustainable development and preservation of ecosystem integrity and functionality.

In this delicate balance, the extraction and production of raw materials (mining of minerals in particular) play a major role. The role of metals and mineral production can be conflicting, for example it may be associated with negative environmental and social impacts but at the same time seen as essential in high-tech applications (e.g. renewable technologies) or in other sectors (construction, transport) contributing to local and national economies and the achievement of several SDGs (European, Joint Research et al. 2019). In this sense, addressing interlinkages and trade-offs between different SDGs and the various phases of the mineral supply chains are critical in the sustainability debate (Fig. 1). The International Resource Panel Report of the United Nations (IPR 2020) proposes a meta-framework in mining compatible with the 2030 Agenda’s vision of sustainable development. By acknowledging both the opportunities for countries endowed with mineral resources and also the disruptive environmental and social effects of extractive activities, the authors argue that the notion of sustainability requires new metrics to measure the strength of economic effects, good environmental management, the respect of social values and aspirations at local levels and observance to the highest standards of governance and transparency at global, national and local scales.

Lithium is a key mineral in achieving the low carbon energy transition. Although attempts for different approaches to define sustainability related to lithium have been made, the situation is still poorly defined. In the literature, lithium and sustainability have been approached from different angles, for example one study explored the physical resource availability of lithium (including changes in the geographic distribution of lithium availability and the substitution and recycling rates) (Christmann et al. 2015). Other studies investigated lithium sustainability from the whole life cycle angle and the trade-offs between different life cycle stages (Harper et al. 2019; Cong, Liu et al. 2021; Yang et al. 2021).

Discussion around sustainability and raw material supply risks are interlinked and often led by life cycle analysis practitioners who aim to identify sustainability hotspots in supply chains. The typical approach is to take the lithium-ion battery (LIB) angle and focus on the manufacturing stages of the value chain rather than looking at individual

Fig. 1 Key challenge areas and links to SDGs related to the exploitation of lithium from salars



raw materials. Independently of the angle of the analysis however, sustainability mitigation recommendations often include suggestions related to mineral governance, social impacts and supply chain transparency (Thies, Kieckhäfer et al. 2019, van den Brink et al. 2019; Babbitt 2020). The so-called sustainable governance of technology metals like lithium focuses on future availability but acknowledges that mining impacts (environmental and social) can potentially affect primary production and thus the development of clean energy technologies. As such, there is a need for different mechanisms (e.g. alternative service business models) to address the challenges in the global demand and supply (Prior et al. 2013).

Liu and Agusdinata (2020) point out that lithium brine exploitation takes place in a complex social and natural system with multiple interactions across institutional, spatial and temporal scales (Liu and Agusdinata 2020). Of relevance is the focus on sustainability from the local communities' perspective in the Salar de Atacama in Northern Chile. As the authors argue, there are important tensions emerging from lithium mining impacts in terms of water availability, labour influx, employment, social tensions and corporate social responsibility (CSR) dynamics that have immediate

and long-term effects on sustainability at the local level, and we would argue they increase the likelihood of supply disruption globally.

These studies have added important angles to the debate about sustainability and the lithium supply chain. However, there are noticeable gaps that require further investigation. Most of the existing scientific literature approaches the subject of lithium sustainability from the battery perspective. Therefore, the analysis of the raw material production stages is often limited. The focus of current research is based on quantitative data (e.g. life cycle analysis—LCA) often generic in nature and with country-specific case studies that are lacking the systemic understanding of the geo-environmental, governance and social processes associated with lithium extraction in the Andean regions.

In the case of the Andean salars, the environmental, social, political, governance and economic conditions have changed and adapted over time, and these changes have direct implications to the economic potential of the salt flats and the socio-environmental implications associated with their exploitation. The technical and economic challenges associated with the development of the lithium sector in the Lithium Triangle have been explored by other research

(Heredia et al. 2020; Quinteros-Condoretty et al. 2020). However, sustainability remains an ambiguous concept, because it fails to incorporate the significant impacts of the local ESG factors of the lithium sector in the analysis.

Considering the landscape of the Lithium Triangle and the fact that the array of wetlands associated with salars (lagoons) are directly associated with the location and hydrogeology of exploitable lithium brine deposits, there needs to be an acknowledgement of the risks posed by the project-led lithium developments to such High Andean wetlands occurring at a landscape scale. This risk occurs across provinces and countries within the Triangle landscape. The potential for hydrological and hence ecosystem collapse at any given salar system being exploited has the potential to be replicated across many salars in the region. This could result in wetland degradation at a landscape-scale leading to significant declines of already globally threatened species and the triggering of increased threat levels to vulnerable species dependent on such salar ecosystems (Marconi et al. 2022). The exploitation of lithium and the sustainable development of an industry that purports to provide a solution to the challenges of climate change needs to realistically consider and address such risks.

Our work seeks to present a regional perspective on the Lithium Triangle (raw material producing countries) by providing a qualitative analysis and scoring of the identified environmental, social and governance challenges using primary data collected in virtual workshops and semi-structured interviews with stakeholders in Bolivia, Chile and Argentina in 2019–2021. These were combined with the findings of an extensive literature review on the subject. Ultimately, this paper proposes that an understanding and conceptualisation of sustainability in the salt flats should acknowledge the dynamic and multilevel interaction of geo-environmental, social and governance systems as lithium mining expands in the region.

An overview of the Andean salars

The salars in the Lithium Triangle hold more than 50% of the global lithium resources. Andean salars are some of the most complex groundwater systems in the world, combining groundwater, surface water with solute movement and brine generation. They represent endorheic basins of internal drainage at elevations of over 2500 m above sea level (m ASL) and low rainfall.

The salars typically are situated in basin and range settings surrounded by volcanic deposits (e.g. ignimbrites, tuffs) that are a principal source of mineralised lithium, which are leached into the salars. The salars themselves are sedimentary deposits ranging from clays, silts, sands, layers

of volcanic ash and various evaporite minerals through to halite (NaCl).

Rainfall is typically very low on the salars, of the order of 10 mm/a, but rising to 150–200 mm/a as the elevation increases away from the salar itself (Marazuela et al. 2018). Rainfall recharge is therefore very limited, if it occurs at all, in the centre of the salar (nucleus). Surface water and groundwater inflows to the salars, whilst small, are significant to maintain the fresh/brackish surface water systems. Periodic flooding by surface waters helps maintain the water balance, sporadically in salar de Atacama (Boutt et al. 2016) and more regularly in wetter salars such as salar de Uyuni in Bolivia. Outflows are primarily from evaporation, which are the orders of magnitude higher than the rainfall and abstraction. The latter can take place for potable water supply, industrial supply or brine extraction itself. Climate change, likely to increase temperature but forecast to produce variable impacts on rainfall, will change the balance of the inflows over time (Oyarzún and Oyarzún 2011).

Typically, the brines are super-saturated and have densities of around 1208 kg/m³, which is significantly higher than sea water. For the brine solute mass, NaCl is the main constituent with trace elements of metals such as K, Mg and Li. These accumulate over very long time periods as crust-forming evaporites and also in solution in brines (Houston et al. 2011). A series of chemical reactions and precipitation processes take place that result in the brine chemistry evolving over time and across the nucleus (exhibiting a spatio-temporal dimension) (Hamann et al. 2015).

No two salars are alike, although some fundamental similarities exist. Salars are often classified as mature halite salars and immature clastic salars (Houston et al. 2011). Mature salars are characterised by a relatively uniform and thick sequence of halite deposited under subaqueous to sub-aerial conditions. Immature salars are often characterised by higher precipitation, lower evaporation and tend to be at higher elevation towards the wetter northern and eastern parts of the region.

For mature salars with an exploitable brine, the outflow is via evaporation mainly from surface water ponds around the margin and from the centre of the salar (nucleus). Evaporation has an exponential decreasing relationship with depth. This means that once the water table is 0.5 m below the salar surface then evaporation reduces markedly. Potential evaporation is also controlled by the salinity of the water being evaporated, with the magnitude decreasing with increasing brine concentration (Houston 2006).

Circulation of brine in the nucleus (sinking on creation) is an important process controlling the ingress of freshwater and the position and nature of the brine-freshwater interface. Newly created brine is of a higher density than that below it and this can lead to fluid instabilities (Wooding et al. 1997).

Given the geological complexity of the nucleus, including interlayering of clastic sedimentary sequences with different levels of permeability and deposition of low permeability halites, then vertical anisotropy is an important feature which may limit circulation patterns.

Geochemical processes are also important controlling brine evolution and subsequent movement within the salar nucleus (Risacher and Fritz 2008). Precipitation of minerals can occur resulting from concentration by evaporation, as well as temperature effects (Yecheili and Wood 2002).

As well as in the spatial variations of scale, there are a range of temporal scales over which salar processes operate. They range from months to millions of years as follows:

- Annual — rainy season over a number of months each year, e.g. Uyuni
- Inter-annual — droughts and floods through changes to the nature and timing of the rainy season
- Decadal/century — climatic variation and human induced climate change
- Millenia — climate cycles such as wetter and dryer periods (~ 10 ka) potentially related to Milankovitch cycles (see climate.nasa.gov/news/2948/milankovitch-orbital-cycles-and-their-role-in-earths-climate)
- Geological timescales — millions of years for lithium accumulation and evolution of the depositional environment and catchment

These temporal scales are complex overlapping features of the system and their inter-relationship in terms of lithium provenance.

The brine is mined by pumping from the nucleus of the salars and then concentrated using a series of evaporation ponds, although alternative methods of extraction, for example ‘direct lithium extraction’ (DLE) are also currently being investigated. The concentrated brine is processed further to produce lithium compounds that are then shipped as a solid product. Unlike conventional mining, the brine is extracted as a liquid and, therefore, it is important to understand how brines of varying density and viscosity respond to abstraction and its subsequent interaction with the environment.

Method and approach

Data gathering

The analysis relies on qualitative methodologies. The primary qualitative data was collected over a period of 2 years between 2019 and 2021 with the objective to map and understand the different perceptions and views

associated with the mining of lithium. The methods used included field trips in 2019, semi-structured interviews and virtual workshops with key stakeholders in Bolivia, Chile and Argentina. We undertook a detailed literature review that included government reports, legislative frameworks (laws, regulations, initiatives), standards, best practice documents, environmental impact assessments and others. This information was systematised and incorporated as background context.

Stakeholder mapping

Stakeholder mapping was an essential initial step in the stakeholder consultation process. The lithium stakeholder ecology is complex and includes various actors representing different organisations as well as the civil society. The complexity arises from the interconnectivity of these groups, which links to their specific needs and requirements. A representation of the key actors involved in the lithium sector is provided in Fig. 2. The process of assessing who these stakeholders are and in what capacity they participate in the lithium sector requires a systematic analysis of their roles and responsibilities in the lithium domain and relationships.

We have engaged with stakeholders from all the actor categories shown in Fig. 2. The stakeholders involved in our analysis are presented in Table 1-SI of the Supporting Information document together with an analysis of their roles and responsibilities.

