Multi-scale Interdependencies and Telecoupled Impacts of Critical Mineral Extractions on Local Socio-ecological Systems:

A Case Study of Lithium Mining in Chile

by

Wenjuan Liu

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Graduate Supervisory Committee:

Datu Buyung Agusdinata, Chair
Hugo Romero
Hallie Eakin

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ABSTRACT

Global transitioning towards battery-based clean energy and green technologies has rapidly accelerated demands for Lithium (Li) as one of the most important minerals. However, the social and ecological implications of the anticipated growth in mineral extractions have not been acknowledged or adequately studied. Therefore, using the telecoupling framework, this dissertation aims to systematically understand the linkages between globally increasing adoption of green technologies and the social-ecological impacts in Li-extracted places, in order to help identify potential mechanisms or solutions to address such consequences. This dissertation selects the Salar de Atacama in Chile as the study area to firstly provide a socio-environmental assessment to synthesize the interdependent relationship between Li-mining companies and host communities. Then, an agent-based model was developed to demonstrate future social-ecological implications in the mining area for various mining projections. Lastly, the perceptions of end-users of green-tech products (e.g., electric cars) were collected and studied as to the awareness of embodied mining impacts and how these impacts should be addressed. Results found that Li-mining operations and local communities are closely linked at both local and regional scales through the shared resource space, economic opportunities, and resource governance. The excessive groundwater consumption from mining drives the most sustainability concerns. Material uncertainties of groundwater were found to play a vital role in causing the mismatched evolution of environmental and social dynamics, thereby highlighting some governance challenges stemming from resource uncertainties. Meanwhile, among sampled end-users, tensions and conflicts are widely found between the imperative of energy transitions and the reality of adversity mining impacts, along with a general lack of awareness. Fortunately, most respondents recognized the complexity in the supply chain of EVs and the role of consumers in influencing its governance. Overall, this dissertation provides a benchmark of the social-environmental impacts of Li-mining in Salar de Atacama, along with suggestions for decision-makers and mining managers on improved mineral governance. It also highlights the need and urgency for a telecoupling view in sustainable mineral governance and suggests a shift in green-tech supply chain to include broader sustainable development goals and a global community of consumers, affected communities, and the general public.

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CHAPTER 1

INTRODUCTION

1.1 Background

The global energy transition towards a low-carbon economy has been driving the demand for critical minerals used in batteries, including lithium, copper, cobalt, and nickel. Global demand for critical minerals has experienced a strong growth in the past decade, and among others, Lithium (Li) demand shows a skyrocket growth. Lithium (Li) is one of the most important materials in lithium-ion batteries used for electric vehicles and other green-technologies. Driven by global policies encouraging such technologies, the worldwide lithium production for use in batteries has increased by approximately 20% per year since 2000 (Martin et al., 2017), and is projected to keep growing rapidly soon (Deetman et al., 2018). However, these policies could also trigger impacts on social-ecological systems in geographically distal resource extraction areas, as a result of telecoupling between global consumers and local natural resources (Liu et al., 2013).

Many scholars and researchers have expressed concerns over the externalities of mineral extraction for low-carbon technologies. Cobalt mines in the Democratic Republic of Congo (DRC), for instance, have been found to offer toxic working conditions involving the use of child labor, posing serious ethical and health concerns (Sovacool et al., 2020a; Amnesty International, 2016). Similar impacts have been documented in the copper mines (Romero et al., 2012). Lithium extractions also have been attracting attentions as to its extensive water usage and social interruptions.

Lithium is primarily extracted from brines in the South American lithium triangle (Kesler et al., 2012), a region bordering Chile, Bolivia, and Argentina, holding 57% of the world lithium resources on Earth (Gruber et al., 2011). These Li-concentrated brines usually locate in a human-nature closely linked system where the climate is arid, and the ecosystem is fragile but also supports biodiversity hotspots, community livelihoods, and indigenous cultural heritage. Driven by the rapidly growing extraction activities, Li-mining industry have begun stressing the supporting ecosystems, potentially destroying the unique and globally important wetlands and the local economic systems that rely on them (Senner et al. 2018). In addition, the shared groundwater resource (where Li-concentrated brines are extracted from) has material uncertainties that are not directly observable and less predictable, adding to the local concerns as well as the challenge of governing telecoupled impacts.

Mineral extractions are intrinsically destructive to the host place (Franks et al., 2014), which starts prompting questions on the overall sustainability of low-carbon technologies. Of particular concern is the notion that deploying these technologies shifts the socio-environmental costs from wealthier countries to places that are out of sight of the decisionmakers and end-users of these technologies (IRP, 2020; Kramarz et al., 2021). In this case, a comprehensive understanding of the linkages between globally increasing adoption of green technologies and the social-ecological impacts in Li-extracted places becomes necessary and important.

1.2 Problem Statement

Global climate alignment policies have been spurring an increasing uptake of green technologies, which in turn drives an increased production of critical materials (especially lithium) and attracts global investors rushing into the arena of mineral mining. In this sense, the socio-ecological systems at local mineral extraction place are coupled with the policies and actions in countries distant from those mining activities, manifesting features of ‘*telecoupling* (Liu et al., 2013)’. The Li-mining in Salar de Atacama (SdA), for instance, driven by low-carbon policies, accelerates the scale and rate of extraction, threatening groundwater resources, and being contested among other water users. Local communities that independently govern the same focal resource (groundwater) by social norms and institutions become indirectly coupled with global policies in distant places and are being unintendedly affected. Such mineral mining impacts, driven by climate policies, are ‘telecoupled impacts’, which are challenging to manage due to the lack of understanding and interaction of knowledge, actors and activities across the remotely connected systems (Eakin et al., 2014).

On the other hand, local socio-ecological system in the mineral extracted place has *multi-scale interdependencies* with the extractive industry and policies. In SdA, Chile, local communities have utilized, and sustained ecosystem services provided by the natural system since ancient times (e.g., supporting agropastoral lands, cultural attachment to resources, recreation, and aesthetic values). These resources and services were then shared with the Li-extractive industry since the 1980s, creating new linkages between the locals and mining companies (e.g., economic and job opportunities, tensions on natural resources). Vertically, the local human-natural system is also subject to policy and action at regional and national levels, such as mining code, indigenous law, and court decision on mining operations. The rapid growth of mining industry has shown tightened the linkages in the local human-nature system and intensified social tensions in resource-based communities near mining operations (Babidge 2013, 2016, 2018).

Given the prominence of critical minerals in supporting the global low-carbon transition, it is important to understand the wider environmental and social implications of its telecoupled impacts in the mineral extracted places. In this dissertation, the Li-mining industry in Salar de Atacama, Chile is selected as the case to study the multi-scale interdependencies and telecoupled impacts of critical mineral extractions on local socio-ecological systems.

1.3 Knowledge Gaps

1.3.1 Lack of study in Li-mining impacts

Governing the telecoupled impact of Li-mining on local socio-ecological systems firstly requires a comprehensive understanding of the social and environmental impacts of mining. Academic interests assess mining impacts in developing countries from diverse perspectives. Some research has focused on mining-associated benefits: increased economic activity, job creation, infrastructure development, and social benefits (Pegg, 2006; Kitula, 2006; Kotey and Rolfe, 2014), along with governance strategies (i.e., corporate social responsibility, CSR) that contribute to the socio-economic development of resource-based communities (Morrison et al., 2012). Other research focused on environmental degradation, local displacement, social upheaval, and socioeconomic issues that are created by the long-commuting labor influx (i.e., Storey, 2001; Haslam and Hoath, 2014; Aragón and Rud, 2013). However, mining impacts can vary significantly due to the differences in commodity type, local social and political contexts, cultural background, and development trajectory (Auty, 1997).

Only a few studies have addressed the impacts of Li-mining, and their scope is limited to only some aspects of the system. For example, Babidge (2016, 2018) investigated the changes in social values and ethics perceived in the SdA, Chile, while did not provide a holistic assessment. Romero et al. explored environmental injustice in the Atacama Desert by examining the water balance in watersheds where concentrated mining activities are located. But the study covers many types of extracted minerals, and so does not sufficiently reflect the unique characteristics of brine-based Li-mining. Lastly, Egbue (2012) provided a systematic assessment on social impact of Li-extraction, while it does not capture the interdependency of mining and the surrounding socio-ecological system. Overall, the impact for communities in the remote Global South from the recently booming Li-industry can be complex and varied, which may require a holistic analysis of impacts. Holistic impact analysis assesses the activity's impact performance through its most significant impact areas, and it distinguishes itself by the systematic consideration of positive and negative impacts across the three pillars of sustainable development (UNEP, 2020). Research efforts that provide a holistic assessment of both environmental and social impacts and their connections are rare; much of current work is either too broad or has a single or narrow range.

1.3.2 Knowledge gap in telecoupling framework

As introduced in problem statement, the lithium supply chain exhibits many features of 'telecoupling' and the governing the associated 'telecoupled impacts' can be challenging since it's hard to bring distal connections to the attention of decision-makers (Eakin et a., 2014; Moser & Hart, 2015). Eakin et al. (2014, 2017) ascertain that multiple thresholds may exist in telecoupled systems. Among others, a conditional threshold refers to the degree of changes in the resource base conditions, and an attention threshold represents the scale or consequences of the telecoupling impacts to trigger widespread concern and attention of actors. Once either threshold is crossed, telecoupling can become visible to actors as a potential governance concern.

The challenge for the case of Li-mining in SdA is that groundwater as the focal resource has inherently large uncertainties. Different from focal resources such as land resources covered in most telecoupling studies (i.e., Rueda & Lambin, 2013; Sun et al., 2017), groundwater is not directly observable and less predictable in its dynamics due to high mobility. This high mobility means that the groundwater level in aquifers adjacent to where water is extracted can be significantly affected. These uncertainties may obscure the emergence of a threshold (e.g., groundwater level) and make it unnoticeable, thus significantly delaying feedbacks to other resource users.

Uncertainty here represents the unknows about the extent of groundwater and the exact impacts on ecosystem associated with water extraction. Subject to such uncertainties, resource users can have different understanding and interpretations of the changes in resource conditions, depending on their experience and values (Babidge et al., 2019). When certain users perceive that the threshold has been crossed, social unrest can occur and as a result, the current governance system is pressured to address the externalities through new institutional design (Eakin et al., 2014). In the case of Li-mining, these uncertainties may hamper changes in the existing governance, leading to delayed regulatory actions and sustained impacts (Babidge, 2019), which requires a closer investigation on how uncertainties in focal resource affect the emergence of threshold that makes telecoupling visible.

1.3.3 Knowledge gap in consumer perception

On the consumer side, their perceptions can play a vital role in facilitating better governance of mineral resources. Existing mineral resource governance frameworks have highlighted the shift of governance challenges towards the consumers due to the increasing consumption of sustainable products and the increasingly important role of consumers in pressuring the establishment for schemes around sustainable sourcing (IRP, 2020). Similar in academia, studies start emphasizing the instrumental role of consumers in filling governance gaps, calling for more empirical studies on the actors at the end of value chain (e.g., consumers) as well as on the externalities of low-carbon technologies (Kramarz et al., 2021), and promotion of consumer awareness of mineral use and consumption effects (Ali et al., 2017).

Adoption of green technologies, for example electric vehicles (EVs), is usually motivated by various factors including technical attributes (e.g., driving range, vehicle performance), financial aspects (e.g., price, incentives, operation costs, etc.), and socio-cultural concerns and attitudes (e.g., desire to be “cutting edge” in new technology adoption, or for social status) (Liao et al., 2016). Pro-environmental attitudes (e.g., symbolic meanings of EVs, environmental benefits) are found to be the most important in motivating adoption (Kim et al., 2014; Jansson et al., 2017). Consumers are becoming increasingly conscious of the socio-ecological footprints of their purchase decisions (Kramarz et al., 2021), a factor driving automakers to emphasize EV's green credentials in marketing. However, the use and impacts of minerals in EVs are often invisible from consumers (IRP, 2020). Studies about consumer awareness and perceptions of mineral impacts in low-carbon technologies are rare, posing challenges to alter the governance of mineral extraction.

1.4 Scope and Objectives

As elucidated in knowledge gaps, academic studies have not yet kept up with the pace of the growing Li-mining industry and the green-technologies it enabled. Overall, this dissertation aims at gaining a better understanding of telecoupled impacts of Li-mining activities on local socio-ecological systems, material uncertainties of the focal resource that may hamper the governance of these impacts, and the promising role of consumers in facilitating a better governance of mineral resources. Specifically, this dissertation has three aims:

1. **To understand the telecoupled impacts of Li-mining activities on the local socio-ecological systems, as well as the relevant interdependencies occurring at multiple temporal and spatial scales.**

   This aim seeks to establish a baseline assessment of the social, economic, and environmental impacts of Li-mining operations on the frontline communities in Salar de Atacama. To this end, this analysis employs a system approach, with the impact indicators taken from Sustainable Livelihood (SI) approach, to provide a benchmark on the mining-related impacts and a systematic map abstracting the coupled social-natural system and their interdependencies. In doing so, this study seeks to answer the following question:

   How does Li-mining expansion affect the sustainability of local communities based on the interdependency?

2. **To investigate the role of uncertainties in focal resource in affecting the emergence of threshold that makes telecoupling visible to decision-makers.**

   Building on the findings of the first aim, this dissertation seeks to identify why governing the telecoupled impacts of Li-mining is challenging. With the knowledge of telecoupling framework and the thresholds that make telecoupling visible to decision makers, this work adds to the telecoupling framework by exploring the phenomenon that when the affected focal resource in a resource base are essentially marked by uncertainty, the emergence of threshold can be obscure (or unnoticeable) and thereby delays feedbacks to governance changes to occur. In this end, this work builds a dynamics model, which captures the interactions among focal resource (aquifer), mining companies, and local communities, to answer the following question:

   How do uncertainties in groundwater levels affect the mining-induced stress perceived by the locals, and thereby affect the emergence of conditional threshold that makes telecoupling visible?

3. **To explore perceptions of end-users who own minerals-enabled green-tech products about their awareness of minerals extraction impacts and possible governance actions to regulate extraction towards sustainability.**

   In the light of the role of resource uncertainties in hampering the governance of telecoupled impacts, this aim seeks to explore the promising role of resource end-users in facilitating and enabling better governance of mineral resources. This investigation will serve as a pilot study on the electric vehicle users in the United States, offering policymakers and industrial decisionmakers with an initial understanding of public sentiments and reactions to the externalities of low-carbon technologies. In doing so, this study answers the following questions:

To what extent are EV consumers with different motivations for purchasing aware of the impacts of mineral extraction? And when exposed to similar information on impacts, how do they then perceive issues of mineral extraction and evaluate governance schemes?

1.5 Thesis structure

This dissertation seeks to advance understanding of the telecoupled impacts, governance challenge, and public sentiments and reactions of critical minerals extraction, using Li-mining in Salar de Atacama as an example. To this end, the analyses are under the telecoupling framework, utilizing a combination of quantitative and qualitative methods in data collection, analysis and modeling.

An understanding of the previous literature and background is critical to appreciate the directions of this research. Chapter 2 will identify and review major dimensions in the Li-mining impact research, socio-ecological systems, telecoupling framework, and the modeling methods been applied to socio-ecological systems.

Chapter 3 outlines the conceptual framework and the methodological tools employed to address the aim of this dissertation. It then introduces the study area of Salar de Atacama as to its socio-economic status, topography, geology, hydrology, and cultural and biodiversity importance. Lastly, it summarizes the empirical and statistic data collected and used in this dissertation.

Chapter 4, 5, and 6 articulates the problems, analysis, and results for each of the three aims identified in the previous section. And lastly, Chapter 7 provides an overview on how much of the aims are achieved by integrating the major findings from the previous chapters. This chapter also discusses the significance of research, general applicability to other critical minerals, reflections on the process of conducting this study, and key limitations of the study and proposes potential avenues for future research on critical mineral governance.

CHAPTER 2

LITERATURE REVIEW

2.1 Socio-environmental Impacts of Li-mining

Although there is an extensive body of studies assessing mining-related impacts for resource-based frontline communities, academic interests focusing on the brine-based Li-mining only starts in the 2010s (Table 1). Stamp et al. (2012) assessed the lithium carbonate production in the Atacama Desert using the life cycle assessment (LCA) method by examining Cumulative Energy Demand (CED), Global Warming Potential (GWP), and EI99, which is an average weighting indicator combing different impact categories. It estimated that the Li-extraction process consumes 28.43 MJ-eq/kg Li_2CO_3 energy and generates 2.02 kg CO_2-eq/kg Li_2CO_3 emissions, but it did not capture the impact on the local water cycle and landscape, which are of great importance considering the extreme local climates. Romero et al. (2012) provided a comprehensive overview of the contested water resource use among different land use types in the Atacama Desert using a water balance analysis, and it found mining development is beginning to overlap with biodiversity protection sites, indigenous lands, and nature conservation areas. Due to the broad coverage of mineral mining types (e.g., copper, gold, and other minerals), it may not reflect the unique characteristics of Li-mining which is a brine-based extraction, different than other opencast mining types. Egbue (2012) offers a pilot assessment of the social impacts related to Li-mining in Salar de Atacama (SdA) using a systematic social-life cycle assessment (S-LCA) method and revealed social conflicts relating to mining activities including competition for water and issues with indigenous rights. However, it doesn't offer enough nuanced analysis due to the lack of information and empirical data.

Among others, Babidge (2013, 2016) and with her colleague (Babidge and Bolados, 2018) conducted ethnographic studies in SdA by participatory observations, interviews, and field studies to understand the new ‘partnership’ between mining companies and the indigenous people, and document how the extractive industry affects the culture, values, and traditional rituals and practices of indigenous people. These studies provide detailed records about some of the important and non-measurable impacts of Li-mining activities, such as the changes in ethical practice, and indigenous people’s contestations over water value, and also document a dynamic picture of life of the local communities and their relationships with the extractive industry.

Academic interests on the topic are raising in recent years with more diverse impacts being assessed and more advanced tools being used. For environment-centered studies, Liu et al. (2019) assessed and identified the temporal and spatial change of vegetation health, land temperature, and soil moisture in SdA for 1997-2017, using a remote sensing technique. Gajardo and Redón (2019) systematically investigated the change in biodiversity (i.e., flamingo birds) whose habitats are potentially affected by the Li-mining operations in SdA. And Marazuela et al (2019b, 2020) even developed a groundwater model to examine the effects of brine pumping operations on the groundwater dynamics and found the Salar was the most affected area (where mining operations are), and the marginal zones of SdA are beginning to be affected.

As to studies around the various social impacts of Li-mining, recent efforts are still contributed by Babidge and her collogues. Babidge et al. (2019) employed satellite image and participatory mapping method to understand how the locals perceived the changes in landscape features related to Li-mining. It found that people explained environmental change in ways that were layered with memory and lived experience. Through empirical field works, Babidge (2019) also started to question how the material uncertainties of groundwater are hampering the management and governance actions of Li-mining impacts and elucidated how the newly implemented policy on social consultation is burdening the locals due to a deluge of Li-mining investors (Babidge, 2020).

Overall, specific studies on Li-mining impacts are limited in scope and methods being used, especially comparing to mining impacts studies on fossil fuels (e.g., coal, petroleum, gas, etc.). Still, these previous works provide adequate empirical evidence on the impacts of Li-mining, including carbon emissions, energy use, overlapped land use of mining and nature sites, groundwater decline, vegetation degradation, and risks on biodiversity. Separately, the life of local communities and their relationships with the extractive industry is also documented, revealing the changes in ethnical practices, values of water, and social tensions within communities for the indigenous people. These works pinpoint the major concerns related to Li-extraction, which is centered around water resources, thereby laying a vital foundation for this study to disentangle the complex interdependencies of local socio-ecological systems.

The social and environmental impacts of Li-mining are separately studied by previous works, which may overlook the important links and feedback between ecosystem and social livelihood. For instance, the decline of groundwater can affect ecosystem services to local livelihoods by degrading vegetation and reducing biodiversity, thereby hampering the development of other economic activities (e.g., tourism) and impairing the indigenous value of water resources. A holistic understanding of these linkages is instrumental but missing in previous studies because it can help identify pathways to make the impacts visible to decision-makers thereby generating potential governance solutions. To this end, a telecoupling view is needed to capture the relevant linkages and feedback.

Table 1. Summary of Studies on Social and Environmental Impacts of Li-mining[1]

Studies	Study Area	Methods	Impact categories
Environmental impact studies			
Stamp et al., 2012	SdA, Chile	Life cycle assessment (LCA)	Energy consumption. Carbon emissions
Romero et al., 2012	Atacama Desert, Chile	Water balance analysis	Water use. Spatial overlap of mining, wildlife conservation, and groundwater withdrawal
Liu et al., 2019	SdA, Chile	Remote sensing	Vegetation change, Land surface temperature, soil moisture
Gajardo & Redón, 2019	Atacama Desert, Chile	System analysis	Biodiversity, ecosystem dynamics
Marazuela et al., 2019b	SdA, Chile	Hydrological modeling	Mining impacts on groundwater
Marazuela et al., 2020	SdA, Chile	Hydrological modeling	Spatio-temporal trend of groundwater level
Social impact studies			
Egbue, 2012	SdA, Chile	Social-LCA	Social-LCA indicators relating to worker, local community, and society
Babidge, 2013	SdA, Chile	Participant observation, interview	Contested partnership between indigenous community and mining companies
Babidge, 2016	SdA, Chile	Interview	Change of values and ethics of water sources
Babidge and Bolados, 2018	SdA, Chile	Participant observation, Interview	Infrastructure improvement by mining companies and the resistance from indigenous people

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[1] Only brine-based Li-mining studies are included. Similar studies focusing on open-rock Li-mining are out of scope of this case study.

Babidge, 2019	SdA, Chile	Interview	Groundwater uncertainties. Local perceptions of resource
Babidge et al., 2019	SdA, Chile	Participatory mapping, focus group	Local perception of ecological change related to Li-mining
Babidge, 2020	SdA, Chile	Interview	Mining social consultation

2.2 Telecoupling Framework

2.2.1 Evolution of telecoupling concept

Telecoupled systems refer to the concept that social-ecological interactions in one system generate mechanisms of influence over another. This concept is an integrated concept that builds on previously studied concepts of '*teleconnection'* in meteorological and climatic studies, '*globalization'* in socio-economic disciplines, and combines with the theoretical framework of coupled human and natural systems (CHANS). It then evolves towards an analytical framework of telecoupling which enables a systematic understanding of telecoupling mechanism and an analysis of feedback processes between telecoupled systems. The schematic representation on the brief history of '*telecoupling*' concept is shown in Figure 1.

Studies around distant interactions have long been studied separately in many disciplines. '*Teleconnection'* was firstly applied to study atmospheric interactions between distant natural systems (Glantz et al. 1991). Meanwhile, '*globalization'* (Levitt 1983) has also been applied to study intensified socio-economic interactions between distant human systems (Featherstone, 1990). With the increasing recognition of human-nature interactions, the concept of coupled human and nature systems (CHANS), which focus on feedback and interactions that link systems, was also brought to better understand the coupled human and nature system (National Science Foundation Advisory Committee for Environmental Research and Education 2009). Due to the ever-tight connections among countries, *globalization* and *teleconnection* have been suggested to expand to capture the distal interactions among systems (Rueda and Lambin 2013; Erb et al. 2009). However, the feedback dynamics between social processes and environmental outcomes were not successfully captured in these concepts

Built on CHANS, teleconnection, and globalization, '*telecoupling'* emerged as a logical extension to provide an integrated framework to study the feedback between an interrelated set of coupled human and natural systems over distances that are increasingly connected over flows of materials and information (Liu et al. 2013). The analytical frameworks of telecoupling were proposed by Liu et al. 2013 as the structured approach, which focuses on the systematic understanding of five main telecoupling components, or the heuristic approach proposed by Eakin et al. 2014, which elaborates on the processes involved in creating telecouplings between land systems. Attributed to its advantage of detecting externalities and unintended consequences of social and ecological processes that occur in distant locations, the concept of telecoupled system and its associated frameworks started to be widely applied in a broad set of studies across spatial scales, including land-use and land-change science (Eakin et al. 2014; Friis et al., 2015; Friis and Nielson 2017), animal migration (Hulina et al. 2017), species invasion (Liu et al. 2013), and renewable energy system (Rulli et al. 2019).

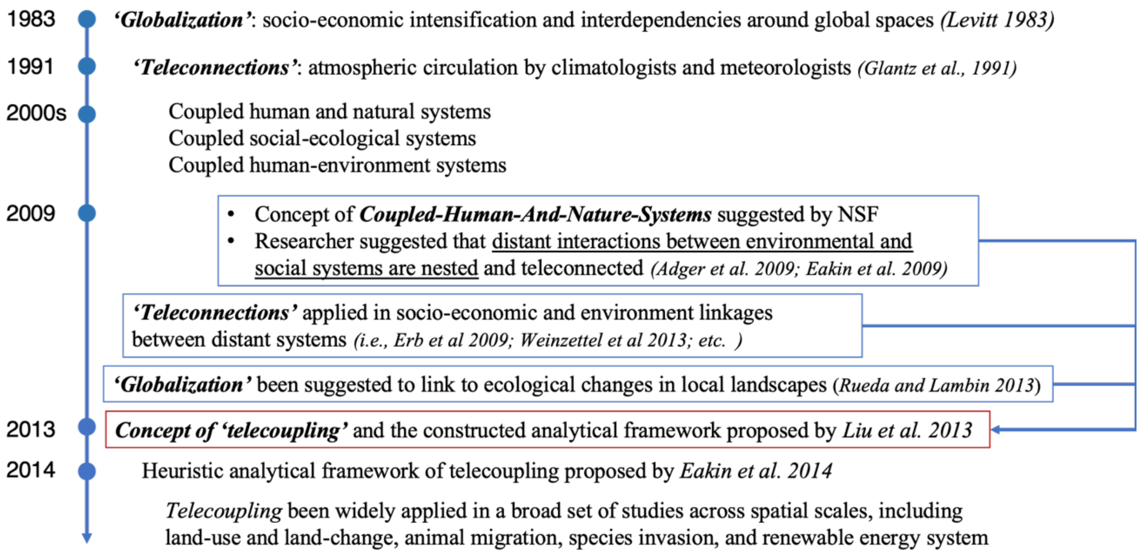

Figure 1. The Brief History of '*Telecoupling*' Concept (Note: blue boxes are concepts contributing to telecoupling; red box is the emergence of telecoupling)

2.2.2 Significance of telecoupling

The concept of telecoupling is particularly meaningful in describing social-ecological systems dynamics, especially in the current era. The social and ecological systems are closely linked than ever through flows of information, materials, and energy. Facilitated by the internet, social media, transportation technologies, the connectivity of socio-ecological systems in the world are intensively enhanced, constituting a novel and important feedback mechanism in telecoupled systems. The limitations on land and resource availability caused by over-consumption and fast population growth also imply less flexibility in system response, leading to more tightly linked and rapid feedbacks. Meanwhile, Globalization has enabled some specific actors today been more concern about the consequences of actions than before. Actors who learn about the distant outcomes related to their behaviors may be motivated to respond with behavioral or political change, creating valuable feedback to change the initial system. Therefore, understanding telecoupling has critical implications for governing global sustainability in an increasingly telecoupled world.

Telecoupling provides a broader analytical lens to integrate distant interactions over socioeconomic and environmental systems that are distinctly governed by actors with different sets of value systems, which can identify unexpected outcomes or externalities that are usually hard to disclose in place-based research. Distant interactions pose unprecedented challenges and opportunities for sustainability with the help of globalized trade, technology in communication and internet. The improved communication technology and internet could enable a new form of linkage that connects the distant systems and then empower distant actions such as social activists and associated social movements (Eakin et al., 2014). But distant forces have been limitedly considered in studies mostly being treated as exogenous variables (Liu et al., 2013). Telecoupling provides a new research framework to fill knowledge gaps and advance sustainability science by taking into account of distant interactions and feedbacks (Liu et al., 2013).

Through considering a system as telecoupled and decoupling system components and their interrelationship, telecoupling can provide a useful means to incorporate feedbacks, trade-offs, and synergies across multiple systems, and improve the understanding of distant interactions and the effectiveness of policies from local to global levels (Eakin et al., 2014; Friis et al. 2015). Telecoupling can also help identify new insights that cannot be obtained from place-based research that has narrowed boundaries or considers one type of distant interaction alone, because many telecouplings may have complex interrelationships. Under the telecoupling framework, the boundary of analysis can be redefined due to the recognition of distal interactions and feedbacks. This recognition of telecoupling can stimulate new forms of governance, while the ignored recognition may exacerbate undesirable social and ecological outcomes in linked systems (Eakin et al. 2017).

2.2.3 Governance challenge in telecoupled systems

Governance is defined by Ostrom (2009) as the actors and organizations that manage a resource base and define how and what rules of management should be designed and put in practice. In this sense, governance includes both the institutions and relevant actors involved. In particular, it incorporates the rules, norms, and regulations of interactions, as well as the values, interests, and actions associated with the actors. Governance here also includes some new and hybrid institutions formed by collaborations among broad stakeholders, or the incorporation of new actors and their concerns that can redefine the analysis boundary of telecoupled systems.

The distance of telecoupled systems is one of the greatest challenges for governance. The distant location of actors in linked systems impedes the effectiveness of information sharing, lobbying, and networking that enable new forms of governance to emerge (Brondizio et al. 2009). This spatial separation also tends to create emergent and unanticipated socio-ecological outcomes that lie outside the domain of the existing governance arrangements (Eakin et al. 2014).

The difference in cultural and economic conditions of the connected systems at the initial phase also poses a challenge for sustainability governance. Actors in different cultural and economic conditions can have very distinct values and priorities in defining the system boundaries for governance, making it hard for them to reach a consensus and thereby hampering the governance transformation in telecoupled systems (Eakin et al. 2017).

The diversity of values associated with resource, food, or animal species among different populations can pose an overwhelming challenge (Eakin et al. 2010). In telecoupled systems, actors may be more likely to mobilize change in governance when the impacts of telecoupling affect ‘boundary objects’, while the misfit in the actor’s values associated with the “boundary objects” between distant systems can create asymmetric influence, which provides no significant incentive for the resource users to modify governance priorities (Eakin et al. 2017).

Telecoupling also shares similar challenges with research addressing socio-environmental changes at multi-scales, including heterogeneous communities, multiple external drivers of change, misfit between natural system boundaries and institutional jurisdictions, and cross-level resource management challenges and structures (Berkes 2006).

With the understanding of these challenges, governing telecoupled systems require innovative solutions that can bring distal connections to the attention of decision-makers. The recognition of telecoupling is important to trigger changes in governance, which may require a sequence of temporal phases that condition the emergence of functional, social, and political pressures (Oliver 1997, Dacin et al. 2002, Eakin et al., 2017). The sending system firstly needs to cause unexpected outcomes (disturbance) in the receiving systems, and the receiving systems would need to be particularly sensitive to the disturbance. Then, the disturbance caused in the receiving systems needs to be recognizable and salient to actors in that system. Lastly, there must exist a mobilization capacity and exert influence on the existing system of governance for such attention to affect the structure or process of governance (Eakin et al., 2017). Ultimately, the potential for significant shifts in governance is also dependent on the receptivity of actors within an incumbent regime to embrace and legitimize change, rather than dismiss, ignore, or resist such pressures (Dacin et al. 2002). On this basis, effective governance of the distant systems requires a complete understanding of the feedback mechanisms connecting the systems (Eakin et al., 2014), cultural and economic conditions of the connected systems, the agency of actors involved, and their political and social relations and networks (Eakin et al., 2017).

2.3 System Approaches

System approaches have been applied to complex problems related to social-ecological systems, including sustainable resource management, community development, and urban transformations, by revealing closely linked feedbacks that form a complex system (Seiffert and Loch, 2005). System dynamics and optimization models, for instance, are useful in modeling and advising conjunctive water use in agriculture practices at local scales (Sedghamiz et al., 2018; Hashemi et al., 2019). System thinking also has been adopted to develop integrated and collaborative resource management practices for building community resilience and sustainability (i.e., Aryal et al., 2019; Musavengane, 2019). The issue of Li-mining essentially reflects the key characteristics of complex social and natural systems in which multiple interactions of system elements lead to emergent system behaviors due to feedback, time delay, and non-linear relationships (Agusdinata et al., 2018). A study of such complex systems requires a system approach that fully considers the interactions across different temporal, spatial, and institutional scales (Ostrom, 2009).

Modeling such a complex social-ecological system is highly data-driven, and the unavailability or mismatch of data sources usually limits the possibility of modeling with a single approach. Therefore, a hybrid approach of multiple methods or analytical tools is usually employed in academic research efforts to help better understand the complexity and dynamics of social-ecological systems. Table 2 shows a review and summary of current combinations of system modeling approaches. In general, for modeling the dynamics of social and ecological interactions, the agent-based model (ABM) and ecological economics model are the two most promising integrative models. However, the distinction between those two is not clear cut, with ABMs often based on specific utilities, but also including social structure or direct interactions that are not as prominent in ecological economics approaches (Schlüter et al., 2012; Parrott 2011).

Based on the brief discussion around hybrid modeling approaches in Table 2, the agent-based model framework, that helps capture and predict emergent phenomena resulting from the interactions of individual entities (Bonabeau 2002), would be effective to understand the complexity and dynamics of Li- mining in SdA. Particularly, mining-related social behaviors are mostly from the bottom up and usually nonlinear in SdA, which makes ABM the most suitable modeling method in this study. ABM is increasingly adopted in environmental management studies (Janssen 2002, Gotts et al. 2003, Bousquet and LePage 2004, Barreteau et al. 2004, Janssen and Ostrom 2005) because it allows explicit consideration of changes in the behavior of individual actors that arise from perceived changes in the natural or social environment. ABM also has the advantage that social and institutional relations between human actors can be represented at different scales.

ABMs embedded with other analytical models have been used to study a wide range of social-ecological dynamics in empirical cases. ABMs have also been used to study the dynamic human-nature interactions over water or resource extractions. Castilla-Rho et al. (2015), for instance, developed a coupled agent-based model to explore how patterns of groundwater movement and social development can emerge from agents' behavior and their interactions. Condon and Maxwell (2014) present an integrated agent-based hydrologic model to study the spatial and temporal patterns caused by feedbacks between irrigation and water availability in the Little Washita Basin in Southwestern Oklahoma, USA. Iwamura et al. (2016) use the spatially explicit agent-based model to analyze environmental degradations on indigenous lands in Guayna resulted from heterogeneous human actions. Academic efforts highlighted the feasibility of agent-based model to address the complexity of social-ecological systems, synthesize interdisciplinary tools and knowledge, as well as disclosing unanticipated linkages within the system.

Table 2. Summary of Hybrid System Modeling Approaches

Model Approach	**Addressing complexity and dynamics**

Spatiotemporal model combined with agent-based model	***Multilayer spatiotemporal model*** can describe changes in land use and hydrological indicators (i.e., soil moisture, water levels, etc.), providing spatiotemporal representations of landscape and water resource dynamics. Combined with the ***agent-based model***, that represents decision-making process of the agents under specific social characteristics and structure, providing an integrated simulation of ecological outcomes resulted from behaviors of resource users, as well as heterogeneous user behaviors in response to perceived environmental changes. • ***Examples***: *Berger, 2001; Le et al., 2008*
Biophysical and social network analysis, combined with agent-based model	**Biophysical network analysis** can map the interconnections in a complex system by tracing the interlinkage and flows across system components. **Social network analysis** allows modeling dynamics and complexity of human interaction in terms of various information and material flows. Embedded with social network and biophysical network, **agent-based model** allows testing the implications of network structure for system dynamics. This combined model can simulate the dynamics of system behavior based on the collective human actions to ecosystems through social networks. • ***Examples:*** *McAllister et al., 2011; Bodin and Norberg, 2005*
Ecological dynamics, combined with game theory model	**Ecological models** of many types have proved useful in detecting threshold effects and irreversible changes is wetland systems (Zweig & Kitchens 2009) and even salt lake ecosystems (Johanson 2011) using state-and-transition models. Underlying ecological processes are usually addressed by field monitoring or experiments, revealing empirical evidence on feedbacks between system interactions. **Game theory model** can be used to investigate cooperation and non-cooperation behaviors in common-property management. With the inputs from ecological models, game theory model can analyze the consequences of changing policy instruments, and the role of cooperation in common-property management. • ***Examples***: *Brekke et al., 2007; Janssen et al., 2000*

Ecological economic modeling	**Ecological economic modeling** allows investigation of optimal decision making under risk generated by temporally variable resource dynamics (Schlüter et al. 2012). Adding nonlinearities and nonconvexities in ecological dynamics (i.e., by including stochastic events) can capture system complexity and lead to optimal management solutions. The role of social systems can be reflected through including specific utility functions varying between individuals or groups (i.e., utility function for mining actors as profit-maximized, governance actors as social welfare maximized, local communities as income maximized, etc.). The ecological economics modeling focuses on the impact of interventions and subsequent consequences for optimal resource management but neglecting the social structure and interacting process. • ***Examples**: Janssen et al., 2004*

CHAPTER 3

METHODOLOGICAL FRAMEWORK

3.1 Research Framework

3.1.1 Conceptual framework

Grounded in the telecoupling framework, this dissertation conceptualizes the issue of Li-mining and its telecoupled impacts as shown in Figure 2. This framework is composed of sending systems, receiving systems, and the flows and governance feedback connecting them. It can serve to understand and predict the direct and indirect impacts and dynamics in receiving systems that are caused by the increasing mineral extraction needs. It also helps promote end-users in sending systems to recognize the impacts of mineral use and consumption in receiving systems through revealing distant interactions between use and extraction, unexpected externalities, and the complexity of governance.

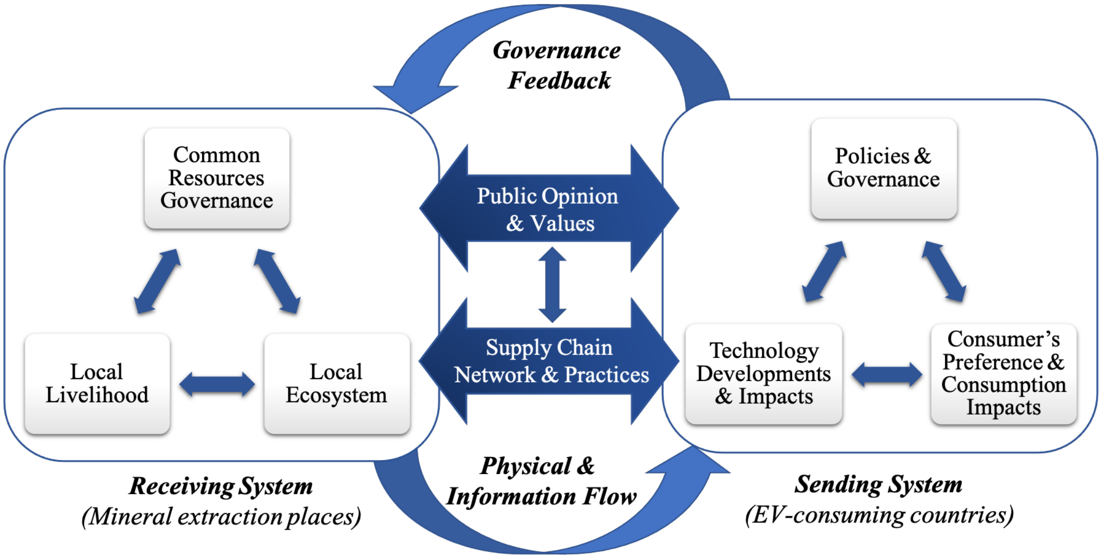

Figure 2. Conceptual Framework

In the scope of this dissertation, 'Receiving Systems' refers to the local socio-ecological system and its resource governance in Salar de Atacama (SdA), and specifically, it represents mining-induced changes to local livelihoods and ecosystems. Li-mining activities take up water and other resources from local ecosystem at an unsustainable rate, damaging social and ecological services that provided by ecosystems. Local communities, who has independently governed those resources by social norms and institutions since ancient times, are receiving the diminishing ecosystem services and the new socio-economic shock brought by the influx of labor, investment, construction, and development. Meanwhile, they're actively protesting against the social and environmental changes brought by mining operations. Governance of common resources involves both institutions at national or regional levels, and rules, norms, values, actions associated with authorities, officials and indigenous people at the local level.

'Sending Systems' represent actors and actions in the end-use phase of green technologies enabled by critical minerals. In this case, it refers to EV-consuming countries where automakers and technology developments of EVs demand more lithium for new products, EV consumers and their characteristics (e.g., values, knowledge, purchase intentions, etc.), and relevant policies and governance actors at all levels which significantly influencing the global demand for critical minerals. The impacts from upstream extraction are usually invisible and beyond the managerial boundary to these end-users and decisionmakers. With an improved understanding of such impacts, these actors may influence the performance of upstream extractors to provide a more sustainable way of extraction.

'Public opinion and values' and 'Supply chain network and practices' manifest the flows of material, information, energy, actors, and technology connecting the distant sending and receiving systems. 'Public opinion and values' include public knowledge of minerals used in green technologies, sentiments of mining externalities, roles of media and public values in helping establish mineral governance schemes. ‘Supply chain network and practices’ represents the supply chain network of green technologies and relevant industrial-led initiatives to promote transparent sourcing and sustainable extraction of minerals. These flows may have the potential to generate feedback on the energy transition progress in the consuming countries. Several events have shown that as the outcry raised by expanding Li-mining projects in South America, media and social networks have delivered these outcomes to the public and consumers, who then exerted pressure on automakers for sustainable and responsible sourcing of minerals. Although feedback to the global policy has not been seen, feedbacks created by supply chain networks are happening to demand upstream extractors for a sustainable form of extraction (i.e., Daimler required suppliers showing a sustainable manner of extraction of lithium).

In general, it offers a comprehensive view of essential components, flows, actors, and feedback in the issue of sustainable mineral extraction. Specifically, this dissertation firstly targets on understanding the current status of extraction impacts in the local socio-ecological system by revealing the linkages, interactions, and feedback in the receiving system, given the lack of relevant studies. Then this study dives into the dynamics in receiving system by predicting the future scenarios of local socio-ecological systems under various mining plans, expecting to pinpoint the challenge in resource governance. Lastly, this dissertation focusses on the role of end-users, consumers specifically, considering the increasing trend of sustainable consumption and consumer knowledge. By understanding their values, knowledge, purchase intentions about green-tech products and its associated mineral extraction impacts, this dissertation seeks to identify potential methods and opportunities that may help mobilize changes and create an innovative governance of critical minerals.

3.1.2 Methodology framework

As previously discussed in the literature review, this dissertation employs system approaches to analyze the complex telecoupled impacts related to social-ecological systems by revealing closely linked feedbacks that form a complex system (Seiffert and Loch, 2005). The overall methodology framework is illustrated in Figure 3.

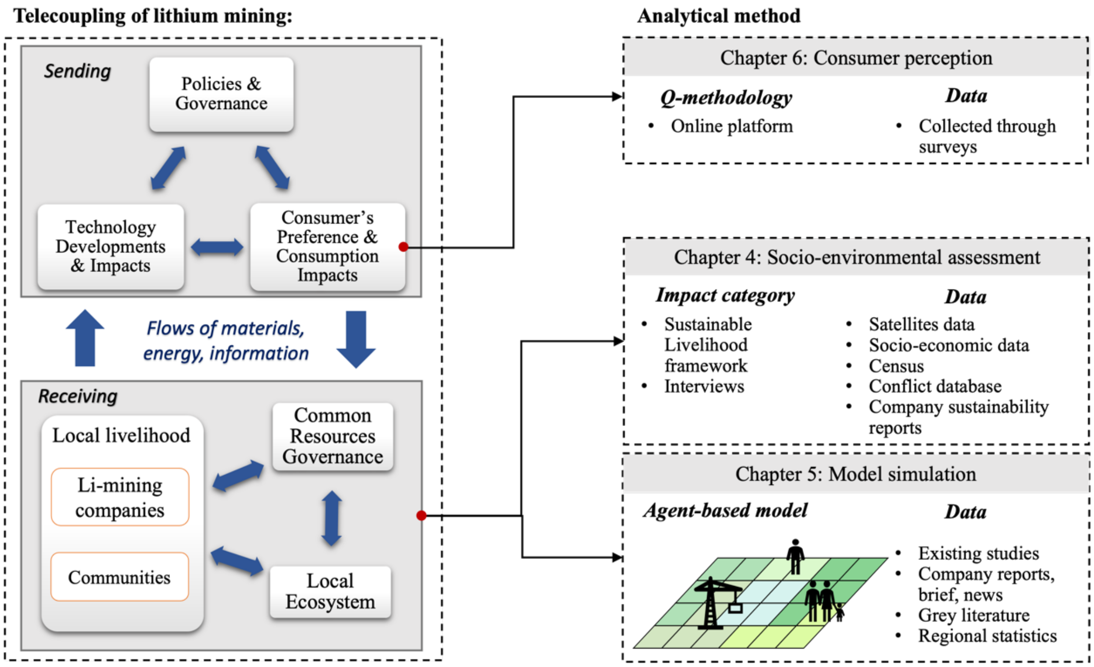

Figure 3. Methodology Framework

Firstly, to understand the current status of extraction impacts in the local socio-ecological system, an socio-environmental impact assessment study is required. Methodologies that allow a systematical and quantitative assessment of socio-environmental impacts are diverse and broad, which includes life cycle assessment

(LCA), various indicator selection frameworks, multi-variant regression, multi-criteria analysis and so on. However, these methods usually require a comprehensive database of high-quality social and environmental data, which is unrealistic for the Li-mining case in this study area given the remoteness of location and lack of transparency in impact monitoring data. In addition, notwithstanding the adequate academic research in mining-related impacts, socio-environmental consequences from brine-based Li-mining are not well understood, raising questions on the selection of indicators in impact assessment studies. Therefore, this work chooses the Sustainable Livelihood (SI) approach as a guideline for pre-selecting indicators that are relevant to the issue of Li-mining, then reducing indicators to only include ones that are mostly concerned and relevant through interviews with local residents.

Next, to examine the dynamics and predict the future scenarios of local socio-ecological systems considering various mining plans, a simulation model is required to represent the dynamic interactions among mining activities, ecological systems, and local residents. This study uses an agent-based model (ABM), a widely used tool to simulate co-evolution of environmental and social systems, and applied to the Li-extraction in SdA. The model will build on an existing ABM model developed by Castilla-Rho, et al., 2015, and incorporates the local hydrological data as well as a new layer of social system according to the social fabrics in the study area. The model allows an enhanced understanding of the extent to which mining activities have influenced groundwater level and the social stress, and of the future outcomes that are resulted from different mining expansion or reduction plans.