Stakeholder consultation

The virtual workshops included 81 participants from the groups identified in Fig. 2. A list of participating organisations is provided in the supporting information document (Table 1-SI) together with a description on the structure of the workshop (Table 2-SI). The participation was voluntary, confidential and anonymised in the analysis. The workshops followed a common structure, which consisted of a mixture of plenary sessions and breakout rooms, to explore the subjects of stakeholder landscape and environment and social and governance challenges. Single workshops took place for stakeholders in Bolivia and Chile. However, given the complexity of the stakeholder landscape in Chile and Argentina, we used an interview-based approach, with groups of stakeholders to further understand the issue raised in the workshop. In total, nine interviews were conducted and took on average 60–90 min each. Before each interview, the objectives, informed consent and questionnaire were sent to the interviewees. The interviews centred on the social and environmental frameworks for mining activities, the institutional and governance challenges. This

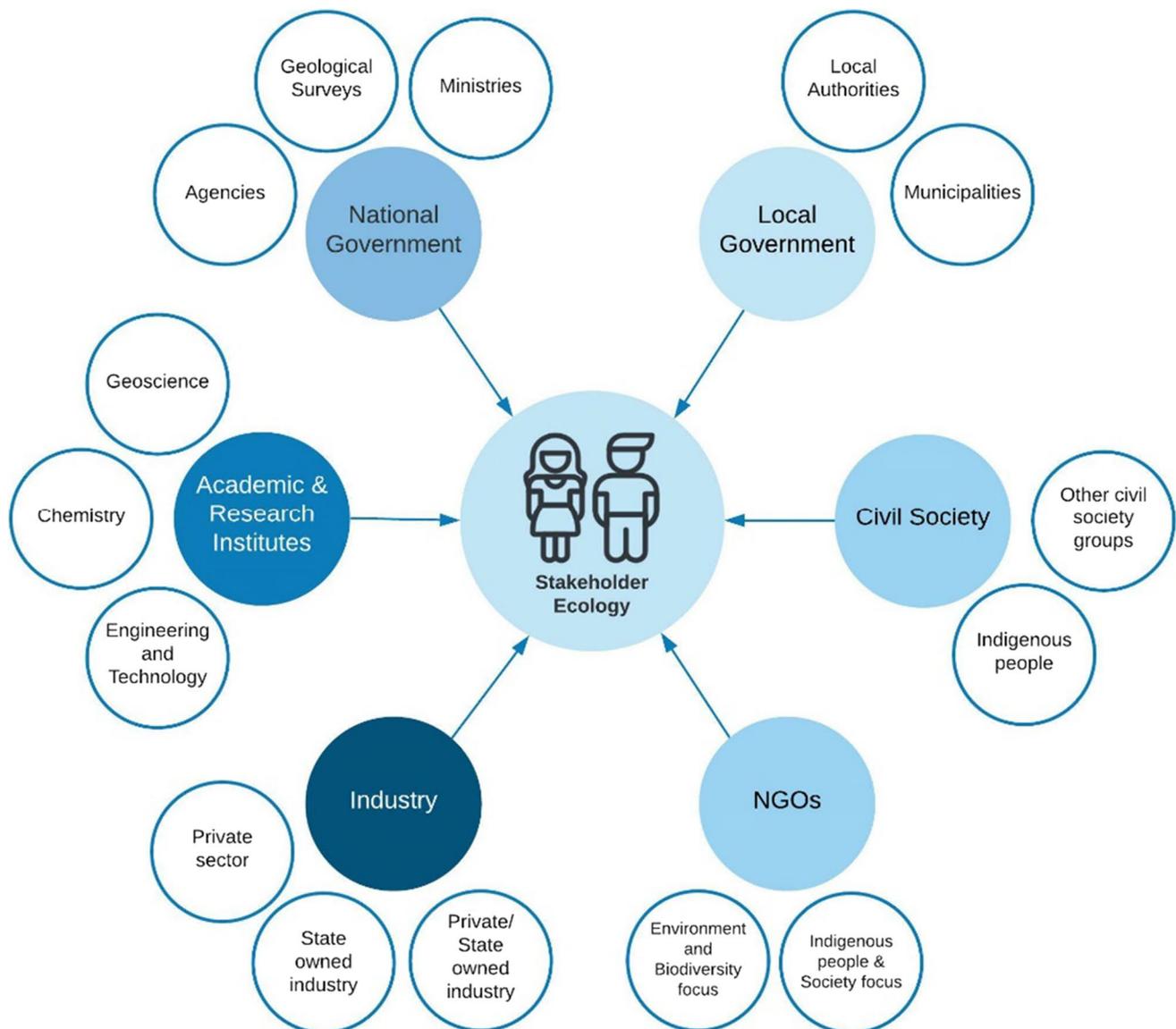


Fig. 2 Key actors in the Lithium Triangle stakeholder ecology

collection of data provided novel insights of the context, conflicts and perceptions around lithium extraction.

Data analysis and interpretation

Country-level perspective

Data both from primary and literature sources were collated and grouped into key impact categories under the environmental, social and governance (ESG) dimensions. At the start of our investigation, we explored the emergence and repetition of ESG issues recorded during the workshops and interviews at the country level. This information was used

to screen their relevance to the story of lithium within the national setting. Issues were scored as follows: one being not relevant to lithium at the country level, two being relevant and three being extremely relevant. The identified ESG issues varied in their context and intensity within the three countries. Figure 3 summarises some of the most salient themes discussed with stakeholder participants.

For the environmental dimension, the results for Bolivia are quite different to that for Chile and Argentina. The latter (Chile and Argentina) outlined environmental concerns as urgent and of high intensity for the future of lithium in the country. On the contrary, in the social and governance dimensions, Bolivian stakeholders discussed a range of issues including inadequate social participation, local

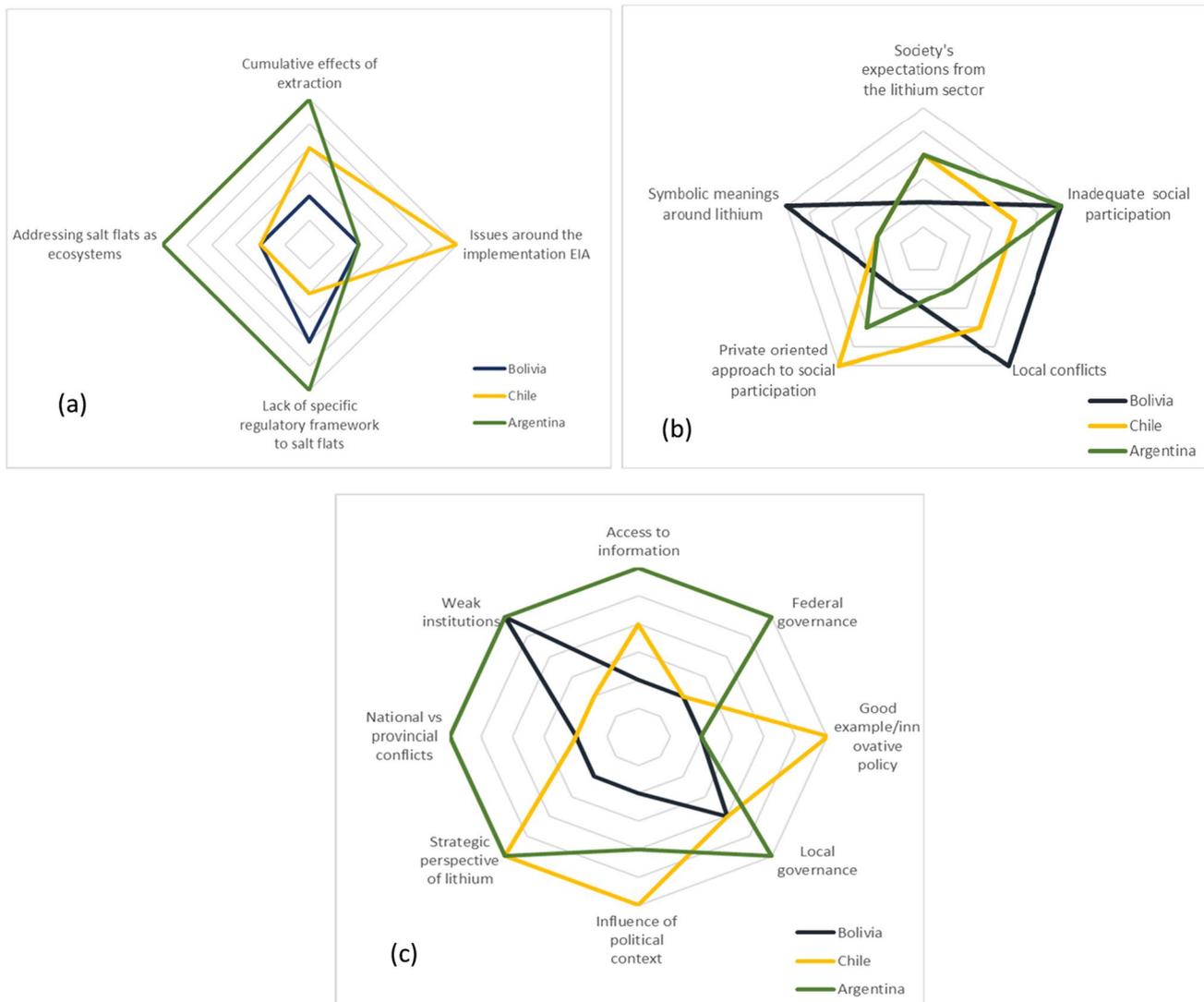


Fig. 3 Environmental (a), social (b) and governance (c) issues of the Lithium Triangle countries identified during our initial exploration. The intensity of the issues is illustrated by points/lines at the outer edges of the spider graph

conflicts, the symbolic meanings around lithium and the presence of weak institutions in the country. In the case of Chile, environmental concerns associated with the implementation of EIAs are identified as critical, followed by governance issues (strategic perspective of lithium in policy making) and social (type of participatory processes). In Argentina, the most relevant dimension encompasses governance issues (e.g. federal governance and the challenges in defining a national strategic perspective on lithium) and environmental concerns (cumulative effects of extraction and the lack of a specific regulation on lithium mining).

This initial mapping at country level provided a variety of common themes, which were used as the basis of the in-depth exploration of the ESG dimensions and their significance at regional (Lithium Triangle) level.

Regional perspective for the Lithium Triangle

The country-level analysis identified a range of issues that may be highly risky for the lithium sector. A more in-depth and systematic analysis was essential to explore the findings further and compare their significance at regional level.

Based on the principles of multicriteria decision analysis (MCDA) (Kulkarni 2022), we developed a scoring framework to assess and prioritise these impacts. The MCDA is based on a systematic analysis that incorporates multiple criteria and order of preference in evaluating the different input (attribute) options. It involves determining the principal path among multiple, conflicting and interactive attributes (Jahan, Edwards et al. 2016). Its use allows for a more logical and scientific approach to ranking and prioritising complex and

complementary attributes. The method gives a ranking result based on the selected criteria, their corresponding values and assigned weights (Linkov and Moberg 2011).

The scoring framework is presented in more detail in Table 1. The assessment is qualitative based on the data and information collated from primary and secondary processes. Our framework considers three different impact receptors. These are the lithium operation, the local communities and the environment (e.g. local and regional ecosystems). The assessment criteria employed are:

- **Severity of impact:** The scope of this is to understand how severe an impact is and the disruption it may cause to the different receptors.
- **Temporal distribution:** This criterion assesses the duration and frequency of an impact to the different receptors.
- **Spatial distribution:** This aims to understand the geographical scale of an impact, which is particularly applicable for the environmental dimension as the greater the scale of an impact the higher its severity. High Andean wetlands, for example, are to be recognised as a composite of ecosystem resources distributed over a wide region, supporting wide-ranging species. For the social and governance dimension, a constant score was used instead.
- **Type of impact:** This distinguishes between direct and indirect impacts, which are likely to result into different implications for the three receptors.