Lastly, even a myriad of studies has explored consumer perceptions as to sustainable consumption behaviors and adoption behaviors of green technologies, their perceptions about the embodied mining impacts in green-tech products have not been collected and studied by scholars, resulting in lack of empirical data to work with. In this work, the Q-method will be employed to provide a pilot study, as it provides more nuanced and sophisticated evaluation of opinions of consensus and discrepancies than a survey (Boudet, 2019; Kamal et al., 2014). Recognizing the upstream impacts of green-tech products can be a critical process, which participants need to reflect their knowledge about sustainability and even break their previous belief in green technologies. In this sense, Q-method can serve an appropriate purpose.

3.2 Study Area

Our study covers the Salar de Atacama (SdA) basin in the Antofagasta region of Chile and the local communities close to the mining operations in the central Salar (Figure 5). The Li-mining in SdA was brought by Rockwood in 1984, which was later purchased by Albemarle in 2015. Sociedad Química y Minera de Chile (SQM) began extraction in 1994 and quickly dominated the global market. Since then, the Li-industry has experienced a dramatic and continuous expansion. Their brine wells, pumping Li-rich groundwater, are clustered in the southwestern Salar, while freshwater wells, pumping freshwater for the precipitation process of Li, are sparsely distributed in the east and south fringe. Measured by the withdrawal rate of brine (i.e., groundwater concentrated with Li), the industry has gone from pumping 0.1 m^3/s of groundwater to more than 1.5 m^3/s, and is expected to exceed 2 m^3/s in the near future (Marazuela et al., 2020).

Generally, the saline groundwater (brine) containing lithium is pumped through a cascade of ponds where impurities or by-products such as halite, sylvanite, and carnallite are precipitated by solar evaporation, wind, and chemical additives to a concentration of approximately 6000 ppm (Tran et al., 2015; Flexer et al., 2018). After that, the concentrated brine is transported back to the recovery plant in Antofagasta for future purification and processing. A general schematic representation for the lithium extraction process in the SdA is shown in Figure 4.

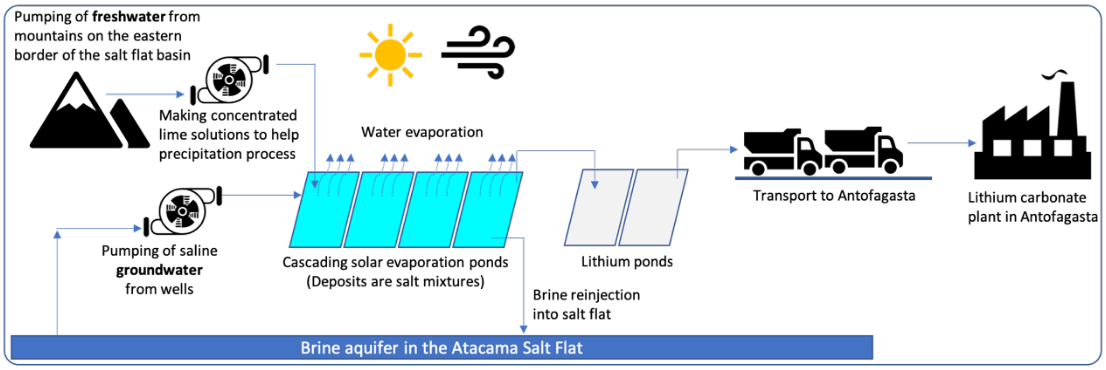

Figure 4. Schematic Representation of Lithium Extraction Process in the Salar de Atacama

Despite the fact that it is not suitable for human or agricultural consumption, the groundwater extracted by mining industries still causes stress to the local livelihoods. According to the 2017 national census, the total SdA basin contains 16 communities, with a total population of 10996; 50% of the residents belong to indigenous groups (INE, 2018). Communities are located in the north and east. San Pedro de Atacama (SPA) is the largest town in the area clustered with other small communities in the north. For communities sparsely distributed on the eastern fringe, the proximity to the mining sites raises more concerns on the socio-ecological impacts of massive water withdrawals.

Local livelihoods mostly rely on the traditional agropastoral economy, although in recent years, they have gradually adapted to the extractive industry (Babidge, 2016).

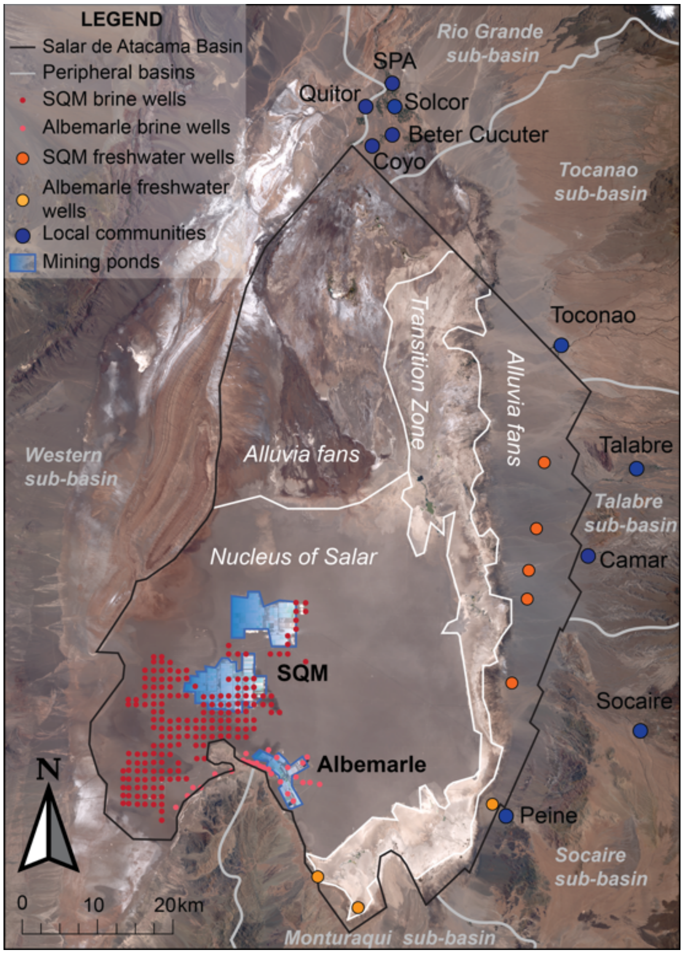

Figure 5. Map of the Study Area in Salar de Atacama, Chile

Geographically, the SdA basin is bounded by mountains without a water outlet. The nucleus of Salar contains concentrated Li and the western and eastern borders are alluvia fans connected to the higher altitude. Between alluvia fans is a transition zone formed by a water density contrast between the recharged freshwater and the brine. The zone constitutes a natural discharge area with a shallower water table and high evaporation rates. The lateral recharge from the peripheral sub-basins, mainly from the

Rio Grande and Toconao sub-basins, constitutes 87% of recharge to SdA (Marazuela et al., 2019b). Elevation decreases gradually towards the center of the Salar, averagely from 3300m to 2300m. Water resources are precious and rarely renewable, and precipitations primarily falls on the north and east boundary. Precipitation level declines from an average of 140 mm/yr in the high mountains to 10 mm/yr in the center of the Salar (Salas et al., 2010). Local livelihoods mostly rely on water from melting ice from the Andes Mountains that is channeled through community-built ditches and catchments. Mining water extraction can affect the agricultural and pastoral lands owned by the local communities through the connected water systems, the habitat of migratory birds which is a major attraction for local tourism industry, and the sacred value of water as a 'living-being' for indigenous people.

3.3 Datasets

Due to the remoteness of the study area, this research collects and incorporates a diversity range of datasets, including national statistics, organizational statistics and database, company reports, peer-reviewed journals, and news media. Table 3 shows the summary of datasets that used in this dissertation. The details of how each dataset is processed and employed in chapters are elucidated in the method section of the following chapters.

Table 3. Summary of Datasets

Name	Time frame	Description
Lithium Statistics and information[2]	1996-2020	Data of global lithium production and demand by country and by end-use (US is excluded).

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[2] Jaskula, B.W. Lithium: Mineral Commodity Summaries (2020) (Reston, VA: United States Geological Survey)

Turismo Informe Anual [3]	2001-2017	Tourism statistics in Chile, including people visited San Pedro de Atacama, number of people stayed overnight, etc.
Visiting statistics of Flamingo Nature Reserve[4]	2007-2018	Number of annual visitors to Flamingo National Park, by domestic and foreign visitors.
Chile National Population and Housing Census[5]	2002, 2017	Demographic survey on occupations, age, gender, residence, residence 5 years ago, ethnics, household statistics, etc.
The Gravity Recovery and Climate Experiment (GRACE)[6]	2002-2017	This satellite set launched in 2002. It provides monthly terrestrial water storage anomalies (TWSA) by measuring Earth's gravity field changes at 100km resolution
CHIM (CHilean Internal Migration) database[7]	1997-2002	Spatial labor mobility in Chile during 1997-2002.
La Tercera[8]	2009-2020	Noted news publisher in Chile
Reuters[9]	2012-2020	Noted global news publisher
SQM Annual Report & Sustainability Report[10]	2001-2018	Company annual reporting on corporate social responsibility initiatives
Conflictos Mineros en América Latina Database[11]	2007-2020	An NGO compiled database of mining-related social conflict in Latin America. Data includes involved actors, affected communities, description of a conflict, rights violated, media related to a conflict, and actions undertaken.
Hydrological parameters in SdA basin[12][13]	2019	These papers provide modeled parameters for hydrological conductivity, evapotranspiration rate, initial hydraulic heads, areal-recharge, and aquifer-thickness

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[3] INE (National Statistics Institute of Chile), 2001-2017. Turismo Informe Annual 2002. INE, Santiago, Chile.

[4] CONAF, 2007-2018. Estadística Visitantes Unidad SNASPE

[5] INE (National Statistics Institute of Chile). National Population and Housing Census Redatam-2002, 2017.

[6] Landerer, F.W., Swenson, S.C., 2012. Accuracy of scaled GRACE terrestrial water storage estimates. Water Resour. Res. 48 (4).

[7] Rowe, F., 2017. The Chilean internal migration (CHIM) database: a temporally consistent spatial data framework for the analysis of human mobility. Region 4 (3), 1e6.

[8] La Tercera archive database. https://www.latercera.com/etiqueta/litio/

[9] Reuters archive database. https://www.reuters.com/search/news?blob=lithium+chile&sortBy=date&dateRange=all

[10] SQM Sustainability reports. https://www.sqm.com/en/sustentabilidad/reporte-de-sustentabilidad/

[11] Latin American Mining Conflict Observatory (OCMAL). Conflictos Mineros en América Latina Database 2.3.1.

[12] Marazuela, M. A., Vázquez-Suñé, E., Ayora, C., García-Gil, A., & Palma, T., 2019a. The effect of brine pumping on the natural hydrodynamics of the Salar de Atacama: The damping capacity of salt flats. Sci. Total Environ.654, 1118-1131.

[13] Marazuela, M. A., Vázquez-Suñé, E., Ayora, C., García-Gil, A., & Palma, T., 2019b. Hydrodynamics of salt flat basins: The Salar de Atacama example. Sci. Total Environ.651, 668-683.

CHAPTER 4

INTERDEPENDENCIES OF LI-MINING AND COMMUNITIES SUSTAINABILITY

4.1 Introduction

The extraction of lithium (Li) minerals for battery production has increased rapidly in the past decade, as a result of globally growing interests in electric vehicles and energy storage technologies. Lithium-ion batteries, known for their high energy intensity, are expected to mitigate the air pollution from burning fossil fuels and make renewable energy more feasible and affordable (Tran et al., 2012). Driven by this trend, global lithium production has increased by approximately 20% per year since 2000 (Martin et al., 2017), and is projected to keep growing at faster pace in the near future (Deetman et al., 2018).

The so-called South American Lithium Triangle, a region bordering Chile, Bolivia, and Argentina, is estimated to hold 57% of the world's lithium resources (Gruber et al., 2011). The Li- triangle is located in salt flats with extremely arid climate and scarce water. The triangle is characterized by complex socio-ecological interactions (Agusdinata et al., 2018), which means that people interact with natural components in an integrated system (Liu et al., 2007) and the resourced used by humans are embedded in complex social-ecological systems (SESs) which are composed of multiple subsystems and internal variables at different levels (Ostrom, 2009). These places usually support biodiversity hotspots, community livelihoods, and a rich indigenous cultural heritage. Sustainability concerns from Li-mining are mostly on threats to local hydrodynamics (Marazuela et al., 2019a), flora and fauna richness (Liu et al., 2019), biodiversity

(Garajardo and Redón, 2019) and social wellbeing (Babidge, 2016, 2018; Egbue, 2012). The rise in mining permissions granted by the lithium governance authority is pressuring the already limited water, which is aggravating social tensions between mining companies and local communities (Molina Camacho, 2016).

To support sustainable low-carbon technologies, we must ensure that all of their impacts on local socio-ecological systems are fully recognized and addressed (Agusdinata et al., 2018). Only a few studies have addressed the impacts of Li-mining, and their scope is limited to only some aspects of the system. For example, Babidge (2016, 2018) interviewed and observed indigenous people to investigate the changes in social values and ethics perceived in the Salar de Atacama (SdA), Chile, where the world's largest brine-based Li-mining is located. The study documented mining impacts as perceived by the communities, such as loss of access to old farmlands, ecosystem degradation, and declining collective practices. While these studies identified some potential socio-environmental impacts, they did not provide a holistic assessment. Romero et al. (2012) explored environmental injustice in the Atacama Desert by examining the water balance in watersheds where concentrated mining activities are located. The study covers many types of extracted minerals, and so does not sufficiently reflect the unique characteristics of brine-based Li-mining. Lastly, Egbue (2012) assessed the social impact of Li-extraction and carbonate processing using a social-life cycle assessment framework, and specifically investigated indicators pertaining to impacts on workers, local communities, and the larger society in Chile. Due to the data shortage at the time, the study only partially represents the social impacts of Li-extraction and does not capture the interdependency of mining and the surrounding socio-ecological system.

This work provides a more holistic view of the impact of Li-mining expansion on its surrounding socio-ecological systems. It assesses the Li-mining impacts on the sustainability of local communities with emphasis on impacts that mostly affect local people, by answering the following two research questions: (1) *What is the mutual dependency between the lithium mining industry and the livelihood of local communities in northern Chile?* (2) *How does lithium mining expansion affect the sustainability of local communities based on the interdependency?* Due to the remoteness of the area and lack of local data, data from diverse sources is used, including the national micro-level census, national statistical yearbook, company reports, mass media, and satellite gravimetry. These results provide stakeholders with a more holistic understanding of the multi-scale interdependency of Li-mining activities.

Academic interests assess mining impacts in developing countries from diverse perspectives. Some research has focused on mining-associated benefits: increased economic activity, job creation, infrastructure development, and social benefits (Pegg, 2006; Kitula, 2006; Kotey and Rolfe, 2014), along with governance strategies (i.e., corporate social responsibility, CSR) that contribute to the socio-economic development of resource-based communities (Morrison et al., 2012). Other's research focused on environmental degradation, local displacement, social upheaval, and socio-economic issues that are created by the long-commuting labor influx (i.e., Storey, 2001; Haslam and Hoath, 2014; Aragón and Rud, 2013). The sustainable livelihood (SI) approach (DFID, 1999) links socio-economic and environmental concerns, which have been widely applied in natural resource management research (Pound et al., 2003) and have revealed the interplay under the context of mining (Horsley et al., 2015). Mining impacts put diverse pressures on resource-based communities due to the differences in commodity type, local social and political contexts, cultural background, and development trajectory (Auty, 1997). This interconnection implies that the impact for communities in the remote Global South from the recently booming lithium industry can be complex and varied. Holistic impact assessment can help examine the activity's performance through its most significant impact areas, and it distinguishes itself by the systematic consideration of positive and negative impacts across the three pillars of sustainable development (UNEP, 2020). Research efforts that holistically address this issue are rare; much of current work is either too broad or has a single or narrow range.

System approaches have been applied to complex social-ecological system problems, including sustainable resource management, community development, and urban transformations, by revealing closely linked feedbacks that form a complex system (Seiffert and Loch, 2005). System dynamics and optimization models, for instance, are useful in modeling and advising conjunctive water use in agriculture practices at local scales (Sedghamiz et al., 2018; Hashemi et al., 2019). System thinking also has been adopted to develop integrated and collaborative resource management practices for building community resilience and sustainability (i.e., Aryal et al., 2019; Musavengane, 2019). The issue of Li-mining essentially reflects the key characteristics of complex social and natural systems in which multiple interactions of system elements lead to emergent system behaviors due to feedback, time delay, and non-linear relationships (Agusdinata et al., 2018). A study of such complex systems requires a system approach that fully considers the interactions across different temporal, spatial, and institutional scales (Ostrom, 2009).

The contributions of this study are centered on two major aspects: (1) a quantitative and more holistic assessment on the sustainability of frontline communities near Li-mining activities in SdA, which helps explain the escalating local tensions on lithium industry; and (2) a coupled natural and social system framework to analyze the multi-scale interdependency of Li-mining activities providing insights for informing policies towards sustainable lithium sourcing.

In this paper, it firstly introduces the coupled natural-social system framework that applied to show the interdependency of Li-mining and local communities. Then, the process for the impact themes selection and the diverse data source used are illustrated. Next, each identified theme is assessed and the dynamics of impact trajectories based on the mining-community interdependencies is synthesized. Subsequently, the implications for other Li-mining areas in the lithium triangle and directions for future research are discussed.

4.2 Materials and Method

4.2.1 Coupled Natural and Social System

Systemic reasoning, which is successful in tackling complex systems under the realm of sustainable resource management (Williams et al., 2017), facilitates the understanding of complex systems (Seiffert and Loch, 2005). Faced with a complex socio-ecological system, this work firstly constructed a coupled natural-social system framework based on empirical studies to integrate the relevant impacts into a more holistic picture by uncovering interdependencies between the expanding lithium industry and local communities in San Pedro de Atacama (SPA) (Figure 6).

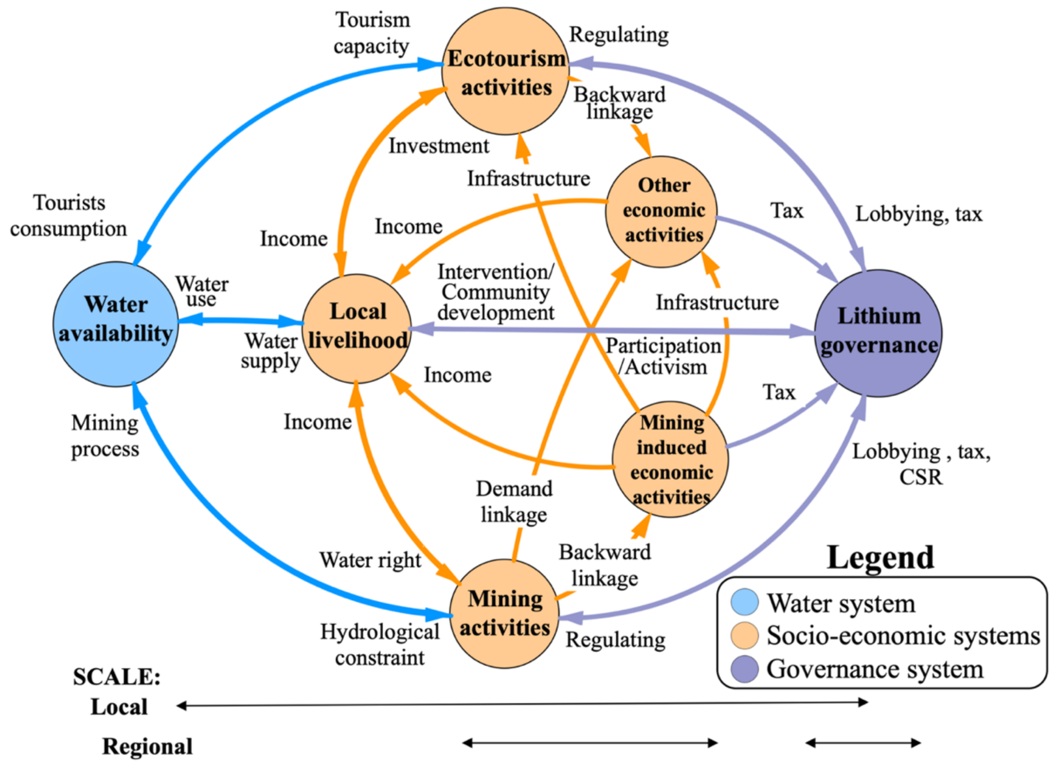


Figure 6. Coupled Natural and Social System of Lithium Mining-community Interdependency

The natural system is comprised of the large endorheic salares (i.e., salt flats and associated wetland systems; Salas et al., 2010). Water provided by the natural system is the key constrained resource and economic basis for livelihoods and activities in the area (Babidge and Bolados, 2018). Mining development has been accused of taking tremendous amount of water resources in this area. Meanwhile, the tourism industry has also increased twelve-fold in the past 15 years, reaching 0.4 million tourists in 2016 (INE, 2003, 2017), which can increase both direct and indirect water use, therefore adding water stress to already water scares destinations (Gössling et al., 2012). In turn, the scarce water resource is also concerned to limit the tourism capacity and mineral development in this area (Enrique 2018).

For the social system, according to the descriptions of empirical studies from Babidge and her colleagues (2013, 2016, 2019), local socio-economic activities can be categorized into four subgroups: mining, mining-induced, ecotourism and other economic activities since local economic structure depends heavily on Li-mining and ecotourism industry (Table 4). Mining-induced activities supporting mining production include construction, transport, and communication; ecotourism includes hotels, food services, and retail; and other activities encompass the remaining local activities. Mining industry has brought opportunities in construction and transport industry, which then created or updated infrastructure for other economic activities, such as paved roads, portable water supply (Babidge, 2019). Contractor workers brought by mining development could also create demand for consumer goods and services (Babidge, 2019). In this sense, mining companies and local communities could be economically interdependent, providing each other with employment and labor, respectively. Sometimes, the locals also illegally trade a part of their water rights with mining companies in exchange for monetary gains or job opportunities (Babidge 2013). Tourism also plays an important role in socio-economic activities here. Local communities have developed forms of tourism that pursuit demands for places of natural and cultural attractions (Enrique, 2018), brining outside dollars into the local economy. Therefore, the social actors that are involved include national and multinational mining companies, local communities, tourism enterprises, and regional and national policymakers.

Table 4. Distribution of Labor Force in San Pedro de Atacama in 2017

Sector	Labor force
Mining	755
Mining-induced	1199 *(Construction: 810; Transport and Communication: 389)*
Eco-tourism	1677 *(Hotel and Food Services: 1215; Trade: 462)*
Others	2316 *(Agriculture: 180; Manufacturing: 245; Utilities: 68; Business services: 237; Public Admin: 944; Comm & Personal services: 612)*
Not defined	1061

Governance systems includes government, decision-making actors and mechanisms that directly and indirectly regulate and govern lithium-related activities and impacts at both local and regional level through laws, procedures, and norms. The government (e.g., Dirección General de Aguas) regulates the water use of each socio-economic subsystem through permit issuing and environmental inspections (Babidge, 2018), thereby governing the total water availability in the natural system. It also receives tax revenues from mining industry and other economic industry. Local governance systems (community, association, ethnic groups) receive social investment funds from mining industry, which then be used for community development (Babidge, 2016). Sometimes, the governance system serves as an intermediator to resolve conflicts between the communities and mining companies.

Based on the stakeholder meetings (explained in section 4.3) and empirical studies of this area, we posit that the coupling of the natural and social systems manifests through the interlinkages. The natural system provides ecosystem services and regulates water availability, both surface water and groundwater, which is shared by subsystems in the socioeconomic system. Water resources are primarily consumed by domestic usage, mining processes, and tourists. Excessive consumption from either subsystem could constrain water available for others. Socio-economic subsystems can be closely linked by mining and tourism. The mining industry attracts a distant workforce who could foster local economy by demand linkage and also could stimulate economic prosperity in relevant industries (e.g., construction and services) through backward linkage. Similar to mining, other subsystems can also interact through economic linkages. Each subsystem provides incomes to support local livelihoods. Social livelihoods, which receives the relevant social and environmental impacts of mining, could form social mobilization and collective actions in demand for a better governing of resource use (water) and extraction (lithium).

4.3 The sustainable livelihoods (SI) approach for identifying impact categories

The SI framework has been widely adopted as a theoretical grounding for measuring sustainable development. Recently, it has been developed as a robust means for understanding the interplay between mining and development (Horsley et al., 2015). Underlying the SI framework are the five capitals that support livelihood objectives: financial (FC), human (HC), natural (NC), social (SC), and physical (PC) (FAO, 2002). The composition of each of the five capitals varies by different mining types, local contexts, and definitions of development.

Based on the SI framework, stakeholder meetings were held to select impact categories perceived as the most relevant to Li-mining activities. Three sets of meetings were conducted with local stakeholders to discuss their concerns over the expanding Li-mining industry. Invited participants included community leaders, ethnic group leaders, representatives from local NGOs, and government officials. Communications were facilitated by a Spanish-speaking colleague from the University of Chile. Meetings were audio-recorded, and then transcribed and summarized to highlight the most discussed themes.

These meetings firstly help define sustainability in this assessment. A clear and consistent definition of sustainability is challenging in implementation studies while assessing sustainability (Moore et al., 2017). Carney (1998) and Scoones (1998) define that a livelihood is sustainable when it can cope with and recover from stresses and shocks and maintain or enhance its capabilities and assets both now and in the future, while not undermining the natural resource base. In the case of SPA, local people perceive that they had developed a sustainable livelihood through traditional knowledge, technology, and ways of living and managing resources. However, such livelihood has been interrupted by the large-scale mining, posing questions on the ability and capacity for the locals to cope with and recover from the mining stresses. In this sense, we adopt the definition of sustainability by Carney (1998) and Scoones (1998).

Based on the information collected from stakeholder meetings, the highlighted themes were then grouped into five impact categories, each reflecting one or more capital assets (Table 5): (1) water availability, referring to local concerns over water scarcity, water loss from mining, water deprived from farming and households; (2) labor influx, including patterns of labor movements, composition of labor influx and its possible economic contributions; (3) employment and displacement, to incorporate employment conditions of local labor and displaced population; (4) social activism, representing grassroot movements against mining (e.g., protest and demonstration events); (5) corporate social responsibility initiatives, referring to efforts by mining companies, and government including investments in social development, cultural heritage, and youth and adult education programs.

Table 5. Impact Categories Most Concerned by Communities in San Pedro de Atacama.

Impact categories	Capital assets	San Pedro de Atacama context
Water availability	NC	• Total water availability • Water consumption by mining, domestic use, and tourists
Long-distance labor influx	FC	• Geographical pattern of labor influx • Migration effectiveness • Composition of labor influx (commuting vs migration)
Employment and displacement	FC, SC	• Sector-wise employment of local labor • Displaced population
Social activism	SC	• Social activism events related to lithium mining in SPA
Corporate social responsibility initiatives	HC, SC, PC	Corporate initiatives on local development in terms of health, education, culture, and infrastructure developments. It includes: • Cultural heritage • Education and culture • Social development

4.4 Data and material processing

Since hydrological records are either unavailable or highly inconsistent, this study investigated water availability through observation data from satellite gravimetry. The Gravity Recovery and Climate Experiment (GRACE) twin satellites, launched in 2002, provide monthly terrestrial water storage anomalies (TWSA) by measuring Earth's gravity field changes (Landerer and Swenson, 2012). GRACE TWSA reveals variations in the total water availability (including surface water, water in soil, snow water, canopy water and groundwater) of examined terrestrial area. Its data product has been examined and validated for multiple scales and environments (i.e., Gemitzi and Lakshmi, 2018), even at a regional scale in Northern Chile (Montecino et al., 2016). In this study, the data is acquired from the University of Colorado GRACE data portal (http:// geoid.colorado.edu/grace/index.html) for 2002-2017, with monthly measurements. GRACE TWSA data has a spatial resolution of 100 km and is scaled with gridded gain factors developed by Landerer and Swenson (2012). Due to the relatively small study area, the USGS Level 2 river basin dataset was selected for the shape of the averaging region. The acquired TWSA data expresses the changes in the total stored water relative to the baseline average over January 2004 to December 2009 in the study area.

The water in the study area is mostly consumed by mining, domestic living, and tourism (Segura et al., 2018). However, the water consumption data is poorly tracked and documented. This study estimates the water use in these sectors from 2002 to 2017 based on the mining production scale, local population, tourist population, and their associated water demand. First, it estimate the mining water use based on the assumption of 500,000 gal/tonne of lithium extracted (Katwala, 2018), and the yearly mining scale from USGS mineral commodity statistics (https://www.usgs.gov/centers/nmic/mineral-commodity-summaries). Second, water for tourism is calculated by an estimated 200 L/tourist daily consumption in Chile (Gössling, 2006) and yearly records of tourists in SPA from Chilean tourism yearbook (https://www.ine.cl/estadisticas/economicas/turismo). Third, domestic water use is estimated by the projected annual population in SPA (INE, 2014) and assumed household water demand of 46.25 m^3/cap/yr in the Antofagasta region (OECD, 2017).

For labor and employment data, this study uses the most recent micro-level statistics from the Chilean housing and population census conducted in 2002 (INE, 2003) and 2017 (INE, 2018), each covering a five-year period of 1997-2002 and 2012-2017. The censuses failed in both 2007 and 2012, resulting in the gap in data between 2002 and 2012. The censuses provide information on personal characteristics, including demographics, labor markets, and economic activities. The CHIM (CHilean Internal Migration) database was also used, developed by Rowe (2017), to extract data on spatial labor mobility in SPA during 1997-2002 based on the 2002 census. The same method in CHIM database construction (Rowe, 2013) was then followed to develop the labor mobility in SPA for 2012-2017. In accordance with the Census and CHIM database, the labor investigated in this study is defined as the workforce aged 15-64, excluding unemployed individuals, students, retirees, and housewives. To measure the spatial impact of migration flows in each industrial sector, the Migration Effectiveness Index (MEI) was selected, which indicates the degree of imbalance between migration flows and counter-flows. MEI has been widely applied in studies on the spatial impact of migration flows at different scales (i.e., county scale (Manson and Groop, 2000) and regional scale (Rowe, 2013)). Formally, MEI is defined in equation (4.1), as (Shryock and Siegel, 1976):

$$MEI = \frac{\sum_i |D_i - O_i|}{\sum_i |D_i + O_i|} \times 100 \tag{4.1}$$

Where D_i denotes the total in-migration to region *i*, while O_i denotes the total out-migration from the same region. The range of the index is from 0 (in-migration and out-migration are equal in number) to 100 (migration is entirely one way, either in or out).

Social activism is measured by social movements at a local or regional scale as a response to Li-extraction activities or governance decisions. This study searched for such events from newspaper archives of El Diario de Antofagasta and El Mercurio, the most widely read news media in Chile, with keywords of *'litio'* and *'protesta'*. Events directly relevant to Li-extraction in SPA was then examined. Events data from the Mineral Extraction Conflict database (*https://mapa.conflictosmineros.net/ocmal_db-v2/*) was also verified and incorporated, which is compiled by a local NGO, Observation of mineral conflicts in Latin America.

As for CSR initiatives, this study recognized that the data are not comparable within reports, between reports of different time frame, or between reports from different companies. However, temporal trend explorations are possible (Jenkins and Yakovleva, 2006). It also detected trends on Li-mining companies' disclosures about sustainability efforts over time from companies' annual reports between 2002 and 2009 and yearly published sustainability reports since 2010. Specifically, this work tracked the disclosures of social initiatives and investments contributing to SPA since 2002, and evaluated how their scope, reporting style, and content have evolved.

4.5 Results and Discussion

In the following sub-sections, we provide an assessment of Li-mining impacts on communities and their interdependent linkages to validate and quantify the relationships in Figure 6. Thereby, it starts with an assessment of community sustainability in water availability, labor influx, employment and displacement, social activism, and long-term sustainability. Next, a holistic analysis of mining-community interdependencies is provided to reveal significant impact feedbacks on their interactions. Furthermore, it discusses the ongoing lithium boom in other lithium triangle countries, as well as the applicability of the coupled natural and social framework in these cases.

4.5.1 Sustainability of local communities

4.5.1.1 Water availability

The changes in total stored water (i.e., surface water, soil moisture, and groundwater) from GRACE are shown in Figure 7. The period before 2004 is the model initialization period and the years 2004-2009 serve as the baseline. Thus, for trend detection only the total water storage anomalies after 2010 is considered. It is still evident that the total water storage shows a depletion trend over 2010-2017. With a passed Mann-Kendal test at a calculated p-value ≤ 0.05, the TWS over 2010-2017 shows a statistically significant decreasing trend with the slope of -1.16 mm/year. This trend indicates that the total water storage in SPA is estimated to decrease by 1.16 mm compared to the previous year. This trend indicates a concerning situation of groundwater in SPA, considering the overall TWS in northern Chile shows an increased tendency (1.5 mm/yr) by Montecino et al. (2016).

Water consumption continuously increased from 2002 to 2017 due to expanded mining production, increased local inhabitants, and increased tourism. Astoundingly, estimated water consumed for mining processes was approximately 50 times the estimated domestic use, and hundreds of times the estimated tourists' consumption (Figure 8). Since estimated water use is based on some assumptions (stated in the methodology section), it may not accurately express water usage but reflect the magnitude difference in water resources consumed by mining industry, local livelihoods, and tourism.

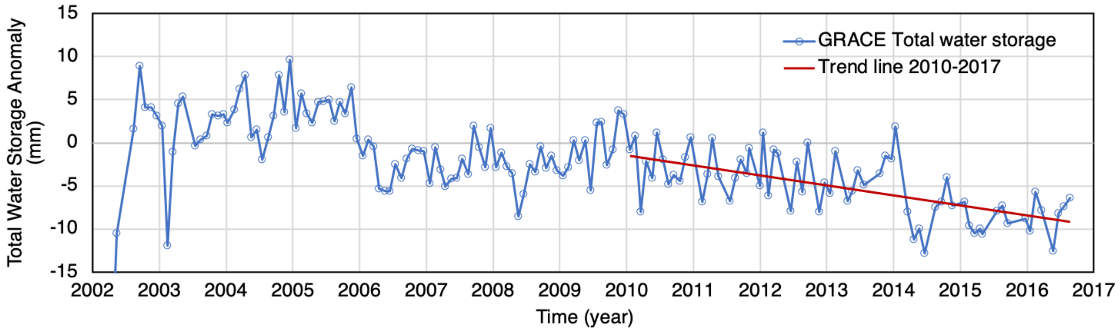


Figure 7. Total Water Storage, 2002-2017.

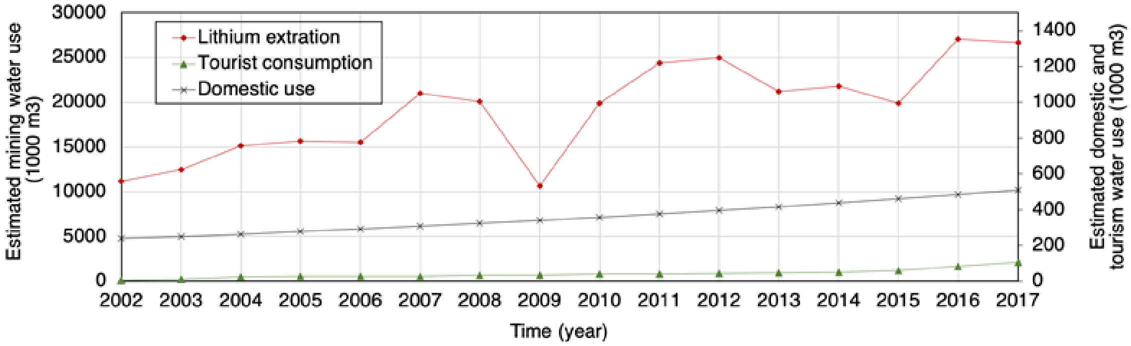


Figure 8. Estimated Water Consumption of Mining, Domestic Use and Tourism, 2002-2017.

4.5.1.2 Long-distance labor influx

To compare the labor influx between the two census periods, the influx is mapped to show the spatial mobility of the long-distance labor to SPA (Figure 9). In general, the local economy attracted long-distance labor, mostly from adjacent regions, during both periods. However, the labor flows during 2012-2017 had greater impacts due to the number of laborers and the distance they migrated. Specifically, a total of 2466 laborers moved to SPA during 2012-2017, which is 20% more than the local labor, and almost 2.3

times more than the long-distance labor in 1997-2002. During both periods, most long-distance labor was inter-municipality migration inside Antofagasta, while more labor was from Central Chile during 2012-2017. The share of labor from the northern regions decreased between periods, from 67% to 47% of the total influx. In contrast, labor from Central Chile was a larger part of the labor influx during 2012-2017 (approx. 48%). Labor from South Chile contributed little to the labor influx to SPA in the period.

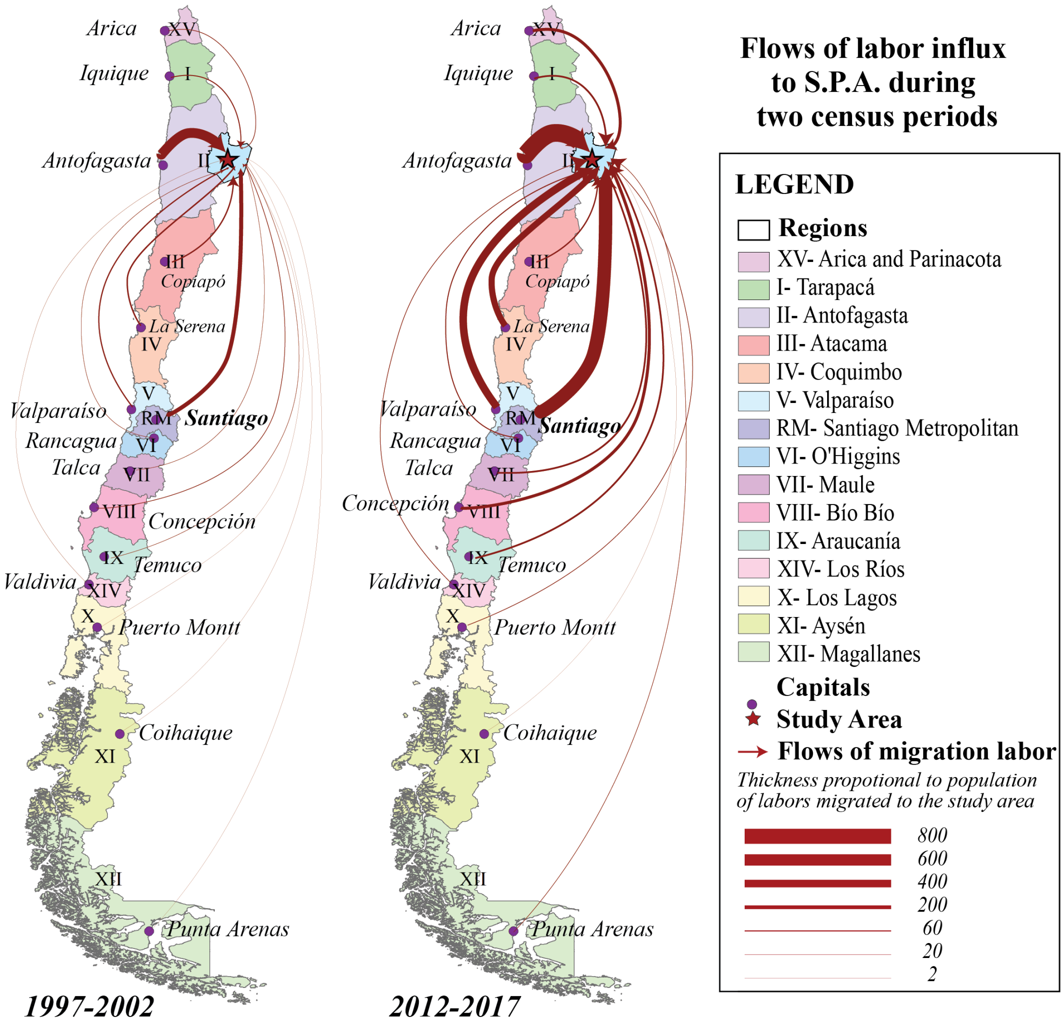


Figure 9. Migration Flows to San Pedro de Atacama during 1997-2002 and 2012-2017

The spatial impact of migration flows during the two census periods show the imbalances between in-and-out flows by industrial sectors (Figure 10). In general, half of the industries showed a decreasing trend of MEI, indicating a reduction of spatial impact of migration and a greater balance of in-and-out labor flows. The decline of MEI that was driven by the growing out-flows implies that migration has become less influential as a mechanism for population redistribution in these industries. At the local scale, the trend may reflect a greater regional dispersal of the employment opportunities that drive labor flowing out of SPA, leading to workforce loss in the area. In contrast, the mobility of workers in mining, manufacturing, utility, and construction increased impacts over the two periods, driven by the greater imbalance of labor in-flows. The increased mobility can be attributed to the economic prosperity brought by Li-mining activities in the area, which promoted not only mining employment but also employment in industries supporting mining production, leading to uni-directional movements of workforces into SPA Another possible reason could be the growing popularity of SPA as an ecotourism destination, driving more investments in infrastructure and utility, and thereby attracting more laborers. The overall migration impact in SPA was noticeable due to the relatively high imbalance of migration flows in both periods, with an average MEI of 68% and 63%, respectively.

In both periods, mining showed a great migration impact due to its high MEI, while agriculture and trade showed the most evident decline due to the large reduction in MEIs. The reduction in agriculture can be explained by the decline in in-flows and the increase in out-flows. The trade industry, which represents economic activities related to tourism, declined from an above-average MEI to a below-average MEI, which is caused by a faster increase of out-flows than in-flows.

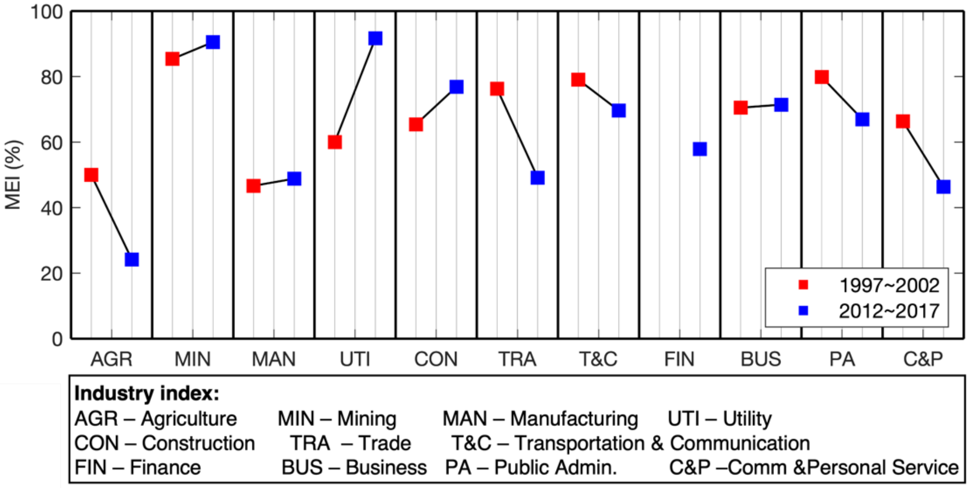


Figure 10. Migration Effectiveness of Labor Migration in San Pedro de Atacama

The labor influx increased in most industries between the two periods, with mining and manufacturing increasing at the fastest rate (Table 6). During 1997-2002, construction and trade were relatively prosperous and attracted more distant laborers, while mining attracted the most labor, due to its rapid expansions in 2012-2017. Notably, the long-distance labor in mining increased in both numbers and share. Even though trade had been a popular industry attracting more long-distance labor between periods, its share stayed stable.

Migration flows are composed of permanent migration laborers, who move to reside in the SPA, and commuting laborers, who commute between work and home. The latter could create a geographical mismatch in the place of earning and spending, resulting in limited economic contributions to the communities where they work (Aroca and Atienza, 2011). Table 6 shows the number of long-distance laborers and the percentage of commuting labor among them in each industry. In this case, most of in-migration workforces in mining and mining-induced industry (i.e., construction) were commuting labor, as a result of the Fly-in/Fly-out characteristics of these industries. Compared with the whole labor (both local and long-distance) in mining industry in SPA, the share of commuting labor was still considerable and even increased from 34% to almost 79% between the time periods. In trade, most of in-migration flows were made up of permanent migration labor during both periods.

Table 6. The Share of Commuting Labor by Industry Sector

Industry Sector	**Number of labor in each industry (Share of commuting labor)**			
	2002 (Total)	2002(Long distance)	2017 (Total)	2017(Long distance)
AGR	108 *(4%)*	24 *(17%)*	120 *(2%)*	18 *(11%)*
MIN	267 *(34%)*	127 *(71%)*	661 *(79%)*	543 *(96%)*
MAN	66 *(9%)*	22 *(27%)*	196 *(30%)*	96 *(60%)*
UTI	13 *(8%)*	8 *(13%)*	48 *(31%)*	23 *(65%)*
CON	391 *(46%)*	239 *(75%)*	487 *(47%)*	314 *(74%)*
TRA	520 *(12%)*	245 *(25%)*	1174 *(10%)*	519 *(24%)*
T&C	174 *(12%)*	77 *(27%)*	331 *(29%)*	162 *(59%)*
FIN	2 *(0%)*	0	18 *(67%)*	15 *(18%)*
BUS	204 *(45%)*	133 *(69%)*	175 *(63%)*	144 *(76%)*
PA	159 *(43%)*	125 *(54%)*	627 *(11%)*	283 *(23%)*
C&P	224 *(7%)*	89 *(18%)*	654 *(17%)*	349 *(32%)*

4.5.1.3 Employment and displacement

The employment condition of local labor is summarized in Figure 11. The number of local laborers in most industries increased between the two periods, except for mining and business services. The trade sector employed most local labor during both periods, more than half of its total laborers. During 1997-2002, mining and construction were common industries for local labor, while during 2012-2017, public administration and communications & personal services became the dominant employment sectors.

It is worth noting that even though the total labor in mining increased almost 2.5 times, the employed local labor decreased by 16%. The share of local labor in mining declined significantly, from 52% to 18%, between two periods. As a result, the mining industry was mostly dominated by long-distance labor between 2012 and 2017. In contrast, agriculture was primarily comprised of local labor in both periods, with 78% and 85% from local communities.