- **Uncertainty:** This indicator is used to assess our confidence in the data collated (e.g. backed up by other stakeholders or by secondary data)

The assessment criteria were equally weighted during scoring. A total score was produced by adding the individual scores together. The unified framework of our approach allows for direct comparison of the results between the environmental, social and governance dimensions. The detailed scoring for each dimension is given in Table 3-SI, Table 5-SI and Table 7-SI in the Supporting Information section.

Identification of the ESG challenges in the Lithium Triangle

Environmental challenges

Given that lithium extraction is theorised to facilitate the carbon transition and to reduce the impacts of climate change, then the environmental impact of its extraction is important to quantify. Alongside this, environmental impacts in these fragile systems are of high concern both to the local population and concerned organisations both locally and globally, as discussed below. There are three key aspects to consider when exploring environmental issues:

Table 1 Scoring framework for assessing the ESG impacts associated with lithium salars

Assessment criteria	Receptor	Score
Severity of impact	Lithium operation	(1 = low) minimum disruption on the lithium operation/local communities/environment
	Local communities	(2 = moderate) moderate disruption on the lithium operation/local communities/environment
	Environment	(3 = high) severe disruption on the lithium operation/local communities/environment
Temporal distribution (duration and frequency) (T)	Lithium operation	(1 = short/rare) short or rare impacts on the lithium operation/local community/environment. Short effects are considered reversible
	Local communities	(2 = moderate/frequent) The duration of the impact on the lithium operation/local communities/environment is moderate, and/or it occurs frequently (i.e. there might be a cyclic appearance of the impact that lasts for a significant period; mitigation measures are deemed to be insufficient)
	Environment	(3 = long term/ongoing) long-lasting impacts on the lithium operation/local communities/environment or/and being an ongoing issue
Spatial distribution (SP)	All receptors	(1 = salar) The scale of the impact is on the salar (2 = catchment) The scale of the impact is on the catchment area (3 = watershed and beyond) The scale of the impact is on the watershed or wider scale *Note: For the governance and social dimensions, a score of 1.5 was used in all cases. This criterion is of less relevant to these two dimensions, but for consistency purposes, it was included in the assessment
Type of impact	All receptors	(3 = direct) Direct impacts have knock-on effects that are highly likely to occur (2 = indirect) Indirect impacts have hidden effects, or the effects of an impact are deflected by intermediate stages/processes
Uncertainty	All receptors	(3 = low) Good data and information is available for the impact assessment (2 = moderate) Partial data or qualitative data is only available for the impact assessment (1 = high) There major data gap and the assessment is highly uncertain

- The water cycle associated with the salars
- The extraction and processing of lithium processing
- The generation and management of waste

Alongside these considerations is the impact of climate change and how this could exacerbate any environmental issues. In total, four groups of challenges have been identified for the environmental aspects as follows:

- (E1), (E2), (E3), (E4) Water challenges
 - (E1) Brine abstraction drawing down of water levels in lagoons
 - (E2) Brine abstraction affects the chemistry of brines
 - (E3) Effect of freshwater supply for mining operation on groundwater levels (from outside the salar)
 - (E4) Effect of freshwater supply for mining operation on groundwater chemistry (up-coning)
- (E5) Infrastructure development and impacts on biodiversity
- (E6), (E7), (E8) Mine design and processing impacts
 - (E6) Mine design and operation and direct changes to land use that affects biodiversity
 - (E7) Waste generation and the impacts on landscape, natural processes and biodiversity
 - (E8) Energy requirements for extraction and processing — carbon footprint of operation
- (E9) Effect of climate change including the nature of rainfall

As Fig. 4 illustrates, most of the environmental impacts falls on the environment (as receptor) itself with impact on the lagoons (E1), biodiversity (E5) and the effect of climate change (E9) having the highest scores. Compared to the three categories of receptor, the lowest scores are for the operators with the exception being climate change (E9). In terms of the environmental impacts on local communities as a receptor, then the majority have a similar, but higher score with climate change (E9) being the highest. The least for the communities is the energy requirement for processing (E8). Table 4-SI in the Supporting Information shows in greater detail each of the challenges, their impacts and associated scale, types of actors (active and passive) and the evidence for impact.

Challenges (E1) to (E4) On water

Here we differentiate between brine pumping from the nucleus for lithium production and other abstraction for mine water supply. Challenges E1/E2 are the resulting impacts from the brine abstraction. In simple terms, groundwater and brine levels can be reduced due to abstraction and the reduction in the brine reservoir. However, this largely depends on the connection between the nucleus, surface water ponds and the lagoons. Whilst the connection between the nucleus and the lagoons has been studied extensively in the Salar de Atacama (e.g. (Marazuela et al. 2019; Boutt et al. 2021; McKnight, Boutt et al. 2021)), given the dynamic nature of the system, this is not proven, particularly as the system is complex and that climatic driven changes can be extremely important. Therefore, more data needs to be collected for the link between brine abstraction and the response of the surface system to be fully established. ReInjection of the brine can mitigate this impact or direct it away from the sensitive areas. This approach is being proposed in a number of development plans for salars and has been undertaken in Salar de Atacama (Marazuela et al. 2020). The lagoons have complex chemistry and are affected by inputs such as rainfall and flooding along with evaporation rates (Boutt et al. 2016). By changing their nature (size, depth, etc.), then the chemistry can be affected. A physical change, therefore, can lead to chemical changes.

Challenges E3/E4 are related to fresh/potable water supply, which given the aridity of the region then any extra calls on water resources will be perceived as environmentally damaging. The abstraction of freshwater for mine water supply both for the salar-based mining operations as well as nearby mining activities, e.g. copper mining, has the potential to further reduce groundwater levels and therefore result in environmental impact. These could be reduction in spring flows used for water supply and ecosystem support such as in the Tuyajto Basin, northern Chile (Herrera et al. 2016) as well as reduction in levels resulting in loss of access to water from shallow abstraction boreholes due to the lowering of the water table.

Given the proximity of the brine body to the freshwater, then there is also the danger that abstraction can induce salinity into otherwise fresh parts of the system (E4). This will reduce the water quality and could result in brackish water being abstracted. However, set against this is the idea that the whole hydrological system in the region is moving from a wetter to a drier state over millennia (see for example Nunnery et al. (2018)), recharge rates are reducing and subsequently groundwater levels are falling, e.g. Salar de Atacama (Boutt et al. 2021). This means that there are natural drivers to changes in the groundwater system which operate

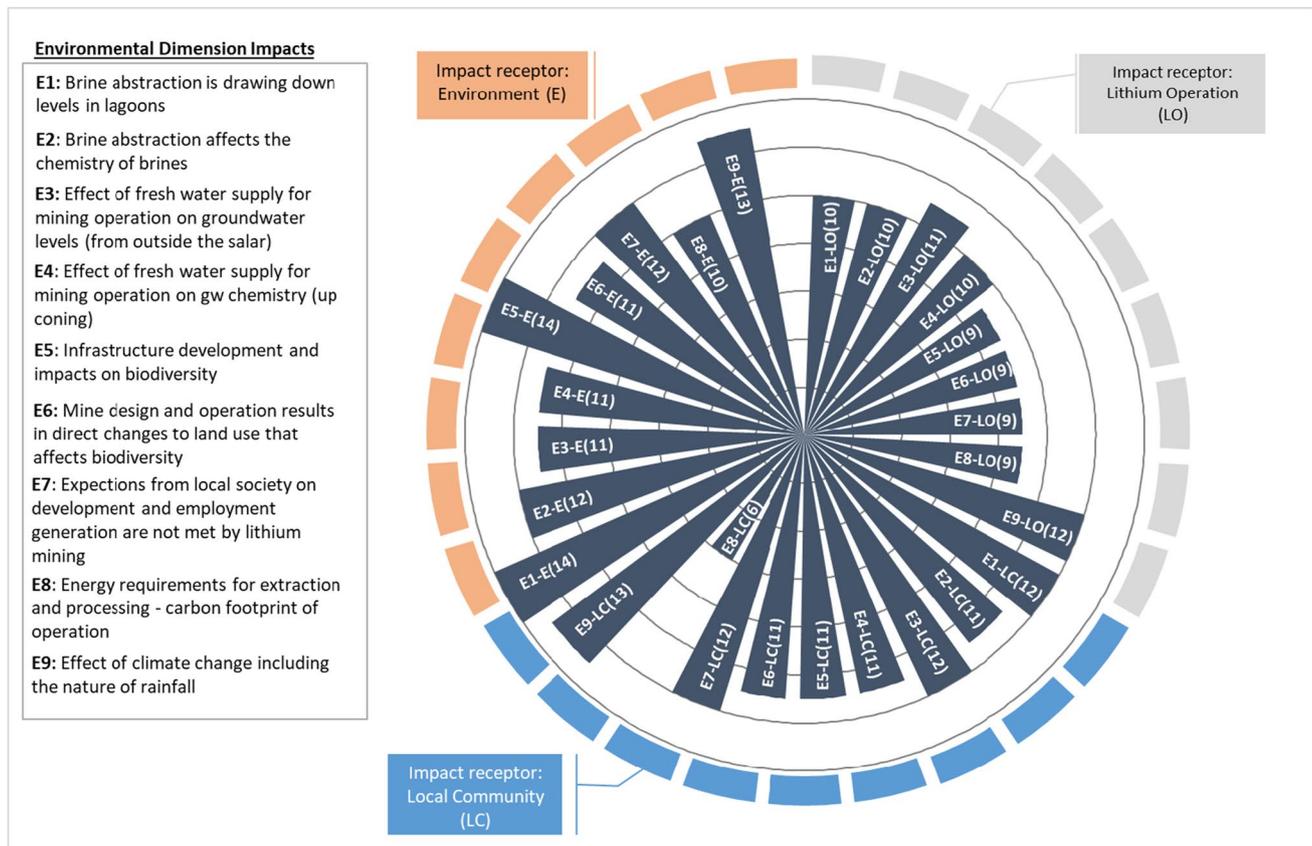


Fig. 4 Impact analysis results for the identified environmental challenges. The challenges are described in the index provided in the graph. Three receptor groups are included in our analysis: environment, lithium operation and local community. The graph labels, e.g.

E1-E(4), describe the challenge number (e.g. E1), then the receptor (e.g. E), whilst the number in the parenthesis represents the score given to a particular challenge

over multiple timescales (seasonal, inter-annual, decadal and longer-term timescales) both in terms of flow and levels which will complicate the understanding of abstraction impacts.

Challenge (E5): Infrastructure impacts on biodiversity

There are a number of features of lithium production that could affect biodiversity. The evaporation ponds create a significant area of open water which has the possibility to attract wildlife and confuse migrating birds. The supply of power and raw materials as well as transport of the product requires the development of linear features such as electrical transmission lines and roads. These have the ability to cause harm to migrating birds through line-collision hazards, linear road features disrupting surface waterflow and to disrupt habitats and migration routes for terrestrial animals. The operation of the facilities themselves can result in indirect impacts such as poor food waste management resulting in increased scavenger populations leading to increased predation impacts.

Challenges (E6) to (E8): Mine design and processing impacts

Challenges E6/E7/E8 relate to the environmental impact of the mine itself and the associated production facilities.

Challenge E6 relates to the ponds area footprint, changes to land use, e.g. processing plants creating issues for biodiversity. Salars are typically a pristine 'green field' site which has delicate hydrologic and hydrochemical balances supporting biodiversity and ecosystems developed over many millennia. The construction and operation of the evaporation ponds and/or processing plant take up land area. Site development can have a direct influence on biodiversity related to its footprint as well as the surrounding area.