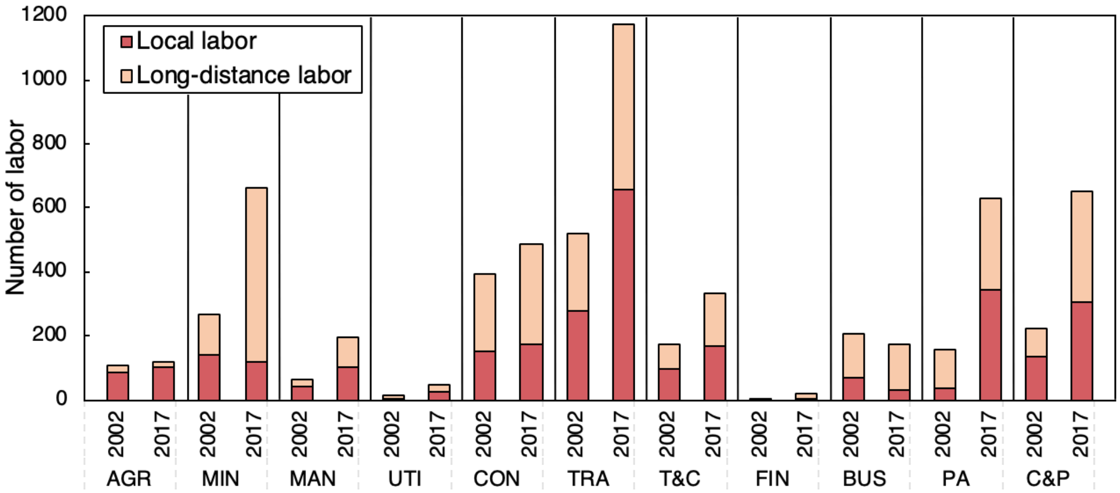


Figure 11. Sector-wise Distribution of Local Labor and Long-distance Labor in 2002 and 2017

As with the displacement of the local population, labor move-out increased more than three times between the two periods, made up of 11% and 15% of total local labor in each period. The industry that hired the most displaced laborers was construction (29%) during 1997-2002, and trade (33%) during 2012-2017. Municipalities within the region of Antofagasta was the most popular destination during 1997-2002, while the Santiago Metropolitan region was the most popular destination during 2012-2017.

4.5.1.4 Social activism

The dynamics of social movements related to Li-extractions must be interpreted with respect to the influence of government actions that arise or appease these movements. This work performed a timeline analysis of major activism events on Li-extractions and related them to major governance actions in Chile (Figure 12). In the early 1990s, social movements related to Li-mining were rare in the SPA since Li-mines just started to operate and were small scale. From 2000 onwards, with a series of expansion permits approved and environmental infractions found, social awareness and movements have grown and intensified.

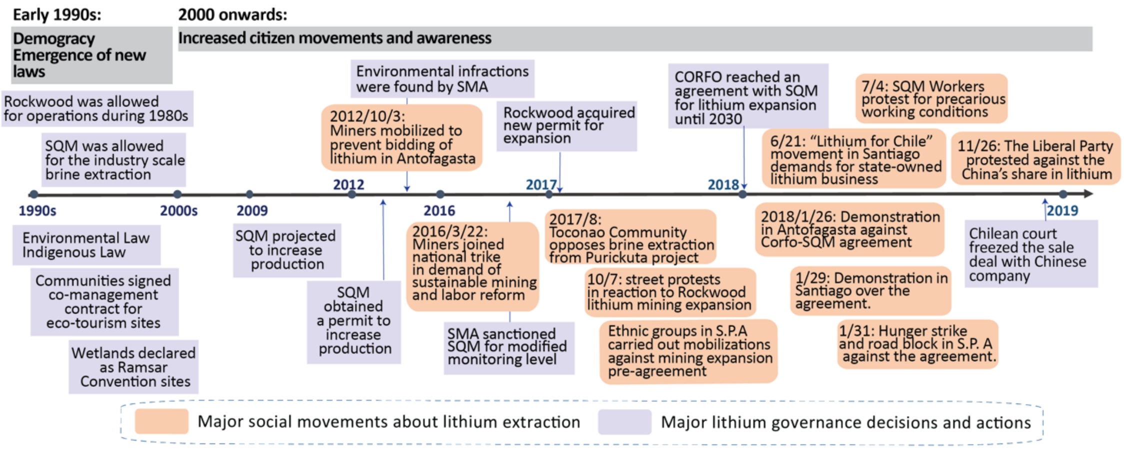


Figure 12. Timeline of Social Activism Events Associated with the Li-mining in San Pedro de Atacama

Social activists had distinct concerns. The objection to excessive water uses by expanding production was the most common reason for local mobilizations. The locals were concerned that the large quantity of water withdrawn from mining operations could stress their livelihoods by exacerbating water shortages and threatening the fragile ecosystem of SdA. At the regional and national levels, objections were directed at the misconduct of mining operations, corruption issues, and foreign investments in the lithium business. One major demand was to re-nationalize lithium production.

Furthermore, the social movements have gone from local to national since 2018, driven by a new contract signed between the Production Development Corporation of Chile (CORFO) and SQM. The contract increases the production quota to 216,000 tonne/yr of Li-carbonate through 2025 in the SdA (Reuters, 2018). After the signing, protestors rallied at the regional capital, national capital, and SPA local, to express their objections. These events were much more intense than in previous movements. The January 2019 demonstration in Santiago, for instance, attracted hundreds of demonstrators and was severely repressed by the police force. Since then, the expansion of Li-mining has become a national issue as a result of increased citizen awareness and movements at all levels.

4.5.1.5 Corporate social responsibility initiatives

To assess the long-term sustainability of communities, this study primarily analyzed the disclosures of CSR by SQM, that has fairly complete records of annual reports and sustainability reports. Because of the 2015 acquisition of Rockwood by Albemarle, records related to Rockwood's sustainability efforts are hard to track since they were not reported in the Albemarle annual reports.

Social disclosures by SQM evolved from a few paragraphs in Annual Report to a stand-alone Sustainability Report. In 2002, community development disclosures were ambiguous, primarily centered on offering research or educational opportunities. In 2004, the CSR program was established in the company annual report with initiatives classified as: historical heritage, education, social development. By 2006, the disclosures started containing data, and specific communities were mentioned, and long-term programs were initiated. In 2010, the first stand-alone sustainability report was issued with more sophisticated content and reporting style. The amount of social development information increased each year, as well as the data and details disclosed even as they were still patchy.

Table 7. Disclosure of Corporate Initiatives for Community Development in San Pedro de Atacama

Corporate efforts in community development		2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018
Cultural Heritage	Cultural exhibit									■								
	Assistance to cultural practices									■								
	Ancient festival celebration													■			■	
	Culture restore initiatives																	■
	Tourism support initiatives																	■
Education and Cultural	Math assistance program						■	■	■	■	■	■	■	■	■	■	■	■
	Psycho-pedagogical program						■	■	■	■	■	■	■	■	■	■	■	■
	Student transport							■	■	■	■	■	■	■	■	■	■	
	Extracurricular workshops																■	■
	Multi-ages games									■	■	■	■	■	■	■		
	Field day												■	■	■	■	■	■
	Support for cultural initiatives									■	■	■	■	■	■	■	■	■
	Christmas celebration						■	■	■	■	■	■	■	■	■	■	■	■
	Educational facility improvements				■				■									■
	Technical professional school program																	■
Social Develop-ment	Micro-entrepreneurs' program						■	■	■	■	■	■	■	■	■	■	■	■
	Atacama agriculture program							■	■	■	■	■	■	■	■	■	■	■
	Emergencies restoration											■		■	■	■	■	■
	Environmental education													■	■	■	■	■
	Tourism infrastructure improvement				■	■				■					■			■
	Apprentice program									■					■	■	■	■

**The color-coded cells indicate reported activity in the company's annual reports*

Table 7 summarizes the appearance of SQM's initiatives in community development in SPA from 2002 to 2018; the colored box indicates the presence of initiatives in each year. Notably, even with few efforts reported before 2006, there is an increased diversity of CSR. Most initiatives were directed to education and social development, while the protection of cultural heritage was limited. As a result of established agreements with some communities, several long-term programs were initiated to support youth education and micro-entrepreneurs and disseminate sustainable agriculture knowledge. Initiatives that can help develop economic independence, such as job training and tourism support, were limited and inconsistent. Overall, despite a trend of more sophistication in content of their CSR initiatives, the actual performance should be externally audited to enhance the efforts' credibility.

4.5.2 Li-mining and community interdependency

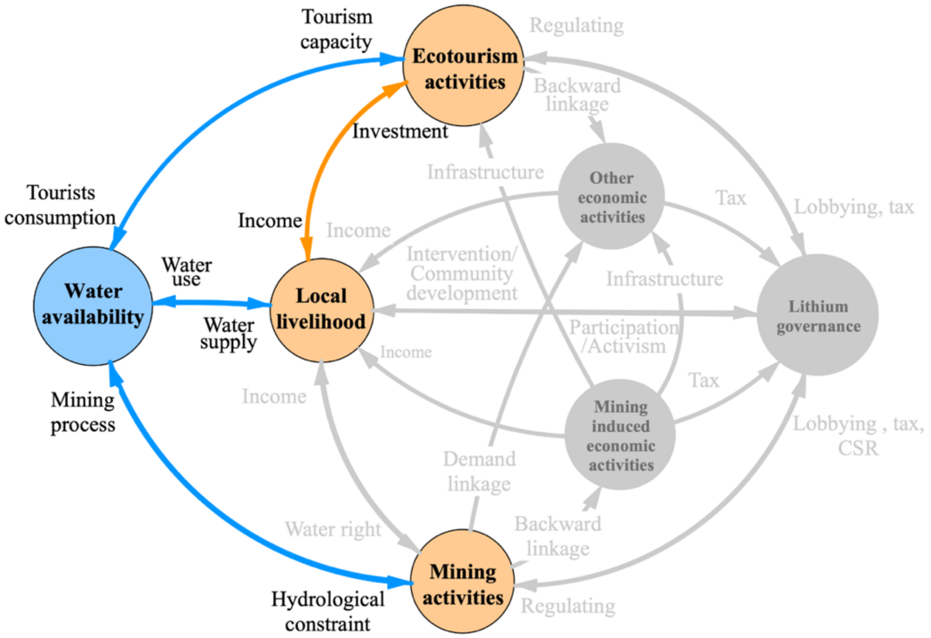
To investigate the impacts of Li-mining expansions on community sustainability, the impact and response trajectory of Li-mining and communities were explored based on their interdependency, and then analyzed the dynamics of these trajectories from the impact categories examined in Table 5. This study categorized these trajectories from the interdependency framework (Figure 6) and displayed each trajectory in Figure 13.

The most important feedback that Li-mining affects local livelihoods is through excessive water consumption (Figure 13a). Local livelihoods and activities, particularly mining and ecotourism, consume water resources from the shared water system. Mining could deplete the total water resources and pressure the area's already severe water scarcity. Decreasing domestic water supply, limiting tourism growth, and even constraining mining production can mitigate water crises, but may negatively affect livelihood incomes, which can result in reducing investments in ecotourism business, reinforcing the negative impacts on livelihood incomes.

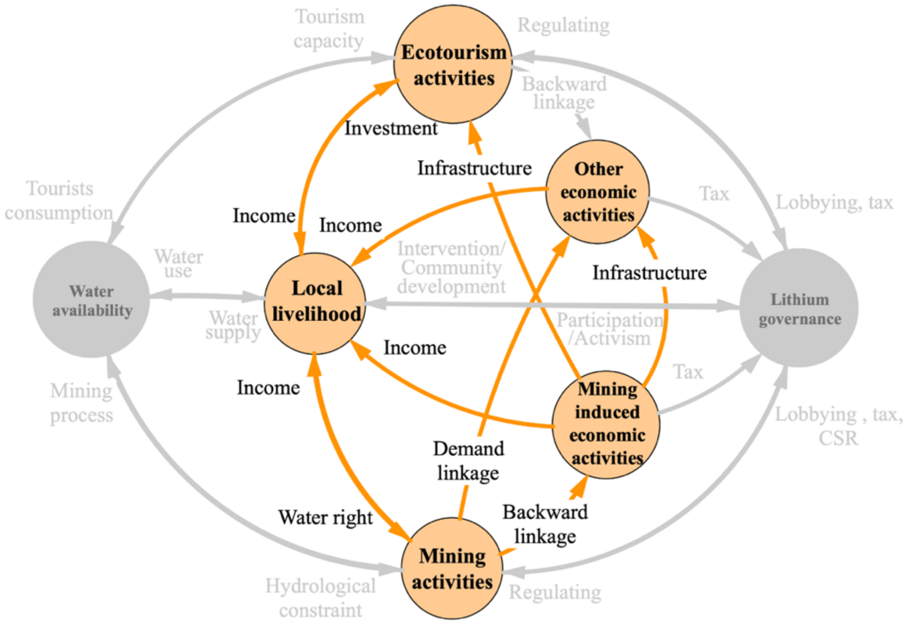
Mining provides direct income and jobs to local livelihoods as well as promotes other local industries through economic linkages, indirectly improving income levels and jobs for communities (Figure 13b). However, the actual share of local laborers in mining and mining-induced industries was limited, thereby restricting the income provided to local livelihoods. Despite a large labor influx attracted by mining, most of the influx was of commuting laborers, who contributed little to local economy. In response, under some circumstances, the locals may illegally sell part of their water rights directly to mining companies for the consumption and hygiene of miners, in exchange for additional incomes (Babidge, 2016). Unfortunately, those transactions were poorly documented, so their scale and frequency cannot be assessed.

Consequently, lithium governance is increasingly important in bridging mining-community feedbacks (Figure 13c). Generally, government receives tax revenues from local industries and regulates mining and tourism operations through permit issuance, environmental inspections, and other regulatory activities. Mining companies usually perform CSR through the channels of the governance system, who facilitates mining-community agreements and conducts initiatives directly with the locals. Locals usually establish decentralized associations or ethnic groups to participate in meetings with mining managers, where they negotiate for better benefits. When social tension becomes fierce, demands for participation are ignored, or promised benefits are impaired, the workers must force governance actions by social activism.

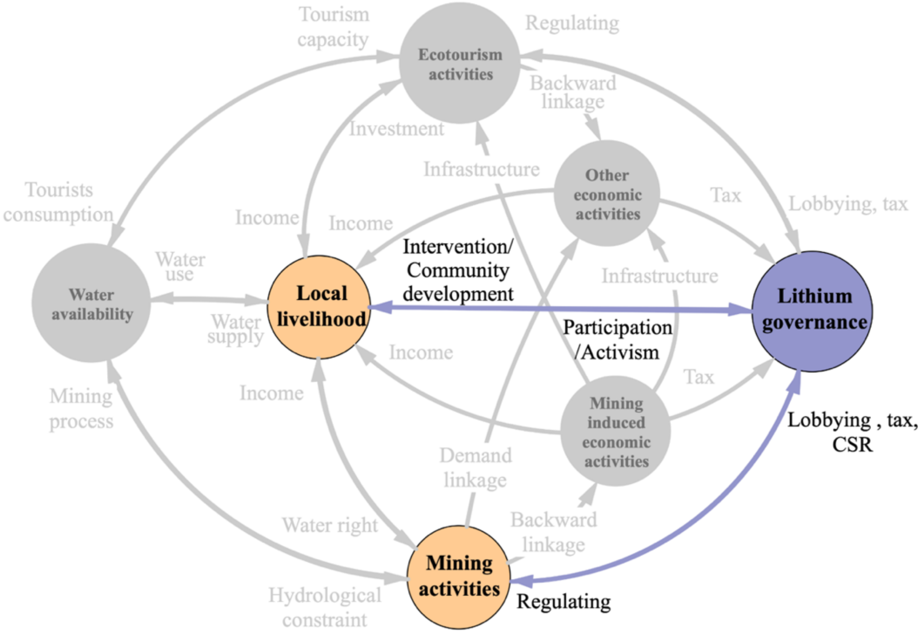
Notedly, Li-mining companies have increased and diversified their CSR efforts in recent years, but social movements against Li-mining have also increased significantly. This contradiction might because the social protests have been successful in creating a response from the mines, and the communities have pursued this action further. It might also raise the question on the actual performance and effectiveness of CSR by Li-mining companies. Meanwhile, such a contradiction implies that the positive benefits from Li-mining companies (i.e., stimulation to local economy, community development efforts, etc.) were not sufficient to offset the negative impacts (i.e., excessive water consumption, labor influx, etc.) as perceived by local communities. The decreased local trust in governance and mining companies, driven by the opaque information and poor implementation of CSR, may help explain this contradiction. Based on the stakeholder meetings, information related to their livelihoods and environment contained in monitoring and assessment reports is not usually shared with them. To remedy this, benefits like employment opportunities and training should be provided to communities as part of the agreements made between mining companies and local communities. Failure of CSR in the extractive sector are frequently seen and sometimes even led to deep resentment and mistrust in frontline communities. Effectiveness of CSR is likely to undermine if companies prioritize business risk over community engagement, neglect past impacts in areas of operation, and act on to deliver both short-term and long-term benefits to local populations (Hoelscher and Rustad, 2019).



(a) Impact from water consumption



(b) Linkage of local economy



(c) Feedbacks through lithium governance

Figure 13. Impact and Response Trajectories in the Mining-community Interdependency Framework (in each trajectory, less important elements and links are blurred out to highlight crucial feedbacks)

4.5.3 Lithium development in the lithium triangle

Debates around Li-mining in the lithium triangle have intensified as global interests in low-carbon technologies have increased. In Chile, state officials perceive lithium either as a banal commodity or a strategic resource that can be used as a bargaining chip in global politics (Barandiarán, 2019). There is also fear of a resource curse that the lithium industry will devastate ecosystems and community livelihoods (Calla Ortega et al., 2014). New thinking of lithium development appeared after the newly advised lithium policy in 2015, where a so-called Li-focused sociotechnical imaginary was promoted. It envisions the transformation of Chile from exporting raw material to value-added exports like solar technologies and energy (Comisión Nacional del Litio, 2015).

Similar to Chile, in Argentina and Bolivia, lithium development has been managed towards a sociotechnical imaginary pathway, where state control over lithium increases along with investments in science, technology, and new industries (Barandiarán, 2019). However, this pathway may lead to broader impacts from spill-over effects, in which the new industries relying not only on mining but also on manufacturing and chemical processes, which could be potentially environmentally and socially destructive. Bolivia, for instance, has built new laboratories and manufacturing facilities for battery components. Similarly in Argentina, along with the expansion of lithium production in at least 15 different salares since 2016 (USGS, 2017), other types of mining took this time to revitalize.

These countries have different policies, and each projects a future in which the state plays an active role in expanding Li-mining. However, impact assessments on frontline communities have never kept up with the expansion of the lithium industry, not to mention the broader impacts under the new lithium vision. Communities close to operations are usually located in rural areas where social status and environmental conditions are poorly documented. SdA has the most data availability but still lacks scale-matched data to generate an overall measure of sustainability.

For future study, the interdependency model could be applied to other Li-mining sites and communities in the lithium triangle, which share similar geography, demographics, history, and culture. However, the impacts may differ by different mining techniques and governance systems. Therefore, investigations must be tailored to local contexts. Besides, this study primarily examined the most concerned impacts but did not incorporate a full set of impacts, especially impacts that are not quantitatively measurable, such as social cohesion and indigenous spirits. Under the global trend of low-carbon technologies, alongside the sociotechnical vision of lithium in Latin America, its associated consequences should be addressed to achieve a truly sustainable future for the industry and communities.

4.6 Conclusion

This study investigated the sustainability of frontline communities near Li-mining sites in SdA, by examining five most concerned themes derived from local stakeholder meetings: water availability, labor influx, employment, social tensions, and CSR initiatives. The analysis reveals some positive contributions to the local livelihoods, but tensions between communities and mining companies have escalated in recent years. The examination of local concerned impacts may help to explain these tensions. In summary, this analysis establishes that, between the 2002 and 2017, the expanding Li-mining activities affect the community sustainability in the following ways:

- Depletion of water availability can be mostly attributed to mining water withdrawals, considering the minimal water taken up by other uses.
- Relatively imbalanced migration flows reveal a much greater number of laborers flowing into SPA than flowing out. Mining causes a greater imbalance in migration flows compared to other industries.
- Mining and mining-induced industries mostly employ commuting laborers that contributes to the local economy in limited ways.

- Despite the increased jobs provided by mining, both the number of local laborers employed and its share in the mining industry, declined significantly.
- Company's CSR becomes more sophisticated in reporting, while the credibility of the actual performance is still in doubt due to the lack of independent audits.
- Despite increased CSR efforts, social activism against the Li-mining expansions have increased in intensity and scale and have mobilized from local to national.

CHAPTER 5

DYNAMICS OF LI-MINING, COMMUNITIES, AND AQUIFER INTERACTIONS

5.1 Introduction

Demand for low-carbon technologies would have to be met through significant extraction of battery minerals, even with improvements in energy efficiency and recycling technologies (Sovacool et al., 2020a). However, existing energy transition studies rarely acknowledged the local social and environmental implications of the anticipated growth in mineral extractions (Lèbre et al., 2020). Mining activities usually bring adverse impacts on the host environment and tend to exacerbate pre-existing vulnerabilities, especially in areas where the local governments are unable to manage the social and environmental outcomes (Bebbington et al., 2018; Lèbre et al., 2020). The Li mining process in Salar de Atacama (SdA), for instance, has exacerbated the drought conditions in the area and raised severe concerns on local groundwater depletion with associated impacts on the local ecosystem and social livelihood. To achieve the low-carbon transition to be truly sustainable, understanding and managing the downside risks that come along with critical mineral extraction is urgent and necessary (Lèbre et al., 2020).

Notwithstanding the increasing academic interests on the topic, specific studies on impacts from Li-extractions are limited in scope and methods being used. Studies have explored relevant concerns on biodiversity (Gajardo & Redón, 2019), flora and fauna richness (Liu et al., 2019), social wellbeing (Egbue, 2012; Romero et al., 2012). Among others, Marazuela et al. (2020) examined the hydrodynamics under current volume-based mining concessions in SdA and found the Salar nucleus was the most affected area, and the marginal zones are beginning to be affected. Babidge (2016, 2018, 2020) conducted 15-month ethnographic research with communities in SdA, documenting the evolving relationship between the locals and mining companies. In particular, through discussions with the locals using environmental change maps, the study investigates how the locals experience stress related to brine extraction in the Salar (Babidge et al., 2019).

The Li supply chain exhibits many features of 'telecoupling' (Agusdinata et al., 2018), which refers to the notion that impacts in one socio-ecological system may be associated with actions, policies, behaviors in another geographically distant system (Liu et al., 2013). The increasing global demand in Li has led to searches for land resources for extracting raw materials, thereby causing policy-driven impact displacement in resource-extracted places. The Li-mining in SdA, driven by low-carbon policies, accelerates the scale and rate of extraction, threatening groundwater resources, and being contested among other water users. Local communities that independently govern the same focal resource (groundwater) by social norms and institutions become indirectly coupled with global policies in distant places and are being unintendedly affected.

Bringing distal connections to the attention of decision-makers can be challenging but instrumental in governing telecoupled systems (Eakin et al., 2014; Moser & Hart, 2015). Eakin et al. (2014, 2017) ascertain that multiple thresholds may exist in telecoupled systems. Among others, a conditional threshold refers to the degree of changes in the resource base conditions. Once either threshold is crossed, telecoupling can become visible to actors as a potential governance concern. The challenge for this case study is that groundwater as the focal resource has inherently large uncertainties.

Different from focal resources such as land resources covered in most telecoupling studies (i.e., Rueda & Lambin, 2013; Sun et al., 2017), groundwater is not directly observable and less predictable in its dynamics due to high mobility. These uncertainties may obscure the emergence of a threshold and make it unnoticeable, thus significantly delaying feedbacks to other resource users. Subject to such uncertainties, actors can have different understanding and interpretations of the changes in resource conditions, depending on their experience and values (Babidge et al., 2019). When certain actors perceive that the threshold has been crossed, social unrest can occur and as a result, the current governance system is pressured to address the externalities through new institutional design (Eakin et al., 2014). In the case of Li-mining, these uncertainties may hamper changes in the existing governance, leading to delayed regulatory actions and sustained impacts (Babidge, 2019). Given the uncertainties in resource base and delayed response, the study explores the telecoupled system in SdA.

To simulate such co-evolution of environmental and social systems, the use of integrated models has been growing in recent years (Kelly et al., 2013) and the agent-based modeling (ABM) approach in particular, has been demonstrated to be effective (e.g., Filatova et al., 2013; Rounsevell et al., 2012; Schlüter et al., 2012). ABMs have been widely applied in studying human-aquifer interactions for water management issues. Castilla-Rho et al. (2015), for instance, developed a so-called FlowLogo model to explore how patterns of groundwater movement and social development can emerge from agents' behavior and their interactions. Noël and Cai (2017) coupled ABM with a groundwater model to explore the role of farmers' behavior in a groundwater-fed irrigation area. Pope and Gimblett (2015) developed an ABM to simulate complex feedbacks between human decisions and environmental conditions in an arid watershed. ABM has also been applied in mining-related context. Boateng and Awuah-Offei (2017), for example, modeled the effect of information diffusion on community acceptance of mining.

In this paper, an ABM is developed, applied in the Li-mining industry in SdA of Chile, to understand how the Li-mining industry's pumping behaviors affect the groundwater conditions and stress dynamics of local livelihoods, under various mining production projections. By factoring in varied actors' perceptions, this study investigates how uncertainties in groundwater levels affect community stress levels and feedbacks. The level of stress tolerance of local communities is also explored to understand the critical range of thresholds in social systems. Results discussed and synthesized in this chapter highlight the importance and ways to build resilience of the socio-ecological system in SdA, which involves the changes, adaptations, and transformations of a system in response to interferences. In the following sections, it firstly presents the modeling framework and detailed design of ABM in section 5.2. Results are described and explained in Section 5.3. Section 5.4 discusses the implications of the results in terms of Li-governance and points out directions for future research. Finally, the chapter concludes with a summary of key findings.

5.2 Materials and Method

5.2.1 Modeling framework

This work presents a unique human-aquifer interactions model for the Li-extraction in SdA. In the ABM, groundwater is pumped from concentrated wells exclusively by two mining agents. While most agents (community members) are restricted from pumping wells, they utilize ecological services (e.g., supporting agropastoral lands) and social values (e.g., cultural attachment to water, recreation, and aesthetic values) provided by groundwater. Thus, the excessive uptake of groundwater by Li-mining could lead to land/vegetation degradation and social disturbance, exerting mining-induced stress on agents' livelihood (see below for a detailed explanation of stressors). Due to groundwater uncertainties, agents perceive aquifer conditions and implications differently based on their experience and value, creating important heterogeneity in the model. Rather than modeling agents' water use behaviors, the model focuses on agents' varied experience of mining-induced stress resulting from changes in groundwater depth and its implications.

This model structure involves social and hydrological systems (Figure 14), which interact through Li-mining companies' daily pumping decisions and water table. Pumping decisions are influenced by global Li demand and governance forces as well as local climatic seasonality. The effect of global policy on pumping decisions is simplified as input in this model since the scope is centered on the local socio-ecological changes. Seasonal water table changes are subject to climatic and hydraulic factors, namely precipitations and evapotranspiration. In the social system, Li-mining companies interact directly and indirectly with local communities and their residents, bringing about social changes to livelihoods. Specifically, mining companies' water withdrawal could directly affect the quality of land and vegetation in community territories. It also brings vast amounts of migrant labor, trucks, and sub-contractors, indirectly disturbing local livelihoods and taking up already limited resources. Coupled with the social and hydrological systems, this model represents the local actors' experience of mining-induced changes in the socio-ecological system, especially on groundwater changes and social stressors.

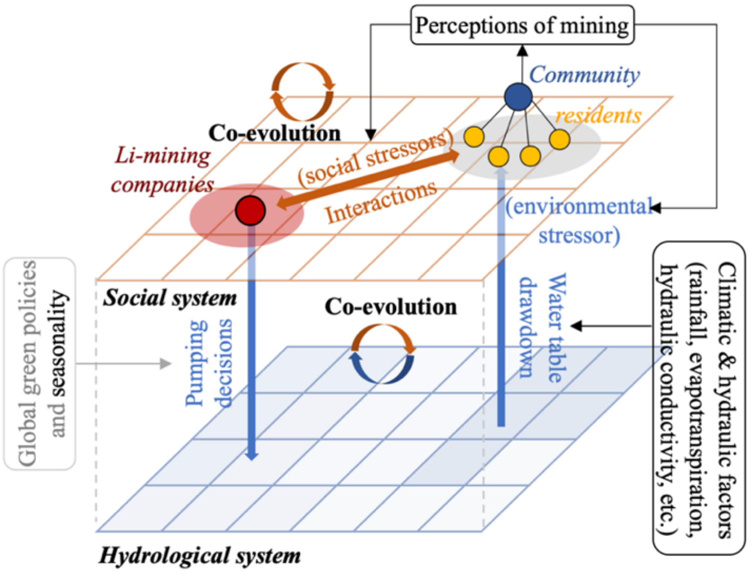


Figure 14. An Agent-Based Modeling Framework for Mining-community-aquifer Interactions

The model is designed based on empirical works on the local experience of mining-induced changes by Babidge et al. (2019, 2020) and stakeholder meetings held in March 2018[14]. According to these studies, the local population has been disturbed by mining projects and expansions (e.g., seeing trucks transporting brines back and forth from mining sites). They also perceive the drying vegetation in pastoral lands and the increased population (mainly from migration) in their community as negative effects of the mining industry. In general, perceptions of mining represent an individual's feeling of the vegetation changes in their territory, population growth rate in communities, and

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[14] Stakeholder meetings with local people (including community leaders, ethnic group leaders, representatives from local NGOs, and government officials) were held to discuss their concerns over the expanding Li-mining industry on March 4-5, 2018.

mining scales. Such perception can vary across individuals depending on their experience and values. In exchange for community agreement, mining companies offer financial compensation to local communities through corporate social responsibility programs. They are carried out either as direct financial support (i.e., 2% of company sales) or as investments in community infrastructure, micro-entrepreneurs, education and so on, but are still inadequate to offset the negative mining impacts.

These insights inform this model in two ways. First, the community member agents are designed to perceive mining-induced changes through three major stressors: (1) drought stress (DS), observing the level of vegetation drying affected by groundwater decline; (2) population stress (PS), experiencing population changes in the agent’s home community; and (3) mining stress (MS), subject to the scale of mining and the agent’s proximity to mining operations. Second, financial compensation from mining company agents is incorporated in this model as a stress relief mechanism.

The ABM is developed in a NetLogo platform (Wilensky, 1999) and implemented according to the flow and calculation iterations. The base model simulates the mining-community-aquifer interactions over 1994-2019, and scenarios of various mining plans are modeled from 2020 to 2030. The model runs 20 times for the baseline simulation and each scenario, and results are averaged for analysis. The model starts with a groundwater initialization to stabilize natural water movements, and the social system is then added to the model. At the beginning of each year, new people enter the basin, and mining companies update their pumping rates. In each time step, community members move and observe mining-induced changes, during which their perception of each stressor is assessed. The total perceived stress (*TSI*) is then calculated based on the agent's perceived importance of each stressor, represented by a set of *weights*. If the agent feels stressed by the overall impacts, it reports to its home community.

At the community level, monthly meetings are held to summarize total reported cases of stress, and if there are more than 30 cases of stress the community is stressed. This threshold value is a calibrated parameter, which is calibrated to match the timeline when the first community declared stress according to news reports (detailed calibration process is in Table A1, Appendix A). After that, quarterly meetings with Li-mining companies are held to discuss compensation. Accordingly, the agent's TSI is then updated to incorporate the relief effect through financial compensation. Financial compensation is given directly to stressed communities, which is then translated into a relief effect to agents within communities. The threshold when the community as a whole is in stress and companies start compensation is calibrated based on the actual time of events. Environmental inspections and mining expansion requests are added as exogenous events to the model. During environmental inspections, the largest drawdown in the basin is reported to each community member, which in turn will change their perceived DS and TSI. Similarly, for expansion requests, the newly requested quota is reported to all community members, changing the perceived MS and TSI accordingly. The flowchart of the model showing major calculations and scheduling are in Figure A2 of Appendix A.

5.2.2 The agent-based model elements

This model represents a 75km *105km landscape in SdA with each modeled cell representing an area of 3km * 3km (Figure A1, Appendix A). A detailed description of this model and associated parameters is documented following the ODD protocol (Grimm et al., 2006) in Appendix A. The hydrological and social parameters used in this model are also documented in Table A1of Appendix A, along with the calibration process.

5.2.2.1 The groundwater component

The groundwater system builds on the FlowLogo model by Castilla-Rho et al. (2015), which was then parameterized and calibrated with hydrogeological inputs from local groundwater studies by Marazuela et al. (2019a, 2020). The model interface (Figure A1, Appendix A) includes an unconfined aquifer bounded by no-flow cells at all boundaries. The modeled landscape elements include the nucleus of SdA, wetlands, and barren soils. The aerial recharge is modeled by an input map of superficial recharge with seasonality variations (peaking at southern hemisphere summer) and a random rainfall event in March in the East or North, representing the significant rainfall likely occurring in the basin (Barrett et al., 2016). Model cells are defined primarily by drawdown (change in water head to initial head) calculated at each time step. The groundwater inputs are also detailed in Appendix A.

5.2.2.2 Type of agents and state variables

The model has three types of agents: (1) community members (person shape); they are characterized by their spatial locations, perceived stress level, and total stress index (TSI); they conduct daily movement randomly (i.e., for working, herding, local guiding, etc.) from home to any location with a maximum distance of 15 km (estimated based on daily activities of the locals; Babidge et al., 2019); (2) communities (house shape); they report on community population and the monthly number of cases of stressed community members; and (3) Li-mining companies (triangle shape); they pump throughout the year and decide when to compensate communities. The pumping rates are determined by the historical record of pumping with seasonality variations using a sinusoidal pumping schedule peaking in January (the southern hemisphere summer). The parameters in the social system are mostly based on national statistics and calibrations, which are detailed in appendix A (Table A1).

The modeled decision-making process describes how a community member agent perceives mining-induced changes referring to the initial state. The total stress index (TSI), interpreted as the agent's personal experience on overall mining impacts each day, is affected by the agent's location, water table changes, and mining rates. As elaborated in Chapter 5.2.1, agents assess the mining-induced changes through personal experiences on three major stressors and will be partially relieved by the mining compensations. For each agent, the personal experience is translated into the weight of each stressor. Following the assessment method widely used in agent-based model studies (Li & Liu, 2008; Murray-Rustet al., 2013), the overall stress that an agent *r* perceives in day *t* is computed as below,

$$TSI_{r,t} = \sum \left(Sw_{\ r,i} \times \ S_{r,i,t} \right) - Cw_r \ \times C_{r,t} \tag{5.1}$$

Where $S_{r,i,t}$ $(Stress)$ represents normalized stress of each stressor *i* at time *t* for agent *r*; $C_{r,t}$ $(Compensation)$ is a normalized indicator of compensation for an agent *r* at time *t*; $Sw_{\ r,i}(Stress\ weight)$ is interpreted as the perceived relative importance of each stressor *i* for agent *r*, and these weights are summed as 1 and assumed constant during simulation; and Cw_r $(Compensation\ weight)$ represents how effective the compensation is to relieve the stress perceived by agent *r*. The values of weights for agent *r,* are assigned randomly through a stochastic process to capture the dynamics in values of the local population.

Specifically, $S_{r,i,t}$ $(Stress)$ includes Drought-stress (DS), Population-stress (PS), and Mining-stress (MS). DS expresses the stress agent experiences while observing drying vegetations due to groundwater drawdown, which is normalized to 0-1 as:

$$DS_{r,t} = \frac{(AD_{\ r,t} - VegD)}{AD_{\ r,t}} \tag{5.2}$$

Where $AD_{\ r,t}$ $(Actual\ drawdown)$ is the maximum drawdown among the cell in neighbors agent r visited at time t, and $VegD$ $(Vegetation\ drying\ depth)$ is assumed as 1m according to local vegetation conditions (Scott et al., 1999; Naumburg et al., 2015).

PS represents the stress from increased population in the home community compared to the initial population at the start of mining-era, which is normalized to 0-1 as:

$$PS_{r,t} = \frac{(Cpop_{\ r,t} - Ipop)}{Cpop_{\ r,t}} \tag{5.3}$$

Where $Cpop_{r,t}$ $(Community\ population)$ is the current population size in agent r's community at time t, and $Ipop$ $(Initial\ population)$ is the population at the start of simulation.

MS describes the stress from expanding Li-extractions in an agent's adjacent area. It also captures the stress originated from an agent's indigenous culture or identity (i.e., knowing the fact of ongoing mining makes the agent feel stressed). It is normalized between 0 and 1 as:

$$MS_{r,t} = \left. \frac{(TMY_{\,t} - IMY)}{TMY_{\,t}} \middle/ \sqrt[2]{Dist_{\,r,t}} \right. \tag{5.4}$$

Where $TMY_{\,t}(Total\ mining\ yield)$ is the total pumping rate of all mining wells at time t, and $IMY\ (Initial\ mining\ yield)$ is the pumping rate when mining starts.

$Dist_{\,r,t}\ (Distance\ to\ wells)$ is the distance between agent *r* and the closest well at time *t*.

Similarly, $C_{r,t}$ is also normalized to represent the level of compensation compared to the maximum possible compensation:

$$C_{r,t} = \frac{(\mathrm{MaxC} - AC_{\,r,t})}{\mathrm{MaxC}} \tag{5.5}$$

Where MaxC (Max compensation)is the level of compensation based on the mining quota of each company, while$AC_{\,r,t}\ (Actual\ Compensation)$ is based on current pumping rate.

This study represents the community tolerance to stress using a stress threshold, the level above which an agent starts to feel stressed by mining-induced changes. It is a characteristic that is intrinsic to a community: the higher the threshold, the more tolerant and resilient the community is to the negative changes due to mining activities. This model defines this threshold as in the baseline model, which is calibrated based on the actual time when the most adjacent community (i.e., Peine) started declaring stress about the mining industry (Babidge, 2020). Once the threshold is crossed, the agent starts reporting to its home community and potentially seeking financial compensation from companies or mobilizing social movements for improved governance. The sensitivity of the stress threshold is explored in scenario analysis to understand the critical range of thresholds in the system, which can indicate possible ways to help build the resilience of local livelihoods.

5.2.3 Future mining projections

Future scenarios of mining plans are investigated to understand their effects on groundwater and social stress. Four mining projections are considered for the period 2020 -2030 (Figure 15). In the Business-as-usual (BAU), both companies expand the mining business following the same trend in the past ten years until reaching the maximum allowed rate, using the equation regressed by the average pumping rate from 2010 to 2019. In the Mining-commitment (MC) scenario, companies strictly follow their sustainable development plan (SQM, 2020b), which aims to reduce consumption of freshwater by 30% and brine by 20% compared to 2019 until both reach the goal of 50% by 2030. In the Maximum-allowed (MA) scenario, driven by the booming lithium market, companies increase the pumping rate to the maximum allowed rate to seize the opportunity. Lastly, the Mining-Recession (MR) scenario represents a case where mining water use capacity is curtailed due to social and regulatory pressure, to which both companies reduce the pumping rate to the level before they were granted an expansion concession in 2006.

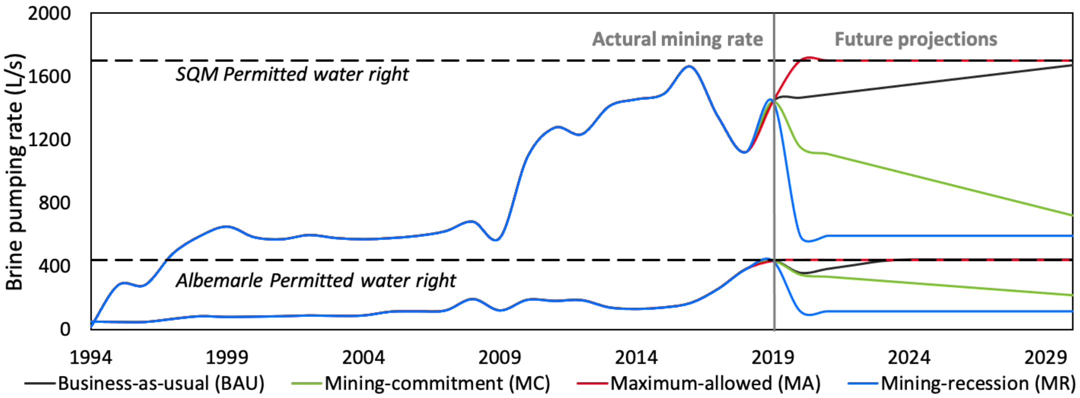


Figure 15. Brine Pumping Rates under Four Mining Scenarios from 2020 to 2030

5.3 Results

5.3.1 Baseline model and validation

The resulting groundwater dynamics are shown in Figure 16 in a contour map showing the spatial distribution of net groundwater drawdowns (due to pumping) and the temporal evolutions at six monitoring wells. Both results show the southwestern Salar was the most affected area, with deeper net drawdowns larger than 5m and the groundwater pumping impacts spread outwards to the edge of the Salar nucleus (Figure 16a). The effect on the transition zone is limited, with only a small decline due to its low hydraulic conductivity. Drawdown effect in communities is similar, with slightly deeper drawdowns in the North than in the East since the northern sub-basins provide major recharge to the SdA basin. For validation purposes, this study compares the spatial patterns simulated in this study to existing literature and found that the simulated drawdowns mostly match the magnitude and pattern reported in Marazuela et al. (2020).

This study also compares the simulated time-series changes of drawdown to data from observational wells (Figure 16b). At specific monitoring wells, the patterns of modeled drawdowns closely mimic those of the measured level, capturing both the oscillations caused by natural processes and the effects of brine pumping. For pumping wells P3 and P4 in particular, the modeled drawdown reflects a similar evolution trend as the observed data, especially on the changing rate (i.e., the modeled drawdown changes slowly at first and becomes much faster after 2010). Although the model does not capture temporary increases as shown in measured data due to the relative simplicity of the model, it successfully reflects the general scale and pattern of groundwater dynamics, which is sufficient for the purpose of this study.

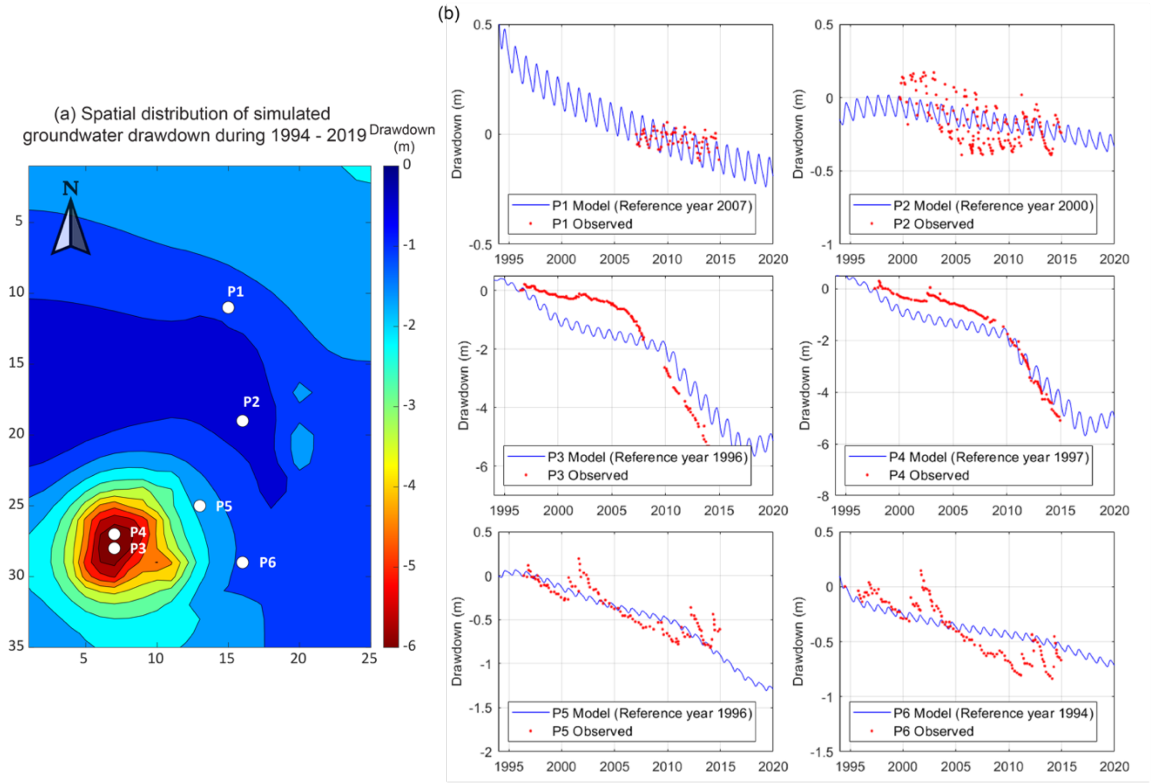


Figure 16. Evolution of Groundwater Drawdown at Six Selected Sites Showing Modeled Results Compared to Data from Observational Wells. (Location and data of observational wells are extracted from Marazuela et al., 2020. Modeled drawdowns (blue line) were calibrated to match the time of observed data (red dots) for comparison)

As for the social system, the evolution of simulated dynamics is compared to the actual timeline of mobilization events in SdA. As shown in Figure 17, the trend and patterns in simulated social stress generally match the actual time of local mobilizations. The modeled system gradually increases in stress with oscillations starting in 2010, which is consistent with the time when Li-mining-community disputes increase as documented by Babidge (2020). The simulated number of stressed communities (Figure 17a) and the share of stressed population (Figure 17b) rose sharply in 2017, matching the intensified anti-mining mobilizations around the same period. The spike of simulated stress in early 2018, for instance, captures the most intense protest over the SQM-CORFO agreement in the area (Reuters, 2018). Overall, the modeled social dynamics capture the increased trend of stress in the area, following the same trend of more frequent mobilizations against Li-mining operations.