Challenge E7 relates to the physical and chemical changes to the environment by the large mass and therefore volume of waste produced as a by-product of lithium production: issues with flood management as well as loading the salar surface with chemical waste. DLE will produce waste on a scale as yet unknown but likely to be of

lesser volume but potentially greater toxicity than the use of evaporation ponds.

Given lithium's role in the energy transition, energy consumption and its associated carbon footprint needs to be assessed (challenge E8). Lithium is seen as the saviour for energy transition but may require significant energy input to produce. Whilst evaporation ponds may utilise 'free energy' from solar radiation to aid evaporation (Flexer, Baspineiro et al. 2018), they consume energy and materials in construction and operation by pumping brines from the wellfield to the ponds and between them. DLE requires significant increased energy for its operation, and the processing plant will require energy input.

Challenge (E9): Effect of climate change including the nature of rainfall climate change impacts

Given the aridity of the region, then future climate change is of significant concern (Oyarzún and Oyarzún 2011). Regional work on the future predicted rainfall and temperature has been undertaken using global circulation models (GCMs) (Williams 2017)). These are in general agreement that rainfall could decrease, and albeit differences between predictions, temperature is forecast to increase consistently between GCMs.

Examples from the triangle countries of climate change on hydrological systems confirm these overall trends. A review of climate change impacts on Argentina (Barros et al. 2015) using representative concentration pathways (RCP) 4.5 and 8.5 shows increases in temperature and more or less similar rainfall for northern Argentina. The results for the different RCPs are same for near future, but differences are observed in change in temperature for far future. Increased temperatures result in glacier melting and resulting modification to the hydrological regime. Similarly for Bolivia, a country-wide hydrological balance and climate change assessment has been undertaken (Escurra et al. 2013). In all, 17 GCMs based on the IPCC special report emissions SRES A2 scenario were used to drive a hydrological model for each basin within the country, showing that the Uyuni watershed has the lowest (greatest negative) Climate Moisture Index (CMI) due it being the driest region. The CMI shows very little variation between the GCMs. Reduction in rainfall is forecast for the 2050s which varies between 5 and 10% for the GCMs used whilst potential evaporation (PET) increases by a similar amount. For Chile, an example of work on the Salar del Huasco basin has been reported (Blin et al. 2022). Results were used from CMIP5 drawing on 219 climate models for four RCPs (2.6, 4.5, 6.0 and 8.5). This work showed that temperature will increase and precipitation is more variable. This leads to varying recharge

response and changes to the basin hydrology, including variation in evaporation from the groundwater system.

Individual environmental impact assessments (EIA) are carried out by each operator for stages of development and are often made available via the Internet. However, these do not enable the potential derogation of multiple schemes to be investigated or understanding how different basins could interact (Risacher and Fritz 2008). Other ways in which communities can be involved is the use of participatory monitoring whereby local stakeholders actually undertake the monitoring and report the results as part of the wider environmental understanding. Good practice has been observed in the lithium triangle countries to this end, in particular in Jujuy Province (Marchegiani, Hellgren et al. 2019).

Social challenges

The challenges emerging from the social perspective are often overlooked in discussions over security of supply, decarbonisation and environmental impacts. Based on the primary qualitative data of stakeholders' elicitation, we identify a range of issues and tensions that can potentially have an important dominance over the future of lithium mining in the region. In this work, we acknowledge two key elements: (i) the relevance of talking about social challenges and impacts recognising their interconnectivity to environmental and governance aspects and (ii) the contextual differences observed across the three countries of the lithium triangle, their political and cultural heritage and their societal construct, including indigenous communities and even societal impacts originating from the geography of the region. We identified six overarching social challenges in our analysis (Fig. 5), which are all considered highly likely to occur at some point in time. The methodology section provides further information on our approach and analysis.

- (S1) Social conflict due to inadequate social participation processes can increase the risk of project development, delay or pause mining activities.
- (S2) The lack of technical knowledge and support for local communities to understand mining regulations and related disclosure documents can impact on the social license to operate.
- (S3) The lack of ongoing mechanisms of communication and engagement with the communities to identify and address potential conflicts throughout the life cycle of a mining project
- (S4) Society's perception of environmental harm from lithium extraction can lead to opposition towards mining development, delays and pause of mining activity.
- (S5) Unsatisfactory mining remittance distribution to local society leads to social conflicts and adverse perception to mining.

- (S6) Expectations from local society on development and generation of employment are not met by lithium mining projects, which could lead to social conflicts.

As illustrated in Fig. 5, most of the identified challenges except for (S6) score highly for the local communities' receptor. In particular, (S4) on society's perception over the environmental harm of mining activities and (S5) on mining remittance seem to be of major concern to local societies and can, therefore, provoke risks to the development of projects. (S4) has been identified as highly risky for the two other receptors included in our analysis, namely the environment and the lithium operation, which highlight how the lack of scientific data that can resolve or endorse any perceptions associated with the environmental impacts of lithium mining are crucial for the future of such projects. The importance of social participatory processes ((S1), (S3)) that can deliver the social license to operate is of great importance to lithium operations, as well as local communities, with the difference that local communities often demand participatory processes that are holistic and extend beyond the preparatory mining

development stages. The following sections explore these challenges in more detail, including their historic development and adaptation. Additional details on the data gathered are provided in the Supporting Information (Tables 5 and Table 6).

Challenges (S1) to (S3): SLO and social participatory processes

The term social license to operate (SLO) made its appearance in the mining sector in the mid-1990s to manage social challenges by ensuring that companies and communities operate under a shared vision and maximum benefits to all involved stakeholders (Boutilier 2014; Ehrnström-Fuentes and Kröger 2017). SLO is entrenched in the exploration stages of the mine life cycle and closely connected to the environmental impact assessment (EIA) requirements. In principle, the way SLO is granted through social participatory procedures in Bolivia, Chile and Argentina presents substantial differences and bottlenecks. It is important to highlight that the makeup of the region consists of 5 main

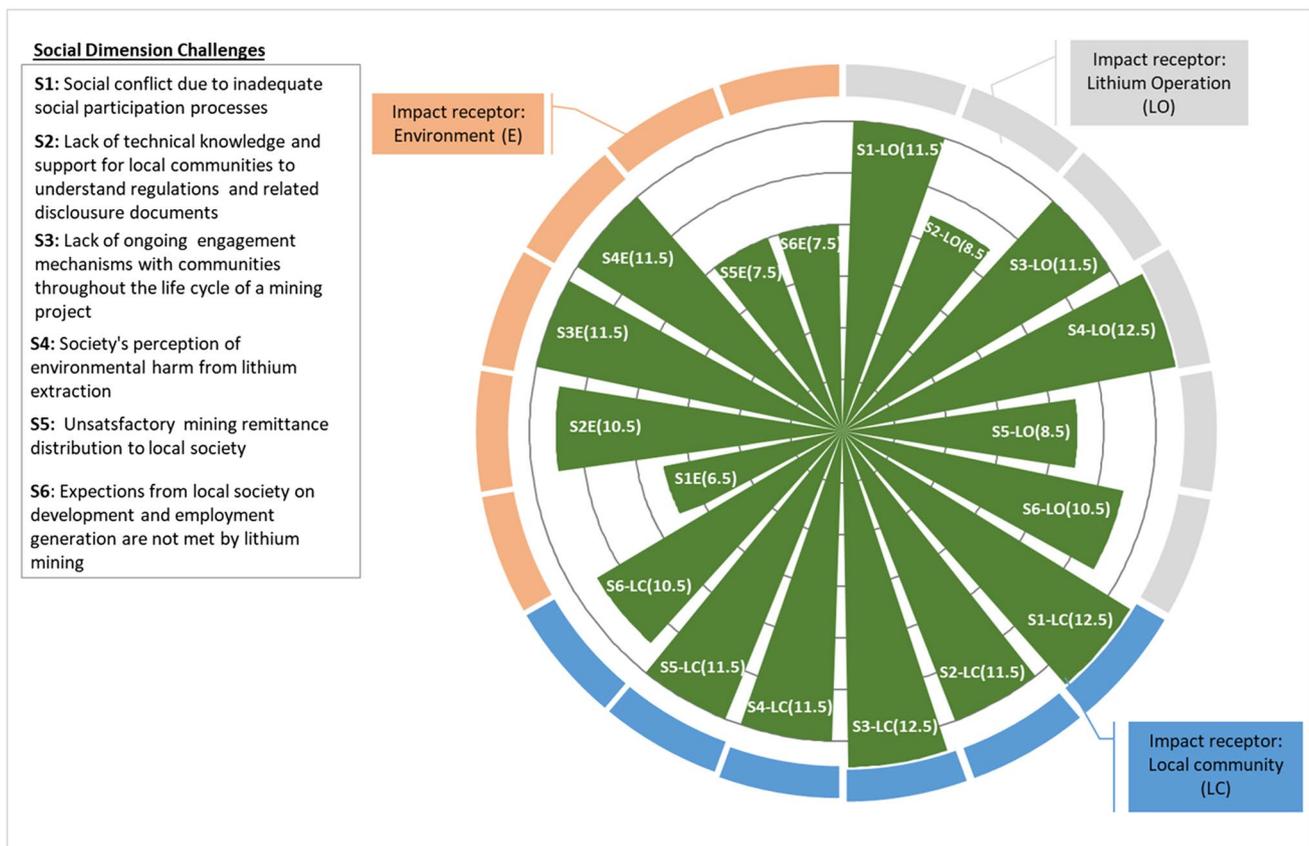


Fig. 5 Impact analysis results for the identified social challenges. The challenges are described in the index provided in the graph. Three receptor groups are included in our analysis: environment, lithium operation and local community. The graph labels, e.g. S4E(11.5),

describe the challenge number (e.g. S4), then the receptor (e.g. E), whilst the number in the parenthesis represents the score given to a particular challenge

locations: Atacama (Chile), Salta/Catamarca/Jujuy (Argentina) and the southwest region of Potosí (Bolivia). Together, they host an estimated population of around 2.9 million people, including 842 indigenous communities (e.g. Quechua, Aymara, Atacama, Lules, Tastiles, Atacama de la Puna, Guaymallén, Diaguita-Calchaquí, Kolla, Guaraní, Kolla Guaraní, Ocloya, Omaguaca, Tilián, Toara, Toba among others) (Gerencia Nacional de Recursos Evaporíticos (GNRE) 2012, Molina Otarola 2018, Instituto Nacional de Asuntos Indígenas 2022).

In Bolivia, where operations are controlled by the State, the Constitution defines social participation and indigenous people rights (Chapter. IV, Art. 30; Chapter. IX, Art. 403). It defines that indigenous communities have collective rights over their territories — including land, renewable and non-renewable natural resources — and the ‘rights to consultation, autonomy and self-governance’ regarding projects and activities that affect their livelihoods (Gaceta Oficial del Estado Plurinacional de Bolivia 2009). These rights are also recognised by ILO Convention No. 169 (International Labour Organization 1989) and the United Nations Declaration on the Rights of Indigenous Peoples (UN General Assembly 2007). The national mining law (535) (Ministerio de Minería y Metalurgia 2014) defines the right of consultation in cases of exploitation, but prospecting and exploration phases are excluded from this process, which is contradictory to the SLO terms of reference. Therefore, although social participation and consultation processes are part of the Bolivian legal framework, their implementation, validity and success in social inclusion and in giving decision-making rights to civil society are highly questionable.