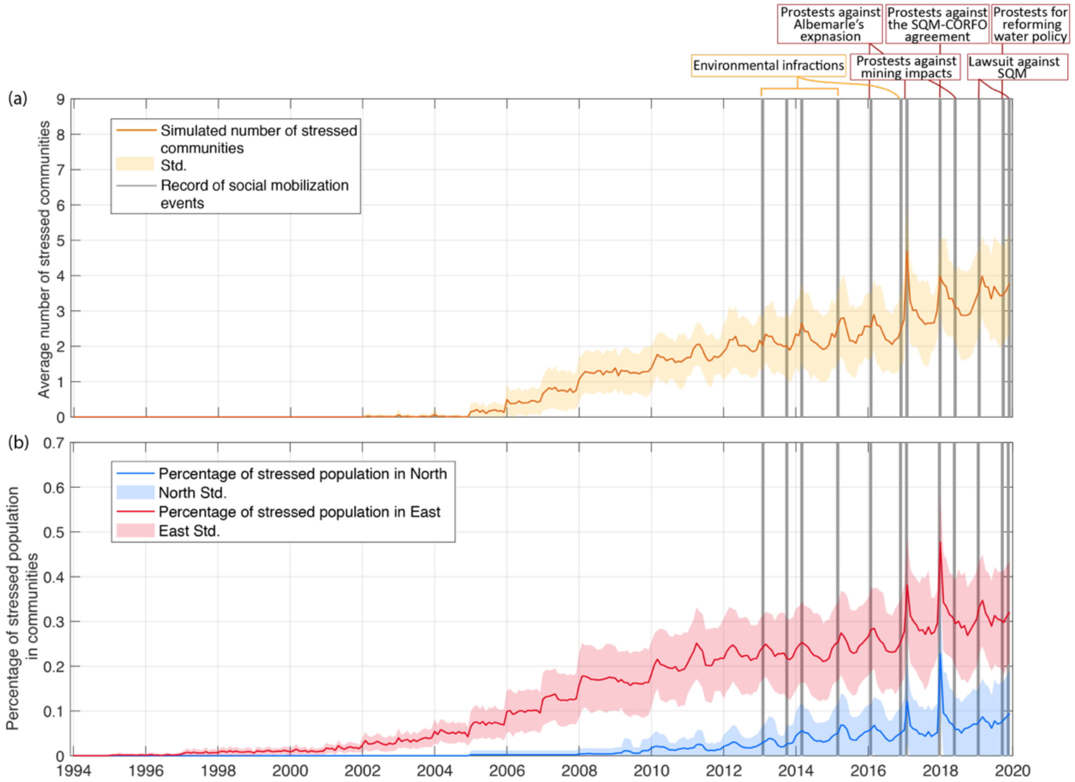


Figure 17. Evolution of Simulated Social Dynamics Compared to the Timeline of Mobilization Events in the Study Area. (a) Number of stressed communities; (b) Percentage of stressed population in North (blue) and in East (red) (Grey bars represent the presence of mobilization events (protests or environmental sanctions) in the actual timeline, and text boxes above brief these events)

5.3.2 Future mining scenarios

Groundwater and social outcomes associated with the four mining projections are shown in Figure 18 and Figure 19. As for the spatial distribution of drawdown (Figure 18a), all scenarios share a similar pattern with the deepest drawdown in southwestern Salar and spreading outwards to the edge of the nucleus. Overall, the MA scenario results in the greatest depletion with the deepest drawdown around 10 m, while the deepest drawdown reaches 9 m in BAU, 5m in MC, and 4m in MR. Compared to the base scenario (Figure 16), the BAU and MA scenarios lead to a deeper drawdown in the whole area of the basin, while the MC and MR scenarios result in groundwater recovery in the mining and its adjacent areas. Under the MC and MR scenarios, the drawdown becomes significantly shallower in mining areas and several eastern communities (i.e., Peine, Socaire, Camar, and Talabre) due to the slower pumping rate in both brine and freshwater wells. By contrast, the drawdowns are almost constant in northern communities (i.e., SPA and Toconao) since the northern sub-basins provide major recharge to the Salar nucleus.

A closer look at the time-series changes reveals that different mining scenarios make little difference in the groundwater level in distant northern communities (Figure 18b). The difference is more evident in the mining area and adjacent communities, such as Peine and Camar. In general, drawdown becomes deeper at the fastest rate in MA and the slowest rate in MR. Under the BAU and MA scenarios, drawdown shows little difference across all communities but is more varied in mining sites, with the difference reaching 1m in the SQM well. Under MC and MR, groundwater table recovers in mining areas, compared to the level in 2019. The MC scenario leads to a steady recovery reaching around 5.5m in SQM and 3.5m in ALB, while the MR scenario has a faster recovery reaching around 4m in SQM and 2.5m in ALB. For eastern communities, groundwater table delays recovery but keeps declining at a slower rate in most areas. Particularly in Peine and Camar, drawdown declines much slower and even indicates a sign of recovery, which is attributed to the slower pumping rate of freshwater wells. In northern communities, different mining plans make little difference in groundwater levels. Notably, the groundwater table still declines and delays recovery in most areas even under MC and MR scenarios. This effect implies that even when pumping has been largely reduced, peripheral sub-basins providing major recharge are still affected.

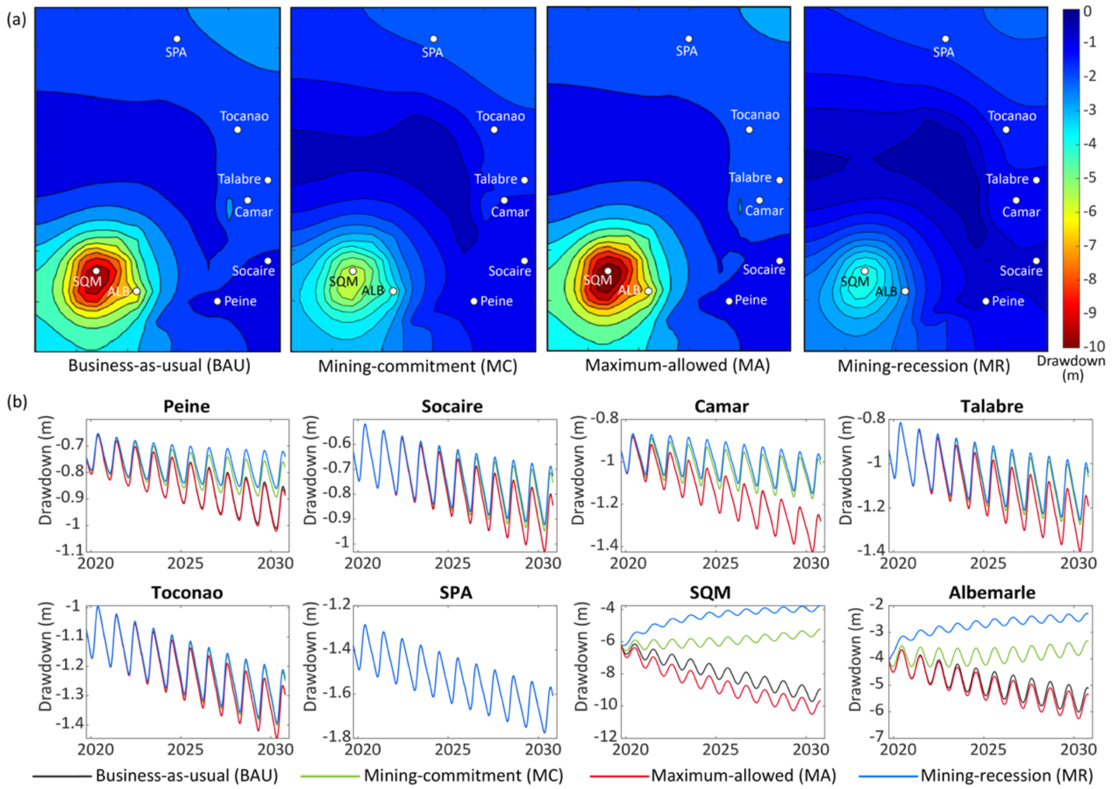


Figure 18. Evolution of Drawdown under Four Mining Scenarios between 2020 and 2030 (a) contour map showing the spatial distribution of net drawdown over 1994-2030; (b)time-series evolution of drawdown in communities and selected mining wells.

In the social system, the number of stressed communities increases from 3 to 5 under all scenarios, with no significant difference across scenarios (Figure 19a). In general, slightly more communities are stressed under the MA scenario, and the rate of increase is slightly higher under the MR scenario. As for the share of stressed population (Figure 19b), the difference across scenarios stands out. The MA scenario results in more stressed residents in the eastern communities, rising from about 27% to 42%, while the MR scenario results in more stressed residents in the northern communities, rising from about 5% to 30%. When mining pumping keeps growing (BAU & MA), the dynamics of stressed communities in the north share the same pattern of increase with the stressed population in the east. When pumping decreases, northern residents become more stressed, even exceeding the eastern residents' stress level in the MR scenario. This seemingly counter-intuitive condition is due to the associated lower compensation from mining companies and delayed recovery in groundwater. Northern residents generally have a relatively lower stress level due to its remoteness from mining activities, so that it triggers the compensation mechanism less frequently than the eastern ones. On the other hand, the groundwater aquifers in the north still recharges the mining area due to the difference in the water head of groundwater, even though mining activities are reduced. In the MC and MR scenarios, the level of stress shows a stable trend for eastern residents. In contrast, northern residents are not relieved, contributing to the gradual increase in the number of stressed communities.

Under all scenarios, seasonal oscillations are evident in community and population stress with peaks during summer and alleviations in winter periods. The occurrence of peaks also becomes more frequent with time. Notably, when companies pump water at the maximum rate (MA), seasonal oscillation in either the community or population stress becomes less apparent with smaller amplitude after 2028, implying higher stress all year round. Compared to eastern residents, the stress experience of northern residents is more fluctuating with larger amplitudes. Despite the similarity to the BAU scenario, the eastern residents are more stressed. The difference in the share of stressed population between northern and eastern communities shrinks with time for all scenarios, especially when mining water consumptions are lessened.

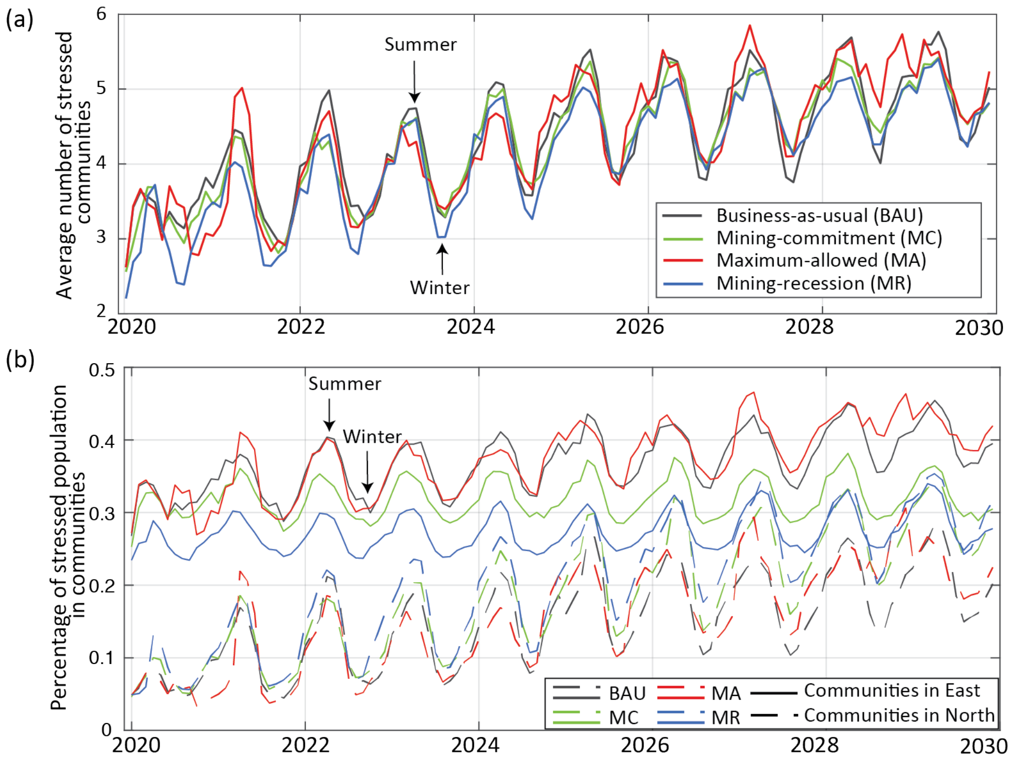


Figure 19. Evolution of Simulated Social Dynamics under Four Mining Scenarios between 2020 and 2030; (a) Number of stressed communities; (b) Percentage of stressed population in North (dashed lines) and in East (solid lines).

5.3.3 Sensitivity of resident stress thresholds

Each resident's personal experience of mining-induced changes is captured by the total stress index (TSI), representing the perceived changes in the current system compared to the initial state. The stress threshold, calibrated to 0.5 in this model, implies that a resident will feel stressed when he perceives that the current state of resources is only 50% of what it used to be (i.e., the initial state of comparison). In general, as residents become more tolerant of mining-induced changes, their stress threshold would increase (and vice versa). The notion of threshold value can also explain why the older generations are more prone to stress than the younger ones (Babidge et al., 2019). Older residents tend to make a comparison between the current states to the time before mining activities took place, which was typically considered better. The social dynamics under varied thresholds are explored in the four mining scenarios over 2020-2030. For ease of comparison, this study groups the scenarios of expansion in mining water use (BAU and MA) and scenarios of reduction in mining water use (MC and MR) and present average outcomes for each group (Figure 20a and Figure 20b, respectively).

For communities to be in a stressed state, the critical range of threshold is similar between the mining expansion and reduction futures, ranging between 0.4 and 0.7. More communities, however, become stressed in the expansion scenarios across all threshold levels. In contrast, when mining water use declines, the occurrences of community stress are fewer and more stable (i.e., Figure 20 pointers A: 12% smaller amplitudes and Figure 20 pointers B: 4% more regular intervals measured by standard deviation). What is common in both expansion and reduction scenarios is that compared to the baseline threshold of 0.5, a small drift towards intolerance leads to about 80% more stressed communities on average over 2020-2030 and a change towards tolerance results in over 60% fewer communities in constant stress. This sensitivity indicates the importance of building community's capacity to endure stress within the social system. Importantly, building endurance of stress should prevent from creating a new form of injustice. Instead, it should incorporate efforts to enhance communities' ability to mobilize resources and negotiate challenging situations (Jenkins & Rondón, 2015).

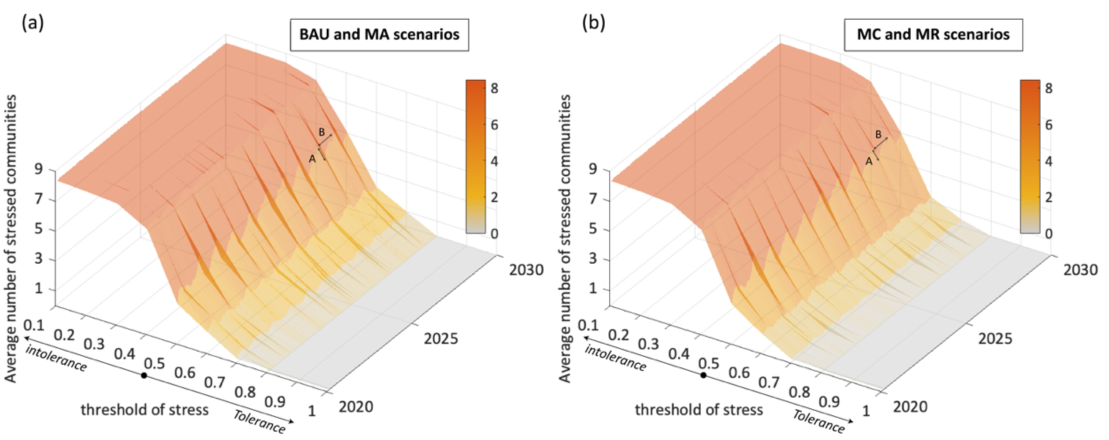
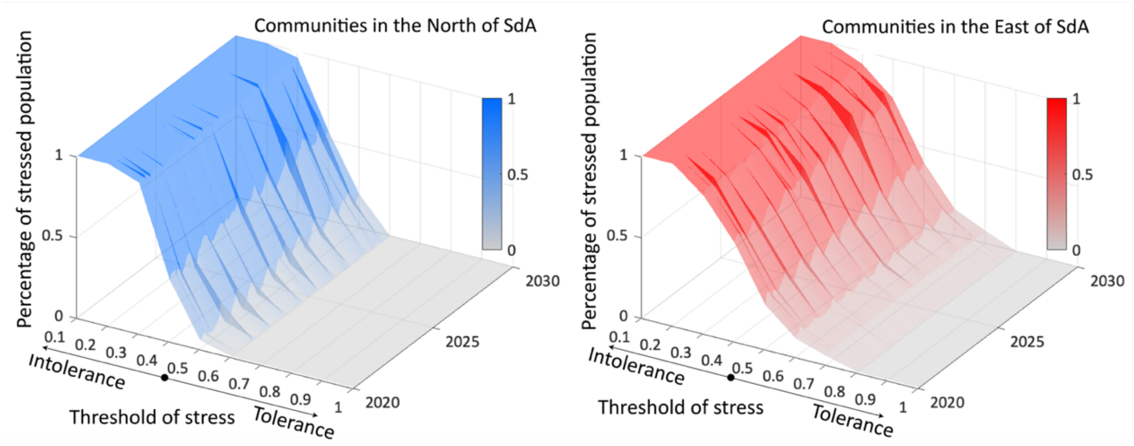


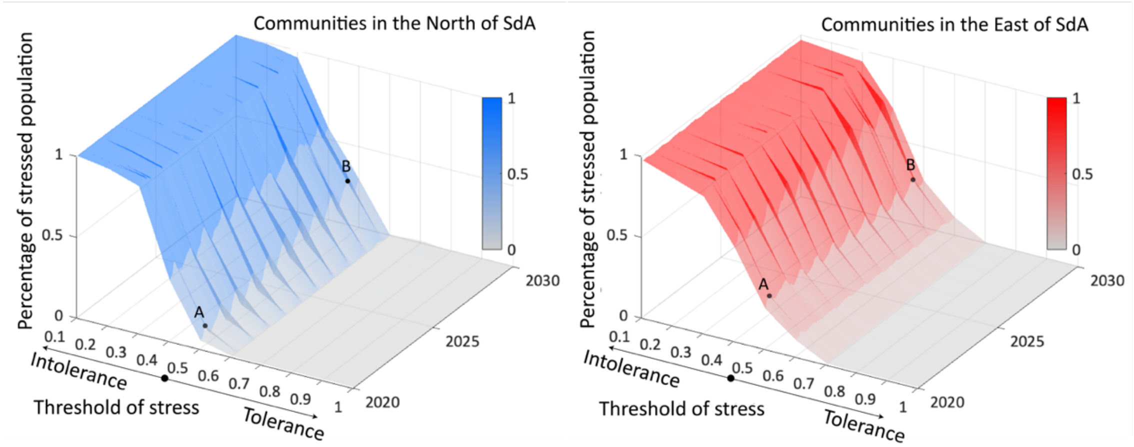
Figure 20. Sensitivity of Stress Threshold (0.1-1) on the Number of Stressed Communities during 2020-2030. (a) Averaged results for mining expansion scenarios. (b) Averaged results for mining reduction scenarios.

Residents of communities in the north and east appear to respond differently to the varied level of stress threshold (Figure 21). Under all scenarios, eastern residents have a more diverse response to different threshold values, showing that their experience of impacts is more spread-out, ranging from 0.2 to 0.8, whereas the perceptions of northern residents are more uniform and consistent, ranging between 0.3 and 0.6. The share of stressed residents in the north increases faster than that of the residents in the east for most threshold levels, especially when mining water use falls. Comparing the scenario groups, the stressed population is more stable with regular intervals under scenarios with mining water use reduction, while small spikes occur in low threshold values undermining expansion scenarios. For example, under the expansion scenarios, when the threshold is 0.4 (i.e., residents are somewhat less tolerant to changes), the share of stressed residents rises sharply from 45% to 70% in the north and from 60% to 85% in the east in 2027 (Figure 21a). As the local population is becoming less tolerant to changes (lower threshold), the stressed population in both areas will increase considerably.

Regarding the population’s responses in the two scenario groups, the stressed population in eastern communities increases faster in mining expansion scenarios for most threshold levels. When mining water use declines, the stressed northern population rises more quickly and even almost reaches the same level of stress in the east in 2030 (Figure 21b pointers A to B), which is due to the associated lower compensation from mining companies and delayed recovery in groundwater. If tolerance were built within the communities, the stressed population in the north would almost return to zero, while a small percentage of eastern residents would still feel stressed even in mining reduction scenarios. Overall, eastern residents have diverse mining-related impacts and are more vulnerable to such impacts, which indicates they’re more likely to form collective actions to protest and demand better management of impacts, especially when extraction (and water pumping) activities are intensive. In contrast, northern residents turn to be more vulnerable and perceive long-lasting impacts once mining largely lessens, who are likely to form collective actions or mobilizations in the long run.



(a) Average percentage of stressed population for BAU and MA scenarios in North (left) and in East (right)



(b) Average percentage of stressed population for MC and MR scenarios in North (left) and in East (right)

Figure 21. Sensitivity of Stress Threshold (0.1-1) on the Percentage of Stressed Population in Communities during 2020-2030.

5.4 Discussion

In general, this simulation shows that: (1) the groundwater declines significantly in the mining area with impacts spreading outwards to nearby communities; (2) communities near mining are most vulnerable to mining expansions, while distant residents experience long-lasting impacts due to lower compensation and delayed groundwater recovery; (3) material uncertainties of groundwater delay feedback, causing mismatched evolution of environmental and social dynamics. These results reflect the complex dynamics and resource uncertainties captured by the model, but also highlight the need for managing uncertainties, building resilience of socio-ecological system, and decoupling water use and mining outputs in governance practices.

5.4.1 Managing groundwater uncertainties

The simulated results in the social and groundwater systems in SdA reveal various effects of uncertainties about water, the focal resource in the area. Such uncertainties are due to the physical characteristics of the resources and their relationships to community members. The groundwater resource is not directly observable by residents and has complex dynamics due to the geographical heterogeneity of the area and varied relations to the social actors. These uncertainties cause a time delay for the social system to get feedback on the state of the resource, leading to a mismatched evolution of dynamics in both social and ecological systems. For instance, in the baseline scenario, the groundwater table in the mining area dropped sharply in response to the rapid mining expansion since 2010. For the communities, such a condition was not noticeable, and it deteriorated until it reached a critically low level in 2017, causing an increase of stress level in the social system which was manifested as social protests in real life. It highlights that social mobilization could serve as a function of creating feedback between residential experience and responsibility of decision-makers (e.g., industrial managers, public sector), which is critical in generating effective management of resources and impacts.

The most affected areas are centered in the mining operation sites in southwestern Salar, but the impacts are not directly observable to residents. With the impact spreading outwards to Salar's edge and around freshwater wells, it becomes observable to nearby residents who visit the impacted area during daily activity, while still uncertain to people without access. The northern aquifers, which mainly feed water to the mining area, are more affected than the eastern aquifers. Thus, the resource condition is more observable to northern residents. Their perceptions are not enough to generate stress since they are more distant from other mining-induced changes. As the impacts accumulate and are sustained even when mining water use largely declines, more residents start to perceive that the threshold has been crossed. This result may underestimate the stress in northern communities due to the weight assigning mechanism adopted in this model. In real life, northern residents may generate stress more quickly than the simulation results due to the more observable resource condition.

The effect of groundwater uncertainties presented in this study is consistent with how local communities deal with groundwater uncertainties in the empirical studies. Uncertainties lie in people's memories of landscape features, referring to wetter and drier areas changing and moving without any clear reasons, and they raise questions about whether areas close to the mining extractions had resulted in drier land surface (Babidge et al., 2019). Uncertainties are also embodied in how local people understand groundwater conditions, reflected in the various conjectures on mining impacts. Some observe local water resources and landscapes are more or less the same in their territory with the conditions before mining began, whereas others perceive mining activity must by drying up the Salar and surrounding aquifers (Babidge, 2019). The diverse understanding of resource condition implies local confusions on the dynamics of subterranean water flows and how they respond to disturbances. This lack of certainty in knowledge enhances concerns on the extent and exact impact of water extraction on unseen aquifers and pastures in their territory.

Such uncertainties pose governance challenges in the regulation of mining activity and its relations with local livelihoods. In the SdA basin, local people had participated in mining activities as paid surveyors since the start of industrialization in the mid-1980s. However, the participation in decision-makings of extractive development only took place until late 2017. Even Indigenous Law was established in 1993 for the recognition of indigenous rights, it has broadly been subordinated to the operation of institutions privileging commodification, such as the Water Code and the Mining Code. Until the 2010s, the institutional structure for regulating mining externalities and recognizing indigenous people's participation in decisions over land and water (Ley 20.417) was introduced, and the regional environmental tribunal was finally established in 2017. Afterwards, community participation rose up as the institution required community consultations for mining projects. However, it is still limited in ways for involvement and even creates new burdens due to the lack of technical assistance (Babidge, 2020).