In Chile, it was only in the decade of the nineties that specific rules were introduced including, the Indigenous Law 19.253 (Ministerio de planificación y cooperación 2020), Law 19.418 (Ministerio del interior; subsecretaría de desarrollo regional y administrativo 2019) (establishes rules on neighbourhoods and other community organisation), Law 20.285 (Ministerio secretaria general de la presidencia 2020) (on access to public information), Chile’s subscription to the ILO Convention No.169 (International Labour Organization 1989), the United Nations Declaration on the Rights of Indigenous Peoples (UN General Assembly 2007), the Indigenous Constituent Participatory process (coordinated by the Ministry of Social Development) (Ministerio de desarrollo social y familia 2022) and others. The social participatory processes are connected to the environmental permitting and impact assessment processes and the requirements for citizen participation may vary depending on the scope of the assessment undertaken, for example for the environmental impact declaration (EID), a formal mechanism of participation is required only for specific types of projects (i.e. energy supply and infrastructure, sanitation). For the environmental impact assessment (EIA), an essential step for progressing with mineral exploration, citizen participation is mandatory for the approval

of a project. This takes place after the submission of the project to the review and approval system. The Environmental Impact Study (one of the main documents of the EIA) must provide evidence on the participatory process and discuss any observations made, issues raised as well as submit responses to them (Rodríguez-Luna et al. 2021). Depending on the location of a project, the participatory process might require engagement with indigenous communities too. Lithium mining in the salar de Atacama has led to cycles of conflicts, social activism and negotiation processes, which clearly outline the interrelationship between mineral governance and social participation processes (Gundermann and Göbel 2018; Liu and Agusdinata 2020). In the case of lithium extraction in Chile, although the regulatory framework and procedures seem to be adequate for setting the conditions for social participatory processes, there is still scope for improvement in capacity building (i.e. community organisations do not have the capacity to be involved adequately in the participatory process or public authorities often lack the resources to respond to the process demands) and technical knowledge in social organisations participating in this process. The private-oriented approach to social participation and direct dialogue with the communities in the Atacama region should also involve relevant public institutions such as the Ministry of Environment and the Superintendency of Environment, which are to some extent disconnected from the processes, although they collect a wealth of information and claims during the environmental permitting, management and monitoring stages. Overall, there are many positive steps taken in social participation, for example the community agreement of the Consejo de Pueblos Atacamenos (CPA) with Albermarle (Armisén 2018), many of which however remain at the project level without any strategic planning and coordination of how to address these at the greater level, e.g. the salar which may include several operators, including the lithium extraction sector in Chile.

In Argentina, social participation is approached from two different directions: citizen participation and indigenous communities’ consultation. The key legal norms in place that relate to social participation include the General Environmental Protection Law (Honorable Congreso de la Nación Argentina 2002), the National Constitution (Honorable Congreso de la Nación Argentina 1994), the Indigenous and Tribal Peoples ILO Convention 169 (International Labour Organization 1989) (ratified in 2000) and the UN Declaration of the Rights of Indigenous People (UNDRIP) (UN General Assembly 2007) (ratified by Argentina in 2007). An additional framework of reference is the Guideline of the Organization for Economic Cooperation and Development (OECD) for Multinational Enterprises (OECD 2011). The recognition of indigenous groups at the Constitutional level occurred in 1994 and in that indigenous communities represent ethnic and cultural groups with land property rights as well as rights to manage natural resources. The above is endorsed by the broader international instruments outlined above, for example the OECD framework states that

companies should recognise local community authorities and provide communities with opportunities to express their views and take them into consideration for decisions regarding projects that could influence them (Secretaria de Ambiente y Desarrollo Sustentable 2018, Marchegiani, Hellgren et al. 2019; Secretaria de Ambiente y Desarrollo Sustentable 2019; Marchegiani et al. 2020). The UNDRIP (article 32) establishes the importance of ‘free prior and informed consent-FPIC’ in which indigenous peoples have the right to ‘determine priorities and strategies for the development or use of their lands or territories or other resources’. It is, therefore, the role of the State to consult with indigenous peoples prior to any project approval to ensure that their free prior informed consent is obtained. In Argentina, the National Constitution makes the FPIC a rule of compliance. However, this is not regulated properly at regional/provincial level through domestic law (Marchegiani, Hellgren et al. 2019). One of the key characteristics of the governance in Argentina (see governance challenges section) comprises its provincial structure and autonomy of the ‘lithium’ provinces of Salta, Catamarca and Jujuy. It is the provinces, therefore, that are responsible for setting regulations related to mining activities, providing mining concessions, interacting with mining companies, managing and monitoring mineral resources, ensuring environmental protection within their area and interacting with civil society and indigenous communities. Hence, the responsibility to ensure SLO and manage social participatory processes is a task allocated to the provinces. The SLO is ingrained within the EIA process, which sets the requirement for a public participation phase (consultation or public hearing). The consultation aims to provide the opportunity for citizens to outline concerns and impacts to local communities in a written form. However, this stage is not binding on the approval of the project. This means that the authority conducting the evaluation may decide differently to the consultation evidence if this is justifiable. This is contradictory to the ILO Convention 169, which states that social participation is binding to any project approval process. Such discrepancies serve as examples that often link to socio-environmental conflicts which in turn may cause delay or pause mining activities. In addition, the approach taken to manage conflicts and territorial claims by each province is unique, which leads to additional complexity and potential cross-regional issues. Two interesting cases of social conflicts are the Olaróz-Cauchari project (located in Jujuy Province) and the Salinas Grandes/Laguna de Guayatoyoc (Province of Jujuy and Province of Salta). In the case of the Olaróz-Cauchari project, the indigenous organisations questioned the participatory processes and quickly established a strategy based on informative meetings with their communities including negotiation actions. This resulted in the company being committed to a series of actions such as ensuring local jobs, annual monetary payments and modest public works to secure the SLO (Marchegiani, Hellgren et al. 2019). The EIA procedure and the first environmental study report were initially submitted in 2010, but due to the additional requirements, the

project was not approved until 2012 (small scale) with additional permitting in 2017 for the larger scale operation (LithiumAmericas 2022). In the case of Salinas Grandes-Laguna Guayatoyoc, the project did not progress further and ceased its operation after facing significant resistance from indigenous communities (González and Snyder 2021). The key argument focused on their right to ‘free prior and informed consent-FPIC’, which led to the formation of an alliance at provincial and national levels with law experts and NGO, a filed petition to the Supreme Court of Justice of the Nation and a lawsuit with the UN Permanent Forum on Human Rights. These cases highlight the value of well-designed and implemented participatory processes and the importance of direct negotiations of mining companies with communities that can result in support for their activities (Göbel 2013; Marchegiani, Hellgren et al. 2019; Pragier 2019; González and Snyder 2021).

Challenge (S4): Society’s perception of environmental harm from lithium extraction

Concerns regarding the environmental impacts of lithium extraction from salars are communicated through various forms in popular media, scientific journals and social media and have also become apparent during the stakeholder engagement undertaken by this project. Often, these concerns are associated with the abstraction and use of freshwater for lithium mining purposes in areas that are known to be arid. The way local societies perceive this problem has led to conflicts and unrest and ongoing discussion for several years that unfortunately has not reached resolution. Our analysis suggests that this is a highly complicated challenge and one of high risk for the future of lithium projects in the lithium triangle.

It is important to understand, however, the underlying reasons that underpin society’s adverse perception on lithium extraction. Overall, mining is often perceived as negative due to impacts from historic projects on waste management, water scarcity, pollution and others. In the case of lithium, issues associated with the legacy of mining are endorsed further by the global escalating demand for lithium resources to move towards decarbonisation, which is perceived as highly impactful by local communities on their livelihoods and ecosystems with which they are co-located. With that in mind, there is the expectation that the environmental governance frameworks applicable in the lithium triangle countries, the environmental impact assessments (EIA), monitoring and management procedures provide the underlying scientific evidence to inform them about potential environmental hazards. However, there are concerns related to not only the lack of adequate procedures for social participation across the whole life cycle of mining project, issues regarding the sharing and accessibility of information collated in EIAs, the lack of baseline data, but also the content of technical information and their user friendliness. These concerns impact the suitability of existing

environmental governance procedures to provide robust scientific data and answers to questions posed by society regarding the exploitation of lithium salars. There are, therefore, several ‘hidden’ reasons behind adverse societal perceptions and conflicts, often expressed under the message of societal concerns over environmental harm, which are complex and require further in-depth analysis and tailored mitigation actions.

Challenge (S5): Unsatisfactory mining remittance distribution

The governance frameworks associated with the management of mining royalties and the approaches taken by the lithium triangle countries have been presented in the governance section and under challenge (G4) (see governance challenges section). ‘Fair’ mining remittance remains an important incentive for local communities and can influence social acceptance as well as the community’s perception of mining. In our research, we found out that often concerns around mining are underlined by unsatisfactory mining remittance distribution. Although this is neither new nor unique to lithium, the level of expansion required to produce lithium for the global electrification objectives, as well as the partnerships being in development with the downstream supply chain (e.g. Argentina Sales de Jujuy project — partnership of Orocobre/Toyota Tsusho Corporation/Jesme), could lead to further conflicts over mining royalties. The Bolivian case, as discussed in the governance section, provides a good example of this, including the impacts that have had on the overall timeline of project, which is still yet to reach operational status since its initiation in 2008.

Challenge (S6): Local development and generation of employment expectations are not met by the mining project

Mining projects can positively influence local communities by providing opportunities to improve quality of life through programmes that enhance access to health, education, business development, infrastructure and employment. Expectations for local development opportunities are always linked to mining projects, but in the case of lithium and its importance to deliver the global decarbonisation agenda, such expectations are much higher both from local communities and national governments, for example all Lithium Triangle countries currently explore opportunities for adding value to their lithium resources through the industrialisation of lithium. In the case of Chile and Bolivia, the declaration of lithium as a strategic resource puts additional weight into these expectations, which trickle down to local communities, who

in turn demand more benefits. However, only a limited number of projects are currently in full production and the future of projects in development are still uncertain. The impact of these demands from lithium projects, both at local and national levels, may not only have adverse implications for the developing projects, by discouraging the social license to operate in a timely manner, but may also impact existing projects that are looking for future expansion opportunities.

These challenges have significant implications for the understanding of how the governance frameworks interlink with environmental impacts, societal needs and expectations. Participatory processes have provided spaces of engagement to communities on mining questions occurring in their area. Despite legal recognition and sometimes a slow and uncoordinated policy implementation, a meaningful, informed and non-hierarchical participation remains as a key challenge for the state, civil society and industry stakeholders. The vested interests and the forms of support or resistance that the different stakeholders have in the lithium triangle illustrate that any notion of sustainability needs to acknowledge the interphase and complexity of regulatory frameworks, environmental conditions and social relations.

Governance challenges

The Lithium Triangle countries share significant lithium resources found in more than 70 salars, with the most important ones being Salar de Uyuni in Bolivia, Salar de Atacama in Chile and Hombre Muerto in Argentina. By contrast, the three countries differ in levels of development, governance regimes and strategies for the exploitation of lithium.

The notion of governance is considered in this work at two levels: firstly, the forms of access to and control over resources, and secondly, the multiple articulations and negotiations with key stakeholders (state and non-state), institutions and scales (local, national, global) (Perreault 2006; Himley 2008). The rules around lithium governance, the stakeholder landscape and the purpose or motivation of different stakeholders are key criteria to understanding the socio-environmental transformations that are currently occurring in the region and will continue to unfold as the global lithium demand grows into the future.

The spectrum of governance frameworks in lithium mining is a key feature. For instance, in Chile, lithium is a strategic resource (in other words, a resource important for the country’s military and economic strategies), as such, it has the status of ‘reserved for the state’ since 1979 and, the mining activities are excluded from the concessional mining regime, except for those entities which had mining

concessions (*pertenencias mineras*) before 1979¹ (Poveda Bonilla 2020). The original designation of lithium as a strategic resource dates back to 1976 when the de facto Government of Augusto Pinochet declared lithium a material of ‘nuclear interest’ in the manufacturing of hydrogen bombs (Law No. 16319) (Obaya and Pascuini 2020).

In 1983, the Mining Code established that non-concessional resources like lithium could be exploited by private entities in three ways: directly by the state through state companies, by administrative concessions or by special contracts of operations (Contratos Especiales de Operacion CEOL). Consequently, lithium has been extracted for more than 25 years by two private companies: the American Albemarle and the Chemical & Mining Co. of Chile Inc. (SQM), both operating in the concession areas of CORFO in the Atacama salt flat.

Similarly, lithium is considered strategic in Bolivia and has a centralised decision-making process, but unlike the neighbouring countries, the governance framework establishes total and absolute control of the state in the upstream and downstream lithium supply value chain. Only in the phase of industrialisation of cathodes and batteries are allowances for public–private partnerships made, with the state retaining no less than 55% of net profits. Over more than a decade since the beginning of the state initiative, and public investment of around US\$1 billion, YLB has had extremely modest results in terms of lithium carbonate production at the pilot scale; it has not yet entered the international market. The industrialisation policy has also encountered important obstacles to consolidate public–private partnerships, especially with foreign partners (Sanchez-Lopez 2019).

In Argentina, lithium does not have a strategic status by the national government. The governance framework establishes a decentralised management of resources at subnational levels (provinces) with the rights to define concessions to private and state actors and regulations for mining activities within their jurisdictions (Slipak and Urrutia 2019). Lithium mining has been carried out for more than 20 years in the north of the country by American and now Canadian, Australian, Chinese and Japanese companies. From the three countries of the region, Argentina is the most dynamic with more than 38 projects at different pre-feasibility or feasibility stages (Subsecretaria de Desarrollo Minero 2019).

¹ These include:

- CORFO — 55% of the Atacama salt flat.
- CODELCO — 100% of Pedernales salt flat and 18% of Maricunga salt flat.
- Empresa Nacional de Minería (ENAM) — 4% of Aguilera salt flat.
- Three private groups holding 25% of Maricunga salt flat.

The governance frameworks influence sustainability through the following two key roles that they play: (i) the state institutions at national and sub-national levels define the different forms of access to and control of lithium; (ii) they also set the social and environmental mechanisms through which the different stakeholders (state, mining companies, local communities) interact and influence the decision-making spheres regarding lithium activities. In social terms, the governance framework set the ground rules for defining how social participation takes place, who are the relevant stakeholders and their degree of influence with the state as well as with mining companies. This complex situation has a direct impact on sustainability in economic, social and environmental terms as it will be explored in the following sections.

In the academic debate, the governance of lithium has been explored in terms of the extractive industry development implications, structural constraints and possible socio-environmental impacts (Olivera 2017; Hancock et al. 2018; Barandiarán 2019; Fornillo 2019; López, Obaya et al. 2019; Dorn and Peyré 2020; Heredia et al. 2020; Maxwell and Mora 2020). Of particular relevance is the argument in relation to governance typologies (centralised-hierarchical in Bolivia, market oriented in Argentina and hierarchical but delegated to private industry in Chile) (Obaya and Pascuini 2020). In each of these regimes, there are complex political and social scenarios in which sustainability intersects with negotiation, consensus and opposition of multiple stakeholders. Sanchez-Lopez (2019), on the other hand, argues the notion of sustainability is variegated as there are multiple interests and scales (local, national and international) interacting, clashing and negotiating the governance frameworks of lithium. An important empirical gap that this paper explores is the diversity of governance issues and the differentiated impacts for local communities and mining operators in the region.

In our analysis, we address this gap by identifying five key challenges (Fig. 6). The methodology section provides further information on our approach. The identified challenges point out to five main areas:

- (G1) Inadequate management and monitoring of cumulative and indirect environmental impacts
- (G2) Current regulatory frameworks do not address sustainable development and/or are not fit-for-purpose for lithium.
- (G3) Fragmented regulatory frameworks address only specific aspects of the mining project (e.g. environment, extraction, human health), whilst unnecessary bureaucracy can cause delays on mining project, increase development risks and loss of credibility on investors
- (G4) The management of mineral royalties and issues around their rates and distribution to local communities

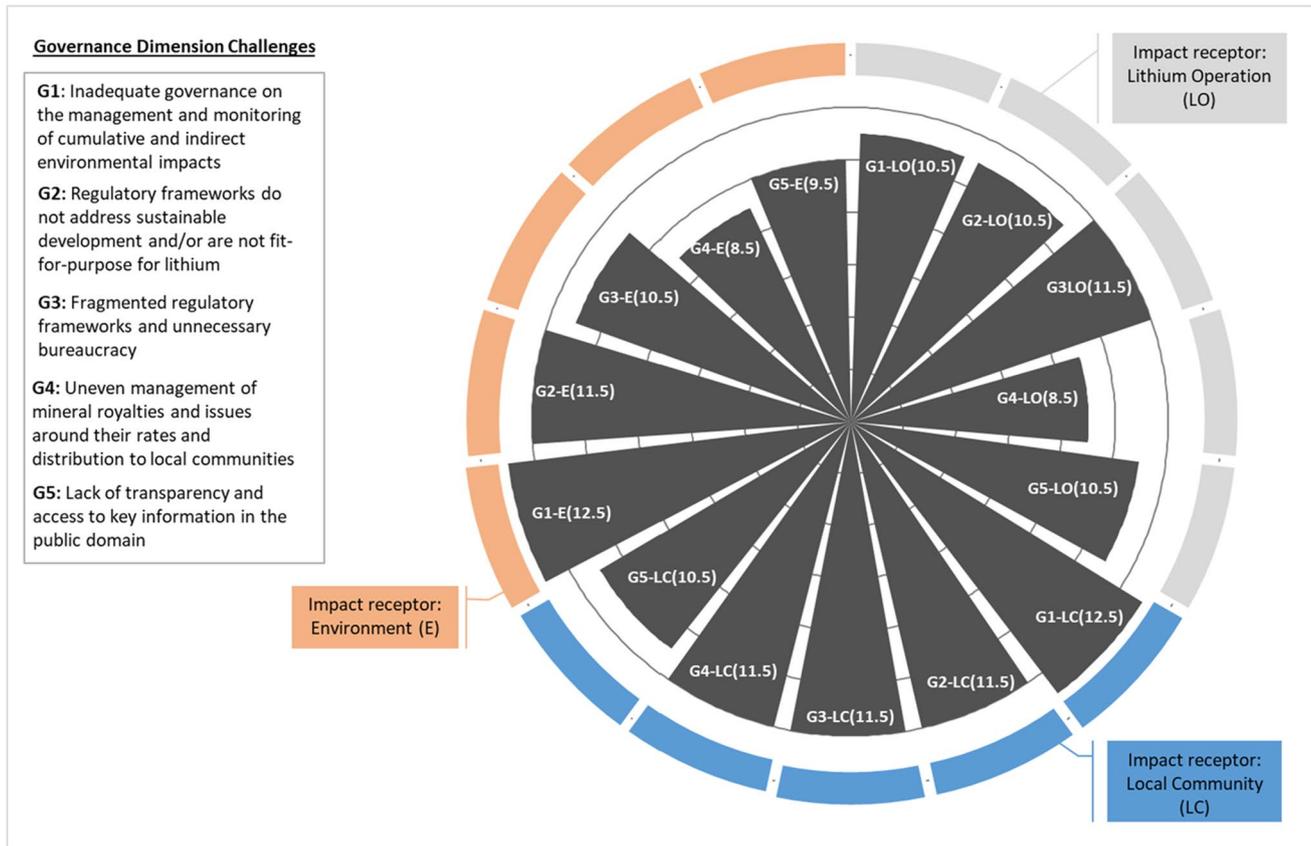


Fig. 6 Impact analysis results for the identified governance challenges. The challenges are described in the index provided in the graph. Three receptor groups are included in our analysis: environment, lithium operation and local community. The graph labels, e.g.

G3-E(10.5), describe the challenge number (e.g. G3), then the receptor (e.g. E), whilst the number in the parenthesis represents the score given to a particular challenge

is linked to challenges with gaining a social license to operate.

- (G5) Lack of transparency and access to key information in the public domain may lead to diminished social license to operate and false perception on the impacts of lithium mining.

As Fig. 6 illustrates, most of the governance challenges have a higher overall impact for local communities, in particular the inadequate management and monitoring of environmental impacts (G1) that do not reflect the complexity of the salt flat as an ecosystem connected to people’s livelihoods. All other identified challenges (G2–G5) score quite high for the local communities’ receptor group. As for mining operators, the most important impacts are the atomised regulatory framework (G3) that is time-consuming and is perceived inefficient and the lack of mechanisms to provide and access relevant public information about mining operations (G5). Governance issues and their impacts to the environment score significantly high primarily due to the lack of clear and adequate procedures for monitoring

and managing environmental impacts (G1) and the deficient regulatory framework that can address sustainable development of lithium mining (G2). The different stakeholders we interviewed for this work also highlighted that the governance challenges in the region are an opportunity to improve regulation, evaluation and monitoring and set a benchmark in terms of community participation. Tables 7 and Table 8 in the Supporting Information shows in greater detail each of the challenges, their impacts, types of actors (active and passive) and the different scales in place.

Challenges (G1) to (G3): Non-systemic approach to environmental management/regulatory frameworks does not address sustainable development and is not fit-for-purpose for lithium/fragmented regulatory frameworks.

Depending on the country and the type of governance regime (centralised or decentralised), the regulatory frameworks for environmental licencing, management and monitoring operate as independent systems with several public

institutions that have different degrees of coordination and cooperation, for instance, in Argentina, the national government has the mandate to establish the basic laws and standards for environmental protection whilst the provinces oversee the implementation and adaptation of regulations.

As for Bolivia, the central government defines the environmental framework and the evaluation and monitoring tools. However, there seems to be an inadequate alignment of sectoral norms (in particular in the mining sector), for example the mining operator is responsible for the development of the environmental impact assessment, the gathering of evidence and the submission of an applications for an environmental licence to the environmental authority (Ministerio de Medioambiente y Agua (MMAyA)) for large projects or special cases in protected areas or the environmental units in the departmental governments for smaller mining projects (up to 300 tons of production/day) (Andreucci and Gruberg 2015). The lack of coordination of decentralised attributions at departmental and municipal levels in environmental management is an important obstacle to implement and enhance the environmental regulations.

In Chile, there are different public entities that form a more or less coherent centralised system of environmental framework articulated and implemented in conjunction with regional institutions. Specifically, the Ministry of Environment (Ministerio del Medio Ambiente (MMA)), the Environmental Evaluation Service (Servicio de Evaluación Ambiental (SEA)) and the Superintendence of Environment (Superintendencia del Medio Ambiente (SMA)) and the Environmental Tribunals are the most important institutions to cover all aspects of environmental management (strategic planning, evaluation, monitoring and legal claims).

Both in Bolivia and Argentina, mining of lithium does not have a particular environmental framework to address the impact and mitigation actions adapted to the peculiarity of the salt flats. Chile, on the other hand, implemented in 2021 the first environmental guideline document for lithium exploitation projects in the salt flats. As the first and only environmental guideline of its kind in the region, the document approaches lithium mining as a different process compared to conventional mining. It acknowledges the fragility of the ecosystems in the salt flats and brines. It also highlights the need to preserve the salt flats in a sustainable way and identifies more than 150 different environmental impacts in the different phases of a lithium project.

There are three important implications in relation to the governance and the environmental frameworks in the Lithium Triangle:

1. The current regulations and procedures on the environmental management of mining projects focus on the project scale. Therefore, data available on cumulative impacts or impacts to wider ecosystem and the environ-

ment are either missing or difficult to access due to poor stakeholder and institutional connectivity. EIAs required by mining development projects will frequently have inadequate baseline surveys, resulting in poor assessment of direct and indirect impacts. Indirect impacts will generally not be addressed as they fall outside of regulatory requirements. In addition, cumulative impacts can best be assessed through coordinated evaluations of multiple projects acting over a wide spatial area, which presents challenges to monitor over time. Such coordinated efforts are difficult to resource and manage, as the institutional mechanisms are not in place. This is particularly relevant for Chile and Argentina where extraction has taken place for decades now and the cumulative, indirect and wider impacts are not yet accounted properly in current environmental management procedures.

2. The analysis and stakeholder engagement undertaken suggests that the regulatory frameworks in the Lithium Triangle countries are not fit-for-purpose for the lithium sector and cannot address sustainable development sufficiently. There is a diverse range of issues associated with the regulatory frameworks, e.g. concessions given for resource exploitation in Chile, mining regulations set by the provinces in Argentina, which lead to different risks regarding the future of lithium from brines. In addition, the national governments undergo different approaches for improving and resolving some of the present issues.
3. In the governance of lithium, parameters such as the ownership and management of lithium related projects are of key importance for defining the legal and regulatory frameworks. However, both parameters are associated with important political implications that extend beyond mining activities in the producing countries, for example state ownership in Bolivia is linked to issues around resource nationalism for the industrialisation of lithium. The ownership of lithium resources by provinces in Argentina leads to convoluted regulatory and policy processes between the federal government and provincial authorities. In Chile, lithium has acquired a prominent role in the public debate, and it is likely to become a sensitive topic in the drafting of a new constitution in the coming years.

Challenge (G4): The management of mineral royalties and distribution to local communities.

Each country in the lithium triangle has a different approach for collecting and distributing royalties. Currently none of them is entirely unique to the lithium sector and issues around their rates and distribution to local communities is linked to the social license to operate.

In Argentina and Bolivia, there is a unique lithium royalty of 3% of the gross value of production (*valor en boca*

de mina) but the distribution follows different patterns in each of these two countries. In Argentina, the royalty is paid directly to the host province, whilst in Bolivia, the royalty is transferred to the Departmental Government of Potosi, not to the municipalities directly surrounding the salar. This distribution is exceptional for lithium, since the mining law (No. 535) states that the royalty rate should be transferred to the host municipality of the mining location, but since salt flats (and Uyuni in particular) are Fiscal Reserve areas, they do not belong to any municipality. This feature of the governance framework is a potential source of conflict and perpetuates the grievances between the departmental government and the municipalities in relation to income distribution and uneven development (Sanchez-Lopez 2019).

Chile has recently changed the royalty structure to a dual structure: (a) Variable (from 6.8 to 40% of the sale price) paid to CORFO and (b) differentiated payments according to the mining operators. In the case of SQM, a royalty of 1.5% of the annual sale value is going to be transferred to the Regional Government of Antofagasta and Municipality San Pedro de Atacama. In addition, SQM will contribute with a payment of US\$14.3 million/year for the next ten years to support the national Research and development Centre (Instituto de Tecnologías Limpías/Institute for Clean Technologies — ITL) (Poveda Bonilla 2020). In the case of Albemarle, the negotiation with CORFO included an increase in the quota of extraction (from 200,000 to 263,132 tons), but with the condition of selling 25% of the production at a preferential price to companies seeking to add value in Chilean territory. It also incorporated a corporate contribution to research and development in the country (between US\$6 and 12.4 million) and a royalty of 3.5% of annual sale value to be directly transferred to the communities of Atacama (Obaya and Pascuini 2020; Poveda Bonilla 2020). Our analysis concludes that the management and distribution of royalty payments is an important issue and a key incentive for local communities. It is, therefore, linked to several of the other challenges identified (e.g. on the social dimension). There are potential conflicts arising at local level that could jeopardise the future of lithium projects and their sustainability, especially if national regulations, mining law and the tax and royalty systems are modified.

Challenge (G5): Lack of transparency and access to key information in the public domain

Although each country has some sort of regulatory framework in place to promote transparency of public information, the three countries present a lack of baseline information for the environmental impact assessments (EIA) and in general the information provided by mining operators is not publicly available. The official sources are not up to date, and the lack of a systematisation of environmental information is an

important obstacle for an informed debate based on credible scientific evidence.

The implication of the lack of information in the public domain leads to mistrust towards institutions, EIA, environmental management, environmental monitoring and mining in general. The lack of scientific evidence fuels certain narratives and perceptions, which are likely to initiate social conflicts, especially in Chile and Argentina. The combination of mistrust and perception not underpinned by scientific evidence could affect the sustainable development of lithium projects in the region. At the same time, if properly addressed, transparency and access to information could become important contributors to the social and environmental dimensions of sustainability.

Taken together, these challenges propose strengthening the governance frameworks in the region by considering the physical, technological and socio-economic peculiarities of the salt flats. Effective and inclusive multistakeholder participation is essential to enhance transparency, accountability and sustainability in a holistic way. The participatory processes and society perceptions and expectations are important components of such a holistic approach. These are explored further below.

Discussion of results

The transition towards electrification will require the intensification of mining in prospective areas such as the salars in the Lithium Triangle countries. The short timescale projected for the electrification transition driven by climate change targets and the associated exponential growth in demand for lithium present significant challenges. The additional prerequisite for sustainable and responsible supply of lithium adds an extra layer of challenges associated with its supply. Although a range of challenges have been identified under each dimension (ESG), in principle, many of them are interconnected, complex and can escalate conflicts in any of the other dimensions. The developed multicriteria decision analysis framework allowed for a systematic and consistent analysis and comparison, which enabled the prioritisation of high-risk issues in this complex picture.

The analysis on the country perspective showed a series of common problems that intersect the ESG dimensions. Each country has its own particularities and issues which we expanded upon during the regional analysis and scoring. One important parameter to consider when using the scorings from the regional analysis to understand their meaning at the national scale is the different paces in development in lithium exploitation. For instance, Chile and Argentina have active operations, whilst Bolivia is still in the exploration stage of their lithium projects and therefore much earlier in the mine life cycle. This is important, as some

of the challenges outlined as critical in our analysis (e.g. environmental dimension — water/brine-related issues) may have not yet become a concern in Bolivia, but are likely to become so as the operations progress. The difference in the geographical distribution of lithium salars in the three countries is also an important factor, for instance, in Chile and Bolivia, lithium projects are geographically concentrated, although in the case of Chile, exploration elsewhere (i.e. outside of the Salar de Atacama) is also taking place. In Argentina, there are multiple projects in various locations and in different levels of development. There is therefore a concern that issues seen from existing active operations may be exacerbated in the future due to the plethora of projects being developed. In Bolivia, our analysis identified that the most important issues are around the governance and social dimensions, with key problems being local conflict over the distribution of royalties, the weak institutional frameworks and the symbolic and political content of lithium. This aligns well with the regional analysis results and in particular with the high scores regarding society's perception on environmental harm (S4), the unsatisfactory mining remittance distribution to local societies (S5), the inadequate management and monitoring of environmental impacts (G1—local community receptor) and the management of mineral royalties and distribution (G5—local community receptor). It is interesting to note here that discussions around environmental concerns in Bolivia are often used to convey the dissatisfaction of local communities towards mining remittance distribution and the centralised decision-making process on lithium. In Argentina, the processes of participation with communities, the local governance and the challenges of a joint holistic and strategic perspective to lithium were highlighted as important. In Chile, challenges around the implementation of EIAs and ongoing environmental management, the need for innovation in environmental policy and tools and the social participatory approaches were highlighted as critical. These interview findings are endorsed by the regional level analysis and the high scores in several of the environmental dimension challenges which are reflected in similar elevated scores for the social and governance dimensions.

A key example of this and the interconnectivity of the three dimensions is the case of the water cycle in the salars. Several challenges have been outlined in the environmental dimension regarding brine abstraction, freshwater abstraction and effects on brine chemistry and groundwater levels and chemistry ((E1), (E2), (E3), (E4)). In addition, the interactions between water/brine, extraction and ecosystem are complex and the pumping of brines could potentially have damaging effects to the fragile ecosystems and biodiversity of the regions. This is outlined by the high scores of (E5) for the environmental receptor. The consultation undertaken has raised concerns around the water cycle multiple times, and from many different stakeholder groups (civil society,

industry, public authorities), for example in the governance dimension, the challenges around the non-systemic approach to environmental management and the fragmented governance frameworks ((G1), (G2), (G3)) are connected to the issues raised around the water cycle in the salars. Equally, the perception towards environmental harm from lithium brine operations (S4) recorded under the social dimension is driven by societal concerns not only on brine extraction and its impacts on water, but also on water demand from competing societal activities, such as agriculture and tourism. The latter is often related to social license to operate issues (S1) that can have detrimental effects to the future of lithium projects. However, detailed studies to understand these complex systems are often missing, as well as consistent baseline data, models and a coherent articulation of their findings to the wider stakeholder groups and communities. In most cases, operators in the region are aware of the hydrogeological complexity associated with the extraction of brines and have data and models that are reviewed continuously. These constitute an important part of their EIA reporting requirements. Although these are extremely valuable and necessary, the scale of these data, analysis and modelling does not go beyond the project level, which is particularly problematic when multiple projects take place within a watershed. It is however a common recognition that hydrology and water resources need to be assessed and monitored across complete watersheds and not only focused on projects. This project-scale approach and EIA reporting is not therefore sufficient to identify environmental impacts associated with water/brine resources.

Recommendations for moving towards a sustainable lithium supply

Addressing the brine/water challenges

Some positive actions have started taking place, for example the General Water Directorate in Chile (DGA) (Dirección General de Aguas-DGA 2016) has undertaken baseline studies, identified gaps and are working towards filling these gaps to develop a comprehensive understanding of the groundwater/freshwater flows. The results from these studies are made fully available with both reports and the data used as the basis for these reports made digitally accessible. Willingness to address whole-watershed approaches is definitely evident across the region and has been emphasised by many stakeholder groups (e.g. government, local authorities, operators, NGOs). Local and indigenous communities are well aware of the lack of this information, which links to many of the challenges identified in our analysis. This is an area, nevertheless, that has just started to be explored by the research community and the multidimensional complexity of

these systems with society and governance playing equally important roles in the exploration demand for interdisciplinary approaches for system understanding and the development of holistic mitigation actions. Urgent mitigation actions that emerged from our analysis to tackle the challenges associated with the water cycle in salars include:

- The need for consistent baseline data that characterise the complex systems within each salar and its associated watershed. Such data should be collected, analysed and made available in a FAIR manner (findable, accessible, interoperable and re-usable). Sharing of information and practices among countries could strengthen collaboration and assist the process of overcoming barriers quicker.
- Strengthening institutional capacity particularly within governmental organisations to enable assessment, monitoring and management of social and environmental risks and to collaborate for the pursuit of consistent standards in assessment
- Environmental accreditation: an equivalent for lithium as used for other resources such as the FSC for timber and the Fairtrade mark, recognising the specific challenges associated with brine resources. However, private and international standardisation and certification should be carefully thought through and should rely on multipartite cooperation among industry, authorities, communities, supply chains and international bodies. As with FSC and the standards associated with the International Finance Corporation (IFC), the recognition of biodiversity sensitivities associated with salars needs to be incorporated into any environmental certification approach.
- Consistent, appropriate and strong environmental regulations interlinked to mineral regulations that look beyond just water abstraction and address derogation issues related to different operators not just in the salar scale but in the basin to identify demands and impacts from multiple industry sectors not just the mining.
- Transparency and access to information and understanding following a consistent approach that enables making data, reports and the outcome of decision-making both available and accessible

Addressing biodiversity challenges

Effects on biodiversity may have the potential to be significant if key wetlands of importance to flamingos are exploited without due consideration of the ecological requirements needed to sustain these species which are dependent on these ecosystems. Whilst the flamingos are of global significance, they also serve as a flagship species profiling the conservation importance and fragility of these diverse communities of plants, invertebrates and other bird species that are directly associated and dependent on these

Andean wetlands. Such high Andean wetlands also are critical habitat for a range of other waterbird species, some of which are endemic to the region. In addition, they support migratory shorebirds that use these salars and their associated vegas and lagunas, both as migratory passage habitat and/or as overwintering areas from their Nearctic breeding grounds.

The biodiversity values of the region are represented to some degree within and across a network of Protected Areas, Ramsar sites, Important Bird Areas (IBAs) and Key Biodiversity Areas (KBAs). Ramsar sites, IBAs and KBAs are identified and selected on the basis of their biodiversity values meeting a range of globally significant and recognised criteria with regard to species diversity, biome representation, endemism, abundance and threat status. One of the key strengths that the region has developed over the last 25 years is an outstanding dataset of priority wetland sites, particularly those that are considered to be important for Andean and Puna Flamingos (Marconi, Sureda et al. 2011). For a developing lithium industry in the region, individual mining projects would benefit from being able to progress through a planning framework that recognises the key biodiversity risks and the threats to the ecosystem services that are provided both by Andean wetlands and by the wider environments (ecosystems) that contain them. Therefore, it would be useful if all proposed and ongoing developments that have the potential to negatively impact the important biodiversity values and associated ecosystem services across the region could be assessed and designed with the mitigation hierarchy in mind (Cross Sector Biodiversity Initiative 2015). Priority sites for flamingos and biodiversity are defined by watersheds but within such endorheic systems a whole-system understanding of hydrology is critical, particularly where many companies are operating within one endorheic system. The potential biodiversity issues are not only an ‘ecosystem’ or environmental problem, but a societal, mineral governance and economic problem too. Our key recommendations include:

- The use of the mitigation hierarchy as an approach to avoid and minimise impacts. The mitigation hierarchy is a tool designed to help users limit, as far as possible, the negative impacts of development projects on biodiversity and ecosystem services (BES). Its approach involves a sequence of five key actions—‘avoid’, ‘minimise’, ‘restore’, ‘rehabilitate’ and ‘offset’—and provides a best practice approach to aid in the sustainable management of living, natural resources by establishing a mechanism to balance conservation needs with development priorities. It is hierarchical in that it places a primary emphasis on ‘impact avoidance’ as much as is possible, so reducing the scale of

ongoing obligations to minimisation, restoration and (biodiversity) offsetting. In a development landscape such as is evident across the Lithium Triangle, biodiversity offsetting can be a challenge, as offsetting the net negative impacts at any project effectively requires a 'like-for-like' offset commitment that will bring additionality to the overall impact response. This cannot be achieved where critical habitats being impacted are already effectively safeguarded or protected, and they are difficult to realise where similar habitats may already be under mining concessions, either for exploration or for operational development. In such a situation, identifying and procuring significant areas that can serve as effect offsets may be challenging. Within such a context, the consideration of coordinated efforts to identify and agree aggregated biodiversity offsets may be invaluable.

- The use of the IFC's Performance Standards, and in particular Performance Standard 6: Biodiversity Conservation and Sustainable Management of Living Natural Resources (2012) (with guidance last updated June 27, 2019), which provides a recognition of the risks that extractive industry developments can have on biodiversity and ecosystems services (International Finance Corporation 2012). Overall, there is a need for standards that require the identification of critical natural habitats for species that may be negatively impacted by lithium development. The identification of Key Biodiversity Areas (KBAs) and globally and nationally threatened species which may feature within such KBAs (or outside of them) will be key features of interest, guiding and informing how the mitigation hierarchy is to be applied to a lithium project. Such biodiversity values need to be identified in the development and profile of baseline studies used in EIAs.

Flamingos are recognised as high-profile representative species of the 'Lithium Triangle' landscape. They are also visually appealing and enigmatic species. Should negative impacts and potential declines result from inadequate assessments and mitigatory management of these flagship species and the critical habitats on which they depend, then there are likely to be reputational risks associated with the industry and its development as a green climate-solution. It is, therefore, very important that such impacts be avoided and the industry needs to address, avoid and safeguard such critical species and habitat values, on a project-specific basis as well as at national and regional levels. Should it fail to address such risks proactively and as part of the EIA process, the threat to Andean flamingo species could lead to an internationally negative profile for the industry.

Addressing societal and governance challenges

Another important aspect for moving towards sustainable lithium supply concerns the role of society and, in particular, local communities and indigenous people. A collective vision to attain sustainable development demands societal participation. Although social participatory processes are defined to some degree across the Lithium Triangle countries and are sought during the project development stages to ensure SLO, their overall implementation is often deemed poor, inconsiderate and not inclusive enough. In many cases, social participation is seen as a bureaucratic requirement and not as a tool for environmental management and sustainability. We also note the implementation of public consultation and the previous, informed and free consultation with indigenous communities does not have a unified protocol. Each country has incorporated them in different forms. The result of this is opposition, conflict and complaints that may relate to a range of issues, for example territorial matters, cultural aspects, environmental concerns, economic gains and others, many of which have been discussed in the social dimension section. All these are extremely important and should be taken into consideration and are highly influential for the future of the lithium industry in the region. Local interests and benefits should be weighted properly against economic benefits, and the voices and concerns of civil society and indigenous communities should be properly listened to. A shared vision for the lithium industry is only achievable if all stakeholders show willingness to collaborate and commit to it. Our key recommendations for improving social participation processes include:

- Achieving a collective vision to improve the involvement of local societies in decision-making, environmental monitoring and management. In this sense, the establishment of an open and ongoing dialogue between local communities, local authorities, national governments and industry should take place through the whole life cycle of a mining initiative. Stakeholder engagement plays an important role in this, especially as the concerns and needs of local communities are dynamic and require a continuous process of reflection.
- A meaningful participatory process requires capacity building for the local communities so they can understand and use the information shared as part of the EIA, environmental management and monitoring practices and participate in these.
- However, capacity building requires resources and access to funding that the countries of the Lithium Triangle may not have. This is a matter that the global community should look at closely and try to address through collaboration with these countries and through provision of suitable support.

- As with the case of the water cycle, underpinning data that quantify the social costs associated with the extraction of lithium are critical. Baseline data in this area are also important as well as ongoing monitoring.

The majority of the aforementioned recommendations cannot take place without significant improvements in existing governance frameworks. Although there are plenty of individual changes that could improve the current legislation and policy, for example the better integration of environmental and mineral governance frameworks, tuning of legal frameworks to address the particularities of the lithium sector (neither a water, nor a mineral resource) or improvements in social participation procedures and transparency and access to information issues, we recommend a more holistic approach that aligns with the definition of sustainability.

- We propose the establishment of a public policy framework that will enable the development of a Strategic Environmental and Social Assessment (SESA) process specific to lithium. The SESA process is the assessment of policies, plans and programmes in a region (within country or across borders) (World Bank 2013). It is undertaken at a higher level than EIAs which are project-based and are often used to inform decision-making as well as a tool to ensure environmental and social sustainability and to highlight any likely significant effects of plans, policies and programmes. This would require the development of standards but also harmonisation and interoperability of existing procedures, e.g. data and EIAs. Accessing, organising and targeting the availability of data identifying biodiversity risks and value across the Lithium Triangle landscape could be realised through a SESA process. Furthermore, institutional changes and strengthening would be required as well as resources (monetary, humans). However, without a timely intervention of a SESA specifically aimed at lithium extraction, the social and environmental cost has the potential to be much higher in the future. A SESA-based approach carries the potential to identify risks and address these positively, proactively and locally and, ultimately, regionally.

As a final remark, we need to reflect on the impact of the wider community and how their demands for lithium resources, research and knowledge may influence the extraction of lithium in the Lithium Triangle. The downstream supply chain (e.g. batteries, automotive) is currently demanding development of sustainable batteries and sustainable decarbonisation technologies. But the sustainability of a product is negated if the production of raw materials is burdened by a range of significant environmental impacts, social and governance issues. This is also endorsed by others (Agusdinata, Liu et al. 2018; Barandiarán 2019; Bustos-Gallardo et al. 2021). The sustainability of lithium extraction is, therefore, an issue that requires the attention

and participation of the international community to assist capacity building in the region, develop standardisation and data infrastructures, participate in research and share knowledge and skills to move towards this shared electrification objective.

Conclusion

In this paper, we investigate the impact of environmental, social and governance challenges to the future of sustainable lithium extraction from the Lithium Triangle countries in South America. We undertook a qualitative analysis to prioritise the risks associated with these challenges to the lithium sector and discussed their interlinkages.

Part of the challenge of understanding and addressing the complexity of mining of lithium in the salars is methodological. The fragmented and heterogeneous governance frameworks have scope for improvement in terms of the consistent and systematic generation of data, the mechanisms of public access, analysis and debate based on scientific, technological and socio-economic qualitative data. In this paper, we propose that a sustainable perspective for lithium extraction in the region requires continuous and informed dialogues among government, industry and community stakeholders and participatory processes that reduce the asymmetries of power and knowledge. We also provided a list of urgent mitigation actions that could assist in preventing some of these impacts and enable the sector to move towards sustainability. Our key recommendations include:

- It is an urgent requirement to expand the research to understand the water cycle of lithium brines in this region. This should be underpinned by baseline data and ongoing monitoring at the watershed scale, capacity building policies to strengthen existing institutions, improved regulations and infrastructures to promote data transparency and accessibility.
- The impacts of lithium extraction on biodiversity should be integrated within existing mining practices and procedures (e.g. EIAs). We propose the implementation of the mitigation hierarchy and IFC's Performance Standards, which can be used to avoid, reduce and offset the risks of lithium extraction on biodiversity and ecosystem services.
- We highlight the importance of social participatory processes that enable the local communities to become actors in decision-making and the ongoing management and monitoring of lithium projects. However, successful participatory processes should be underpinned by baseline data, capacity building and ongoing stakeholder engagement.

- We propose the establishment of a framework to enable a Strategic Environmental and Social Assessment (SESA) process specific to lithium with a regional extend to cover the whole ‘Lithium Triangle’. This could not only unify the region, facilitate knowledge and information sharing, but also provide a systemic approach to assessing and mitigating ESG issues. Such a strategic process has the potential to secure greater institutional connectivity between agencies and stakeholders, provide access to data to allow for more accurate and meaningful baselines and provide a framework for more effective and coordinated impact mitigation, with options for aggregated biodiversity offsetting.

Only by improving the current situation can the needs of the energy transition be successfully met from the Lithium Triangle countries.

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Declarations

Conflict of interest The authors declare no competing interests.

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