Local people have been continuously pressuring the state to regulate water resources and address the externalities with mining. Recent efforts have attempted to improve regulators' understanding of the hydrological balance and the mining-associated impacts in the SdA basin. These efforts, however, have been hampered by lack of reliable data, the remoteness of the locations, and inadequate oversight of mining operations (DGA, 2012), preventing or delaying regulators' actions to address the externalities through new institutional design. This phenomenon is also relevant in mining companies' existing corporate practices, which mishandle these uncertainties in their modeling and reporting, leading to inactions to address concerns by local communities (Babidge, 2019). Furthermore, financial compensations, modeled as a stress relief mechanism, can affect the locals in complicated ways such as increasing disputes among communities and weakening social linkages in some cases (H. Romero, personal communication, November 12, 2020), implying a higher degree of stress than that is predicted in the model. The latest progress towards environmental regulatory decisions (1TA, 2019), online mining monitoring system (SQM, 2020a), and the company's sustainable mining plan (SQM, 2020b), if strictly followed, may indicate a positive sign in mitigating the unequal effects of uncertainties among resource users. It worth to notice that due to the slow recovery of northern aquifers, northern communities could have an increased stress, mining companies therefore should be aware of the long-lasting impacts on northern residents and distribute corresponding compensation. However, the lack of trust in companies may compromise the effectiveness of this progress. How these factors will play out in the future is beyond the scope of the model.

5.4.2 Building socio-ecological system resilience in SdA

A discussion about the stress thresholds should relate to the current social and political context in local communities. The local population turns to become overburdened by the mounting up of mining projects and associated social consultations, spurred by the recent regulation shifting to obligatory consultation between the proponents of mining activities and the locals (Babidge, 2020). The cumulative and complex impacts of the existing mineral industries, added by consistent consultations, have been excessively pressuring the local population, indicating a shift towards intolerance of stress in the social system. The threshold analysis shows a striking increase in social stress for all mining scenarios if the threshold shifts towards intolerance. This intolerance may open a window to the emergence of collective actions or social mobilizations, which can create effective feedback of information and experience to authorities, adding to the potential for more responsible governance solutions. It also indicates the necessity of considering the local context of stress threshold in policymaking and underscores the importance of enhancing resilience of the socio-ecological system in SdA.

Resilience refers to the tendency to return to a reference state after disturbance (Chapin et al., 2002). Socio-ecological system (SES) resilience, in this case, involves the changes, adaptations, and transformations of a system in response to interferences (Quinlan et al., 2016). When translated into community, it represents the overall abilities of community's governance, physical, economic and social systems and entities exposed to impacts to learn, be ready in advance, plan for uncertainties, resist, absorb, accommodate to and recover from the effects of a hazard in a timely and efficient manner, including through the preservation and restoration of its essential basic structures and functions (Jabareen, 2013).

The scenario analysis shows that the eastern communities are more resilient when mining water use is largely reduced since the specific features of the transition zone between the communities and mining operations significantly slow the spreading of impacts. Under expansion scenarios, however, they become more vulnerable due to their proximity. For the northern communities, the impacts on their residents and aquifers, which are the major recharge source for SdA, are more long lasting, especially after lessened mining activities, drawing attention to build resilience of the entire SES.

Ways for building resilience for communities have been increasingly studied (e.g., Aguiñaga et al., 2018; Wasylycia-Leis et al., 2014). The measures include managing risks, adapting to changes, and securing sufficient resources (Pasteur, 2010), which requires critical responsibilities and actions from higher levels actors (e.g., mining managers, public sectors). In this case, actions on risk management may involve increasing awareness and preparedness of mining impacts by building an early warning system that will monitor the conditions of the focal resources. Building adaptation capacity includes enhancing access to relevant and timely information on mining impacts and an improved understanding of uncertainties in local hydrodynamics and broader climate. Securing sufficient resources may involve strengthening community organizations and improving access to skills and technologies of monitoring and assessment for the local residents. Equally important is that such pathways must be customized to fit with the local culture and translated into local forms of communication (Uddin et al., 2020).

It is important to recognize that, without a critical examination, the notion of resilience can be co-opted to privilege existing power relations, causing increased social inequality (Cretney & Bond, 2014). Building resilience should be vigilant of the seemingly effective measures of enhancing tolerance or endurance on the surface, because it can result in reinforcing the political-economic status quo of impacts, undermining the potential for more profound systemic transformation (Eakin et al., 2016). Instead, it should incorporate communities' ability to mobilize resources, form collective actions, and negotiate challenging situations (Jenkins & Rondón, 2015). It particularly recognizes communities' struggles and strengths in resisting mining operations, including dramatic confrontations (e.g., protests) and constant struggles (e.g., generation gaps, fractions within the community). Building resilience should reflect how best to strengthen such capabilities to challenge mining disruptions, thereby creating the instrumental feedback mechanisms to demand responsibility from public sector and mining authorities. Effective measures should address the structural issue of unequal power relations, including community empowerment, decentralizing power, and most importantly offering funding and resources needed for community participation (Cretney & Bond, 2014).

5.4.3 Decoupling water use and Li-mining outputs

Given the water intensity of Li-mining and the impacts water use has on the local environment and livelihood, it is worth asking what can be done about it. How can mining outputs be decoupled from water use? A key answer to this question lies in the mining processes and technologies. Some improved lithium extraction and processing options are available. These include water recycling, minimizing waste products, processing brine more efficiently, creating a smaller footprint, developing technology that is transferable from site to site, extracting several raw materials from the same brine, and minimizing surface subsidence. Additional examples of mining and processing alternative technologies include the following (Kaunda, 2020): (a) adding additives to increase lithium concentration; (b) using material that can selectively adsorb lithium, such as Titanium oxides and hydroxides; (c) treating the brine in adsorbent beds that selectively capture lithium; (d) treating pumped-out brine on ionic-exchange columns, to concentrate lithium chloride prior to placement in evaporation ponds; (e) using of chromatography to separate lithium from both concentrated and diluted brines and (f) selectively capturing of Li-ions using electrolysis.

Some new Li-mining projects aim to do away from brine-based extraction and use less water-intensive processes. For instance, Tesla, a manufacturer of electric vehicles claimed a more sustainable way of obtaining lithium (Scheyder, 2020). The company was planning to develop a 10,000-acre lithium clay deposit in Nevada, USA. Its internally developed extraction and processing technology will mix clay with table salt and then add water, causing a reaction where the salt would leach out with lithium, which can then be extracted. To mitigate environmental damage, the leftover clay would be put back in the earth. In the UK, a pilot plant is being developed to produce lithium from geothermal waters (Leotaud, 2020). Lithium will be sieved out of the water using nanofiltration technology. The leftover water will be reinjected to the ground via boreholes.

5.5 Conclusion

Concerns about the impacts of Li-mining water use have been mounting and put the sustainability of low-carbon transitions into questions. Just as explained by a local resident (interview, Peine, March 2018), stress from Li-extraction is centered on water, since it relates to every aspect of social livelihoods:

> I can see hundreds of trucks taking away the lithium and the water. When I observed the production and the amount of lithium and water being taken away, I fell into tears. Water is the main source for what you see here. They are competing for water, mining and everything. But no one is talking about the farmers. Agriculture is losing. What about the future of agriculture? …. Water is

> alive for us, and the salar is our little sea…. I want to know if there is another way to produce lithium but use less water.

This study developed an ABM model to represent the dynamics of Li mining-community-aquifer interactions in SdA. The model is the first to evaluate the potential impacts of future mining scenarios on the aquifer conditions and mining-induced social stress and investigates how such impacts are affected by the uncertainties embodied in groundwater dynamics. Successfully validated with measurement data, the model confirms the current situations and projects future outcomes under four different water use scenarios. Social stress would increase considerably once the society evolves towards intolerance, while if more tolerance is built, social stress could be largely mitigated. Community intolerance of stress may open a window of opportunity to the emergence of collective actions or social mobilizations, which can channel the feedback of information and experience to authorities, adding to the potential for more responsible governance solutions. This study highlights the importance of understanding and managing the downside risks of Li-extraction to achieve an energy transition with social justice – a transition designed to address climate change while respecting the host communities and protecting the environment (UNFCCC, 2016). This study also anticipates the governance challenges, pathways to build resilience of SES in SdA, and techniques to decouple water use from mining products, that are discussed in this work will help mining regulators, local environmental regulators, local decision-makers, and Li-industry decision-makers provide better management of the world's largest Lithium production sites for a sustainable future.

The results of this model also suggest the need and potential for incorporating some pathways in the future that may help build system resilience of SES in SdA. For future work, increasing early warning and awareness, for instance, could be incorporated in the future model, in which companies share their projections of impact and potential warning signs with local people, thereby altering the reference point for people's sense of change (Babidge et al., 2019). Access to timely information on mining impacts could be added to reduce uncertainties, in which people are no longer subject to the changes in their location but have a broader understanding of the whole basin. Climate uncertainties could also be included by coupling this model with climate models (i.e., CMIP6) to understand how climate change contributes to socio-ecological changes. Other important factors are composed of the uncertainties of mining-community-aquifer relations, such as the cultural relations with water and pathways that are not explicitly designed or could not be translated into models, requiring future efforts with other methods or in broader disciplines.

CHAPTER 6

SUSTAINABLE LI-EXTRACTION FOR GREEN TECHNOLOGY: CONSUMERS' PERCEPTIONS OF IMPACTS

6.1 Introduction

Many countries have been enacting policies to facilitate transitions to a low-carbon society to reach the climate goals of the Paris Agreement, spurring an increasing uptake of green technologies. Electric vehicles (EVs), in particular, offer an important contribution to decarbonization in the transportation sector (Hill et al., 2019). The rapid growth in EV sales necessitates similar growth in the supply of the minerals required in EV batteries, such as lithium, cobalt, and nickel. Global lithium production increased almost three times during 2015-2020 (USGS, 2021), and is projected to increase by 7.9% - 9.7% per annum to accommodate the world goal of 100 million EVs in 2030 (Ballinger et al., 2019). Mineral extractions are intrinsically destructive to the host place (Frank et al., 2014), prompting questions on the overall sustainability of low-carbon technologies. Of particular concern is the notion that deploying these technologies shifts the socio-environmental costs from wealthier countries to places in the Global South that are out of sight of the affluent consumers purchasing EV technologies (IRP, 2020; Kramarz et al., 2021).

Many scholars and researchers have expressed concerns over the externalities of mineral extraction for low-carbon technologies. Lithium extractions in Chile, for instance, have shown to depleting local water resources (Agusdinata et al., 2018), degrading vegetation (Liu et al., 2019), and disrupting indigenous culture and livelihoods (Babidge, 2020). Cobalt mines in the Democratic Republic of Congo (DRC) have been found to offer toxic working conditions involving the use of child labor, posing serious ethical and health concerns (Sovacool et al., 2020a; Amnesty International, 2016). Similar impacts have been documented in the copper mines (Romero et al., 2012).

On the consumer side, EV adoption behavior is usually motivated by various factors including technical attributes (e.g., driving range, vehicle performance), financial aspects (e.g., price, incentives, operation costs, etc.), and socio-cultural concerns and attitudes (e.g., desire to be “cutting edge” in new technology adoption, or for social status) (Liao et al., 2016). Pro-environmental attitudes (e.g., symbolic meanings of EVs, environmental benefits) are found to be the most important in motivating adoption (Kim et al., 2014; Jansson et al., 2017). Consumers are becoming increasingly conscious of the socio-ecological footprints of their purchase decisions (Kramarz et al., 2021), a factor driving automakers to emphasize EV's green credentials in marketing. However, the use and impacts of minerals in EVs are often invisible from consumers (IRP, 2020). Studies about consumer awareness and perceptions of mineral impacts in low-carbon technologies are rare, posing challenges to alter the governance of mineral extraction. This study thus hypothesizes that EV-consumers generally lack awareness of such impacts and knowing these impacts may change their perceptions of EVs. It also posits that consumers with different motivations may perceive the impacts differently, and pro-environmental consumers may be more likely to demand better governance of minerals.

Governance frameworks and actions are urgently needed to manage mineral resources sustainably, considering socio-environmental and governance risks are likely to restrain mineral supply in near future (Jowitt et al., 2020). The mineral resource governance framework, proposed by the United Nation, lays out governance gaps and policy options for unlocking the extractive sector's potential as a catalyst for sustainable development (IRP, 2020). It specifically identifies the shift of governance challenges towards the consumers due to the increasing consumption of sustainable products and the increasingly important role of consumers in pressuring the establishment for schemes around sustainable sourcing. Similar frameworks have also been proposed in academia. Many of them emphasize the instrumental role of consumers in filling governance gaps, calling for more empirical studies on the actors at the end of value chain (e.g., consumers) as well as on the externalities of low-carbon technologies (Kramarz et al., 2021), and promotion of consumer awareness of mineral use and consumption effects (Ali et al., 2017).

Consumer perceptions play an instrumental role in facilitating better governance of mineral resources. Such roles include building policy mandates (i.e., assessing consumer sentiment about an issue and the need for developing a solution; Hastak et al., 2001); helping establish governance schemes (i.e., Dodd-Frank Act was established in response to consumer pressure about 'conflict minerals' free products; IRP, 2020); influencing corporate sustainability efforts (Kang & Hustvedt, 2013); informing educational efforts and predicting potential public reactions (Slovic et al., 1982). Given the rapid growth of EVs, and the fact that consumers of EVs are poorly informed about the minerals used in their products (Ali et al., 2017), understanding consumer perceptions of these minerals is urgently needed.

Interconnections between mineral extractions, the wide adoption of low-carbon technologies and global climate change policies exhibit many features of "telecoupling" (Agusdinata et al., 2018). Telecoupling refers to the idea that geographically distant socio-ecological systems may be connected through actions, policies, and behaviors (Liu et al., 2013). Governing such systems can be challenging, it thus requires the understanding and involvement of knowledge, actors, and activities across the telecoupled systems (Eakin et al., 2014). This study adopts the telecoupling framework since it can be particularly useful in improving consumer's understanding of system components, distant interactions, and unexpected externalities of mineral extraction issues.

This study aims to address the knowledge gap of consumer perceptions about the minerals used in their products and the possible governance actions to regulate mineral extraction towards sustainability. To achieve this, informed by the telecoupling framework, this research asks the following two questions through an application of Q-methodology combined with survey questions: (1) To what extent are EV consumers with different motivations for purchasing aware of the impacts of mineral extraction? (2) When exposed to similar information on impacts, how do they then perceive issues of mineral extraction and evaluate governance schemes? This research selected EV owners with diverse profiles and purchase motivations in the United States, one of the largest EV-consuming countries, as a pilot study. Results provide policymakers and industrial decision-makers with an initial understanding of public sentiments and reactions to the externalities of low-carbon technologies.

Q-method is employed in this work to collect consumer perceptions as it provides more nuanced and sophisticated evaluation of opinions of consensus and discrepancies than an opinion poll (Boudet, 2019; Kamal et al., 2014). Q-method requires respondents to think through their prioritization of statements, which combines the advantages of structure in survey methods and depth in focus group interviews (Zabala et al., 2018). It has been suggested that the development of sustainability policy could benefit from making greater use of Q-method since it could “contribute to better problem identification and definition; estimation and specification of policy options” (Steelman and Maguire, 1999). Although the Q-method is limited in its ability to draw generalizations, that is not the purpose of this study. Instead, this study aims to investigate the consensus and discordance of consumers about externalities and governance of EV minerals. Q-method’s strength in unveiling key areas of interest and concern offers useful insights that could inform governance priorities and measures for sustainable minerals extraction (SME).

Q-method has been increasingly applied in fields of renewable energy, climate change, and sustainable consumption. The majority of relevant Q-method studies focus on social acceptance (or opposition) of renewable energy projects in the local context, such as wind farms (Fisher and Brown, 2009) and electric vehicles (Kougias et al., 2020; Cools et al., 2009). The method has also been used to collect public attitudes to sustainability and resource policies (Curry et al., 2013) and consumer traits of sustainable consumption (Qu et al., 2015). Some recent efforts applied Q-method to mineral extraction issues, but most are limited to perceptions from host communities (e.g., Nguyen et al., 2018). The application of Q-method to explore perceptions about mineral extraction externalities and governance from the consumer's view is still rare.

The aim of this paper is to provide a better understanding of challenges and opportunities to manage EV minerals more sustainably. In the remainder of this chapter, it starts by introducing the telecoupling framework employed to guide the research design. It then explains the development and implementation of the Q-method. This is followed by a detailed discussion of the Q-method study results. The final section provides policy implications of the findings.

6.2 Materials and Method

6.2.1 Q-methodology

Telecoupling framework investigates how geographically distant socio-ecological systems are connected and the governance of such connectivity (Liu et al., 2013). It can serve to promote consumers' cognizance of mineral use and consumption effects through revealing distant interactions between consumption and extraction, unexpected externalities, and the complexity of governance. This study thus adopts the telecoupling framework introduced in Chapter 3 (Figure 2), as a foundation for Q-concourse development and result synthesis.

This research employed a Q-methodology approach (Stephenson, 1953) combined with survey questions to understand how EV consumers perceive minerals used in their EVs and ways to achieve SME. Q-method consists of concourse development, participant selection, Q-sorting administration (the process of sorting the statements according to participants' viewpoints), and data analysis to identify similarities and differences in responses. Prior to sorting, participants first answered pre-sorting questions about EV minerals extraction impacts. Then, they were presented with a factsheet in accordance with pre-sorting questions to expose all respondents to the same knowledge before the Q-sorting process. Each of these steps is explained in more detail below.

6.2.1.1 Pre-sorting survey

Even as consumers are increasingly conscious of their purchase footprints, the use and impacts of minerals in EVs are usually not disclosed to them. To understand the level of consumer awareness, this study conducted a pre-sorting survey with eight questions pertaining to the “receiving systems” (Figure 2) in the case of lithium (Li) extraction. The questions, in Likert-scale, were developed from academic papers and news articles. The survey covers Li-extraction impacts on the host place including negative impacts on the natural system (i.e., water availability and quality, ecosystem health) and social system (i.e., social disruption, cultural discontinuity), and some positive impacts on the local economy and infrastructure. Participants were asked to choose from a scale of 0-5 based on their feeling of agreement and disagreement (0 represents “I don’t know” and 5 “Strongly Agree”). Once the survey was completed, a factsheet was provided to inform the participants about the detailed Li-mining impacts for EVs. The survey and factsheet can be found in Appendix B-Table B1.

6.2.1.2 Concourse construction (Q-set)

The statements (Q-set) are designed based on the components in the telecoupling framework (Figure 2). The Q-set largely focused on the “sending systems” and flows. Namely, the Q-set organized respondents thinking around the five categories: 1) Technology development and impacts; 2) Consumer’s preference and consumption impacts; 3) Policies and governance; 4) Supply chain network and practices; and 5) Influence of public opinion and values. Information relevant to each category was compiled from scientific literature, news articles, and policy reports. Initially, a large number of statements was created, then, after in-depth interviews with three EV owners in November 2020, the Q-set was narrowed down to 37 well-targeted statements to ensure unambiguity and inclusiveness. Table 8 shows a brief summary of the Q-set statements in five categories, and the full statements are provided in Appendix B-Table B2.

Table 8. Brief Summary of the Q-Set Statements in Five Categories

Technology developments and impacts (S1-7)

1. Technology developments on driving range and fast-charging innovations
2. Technology improvements on driving experience
3. Battery advancements to lower battery costs and make EVs more affordable
4. Other electricity storage technologies with lower costs and better environmental performance
5. The importance of developing technologies and policies to manage mining impacts
6. The importance of developing EV batteries with lower impacts
7. Reuse and recycling of expired lithium-ion batteries

Consumer's preference and consumption impacts (S8-16)

8. Technological advancement of EVs is my primary motivation for purchase.
9. Financial aspects play a critical role in my EV purchase decision.
10. Environmental benefits of EVs are an important attraction for my purchase.
11. EV is cleaner than gas-powered vehicles.
12. EVs are generally environmentally friendly technologies.
13. EV-minerals create other environmental and social concerns.
14. The important of addressing the extraction impacts from a consumer's view
15. Active consumer-automaker interaction on vehicle performance improvements.
16. Active consumer-automaker interaction on impact reduction.

Supply Chain network and practices (S17-23)

17. EV automakers should urge mineral suppliers for SME.
18. Lithium mining companies should primarily manage mining impacts.
19. As an EV consumer, I feel it is necessary to build a global partnership to bring transparency.
20. The insufficient efforts from automakers on SME, serious commitment and investment are needed.
21. Extraction always has impacts and automakers should not be obliged to manage impacts.
22. Same importance between SME and emission compliance for automakers.
23. Mining companies' sustainability initiatives are not properly exercised.

Influence of public opinion and values (S24-29)

24. The role of media in raising public awareness.
25. The role of media in pressuring SC actors for SME.
26. The role of consumers in urging SC actors for SME.
27. News and reports of mining impacts are unclear and have false information.
28. Public opinions should not affect future EV development.
29. Knowing the impacts changes my perceptions of the promoted green image of EVs.

Policies and governance (S30-36)

30. Governments in EV-consuming countries should coordinate SME for EVs.
31. Policy shifts on financial support for SME initiatives from EV-consuming countries.

32. Governments in EV-consuming countries should lead the impact management.
33. Governments in EV-consuming countries should only set frameworks for building SME partnerships.
34. Governments in mining countries should manage impacts.
35. Policies and initiatives on SME will discourage the wider adoption of EVs.
36. Global politicians should prioritize SME rather than promoting EV adoptions.

6.2.1.3 Participant's selection (P-set)

Since this study intend to compare the perceptions of EV owners who had different vehicle purchase motivations, participants were recruited through a demographics survey that asked about their gender, occupations, and primary motivation to purchase an EV to ensure the diversity of views. The recruitment process was conducted online from the most active online community for EV owners and enthusiasts in the US and Europe (Reddit forum on electric vehicles: https://www.reddit.com/r/electricvehicles/, with 119k users). A total of 88 EV owners with diverse profiles were recruited to participate in the Q-sorting procedure. According to the information collected from the demographics survey, 39 participants bought EVs for predominantly technical attributes, 17 for financial factors, and 32 for environmental reasons (see Table B3). This participant sample allowed us to break the participants into three groups based on purchase intentions for final analysis and interpretation:

- Technology-driven owners (*Tech*),
- Financial factors-driven owners (*Fin*), and
- Environment-driven owners (*Env*).

The number of participants in each group fits the ratio of participants relative to the number of statements (i.e., 37) suggested by Thompson et al. (1983) (1:2 ratio) and Watts and Stenner (2005) (1:1 ratio).

6.2.1.4 Q-sorting process

The Q-sorting procedure was administered through an online Q-method tool, Q-sortware (http://www.qsortware.net/), which mimics the physical card sorting through a drag-and-drop interface. This procedure started with a short explanation of the research objectives and methodology. Then a consent form was provided, followed by a demographics survey. Next, the pre-sorting survey was shown to participants to capture their initial awareness of mineral extraction impacts. The factsheet of Li-mining impacts was then presented to create a similar exposure to information on impacts before the Q-sorting process. Afterward, for introduction purposes, participants were instructed to read all 37 statements and sort them into categories of agree, disagree, and neutral. Finally, a sorting board with a quasi-normal distribution ranging from extremely disagree (-4) to extremely agree (+4) was shown to participants (Figure 22). Participants were instructed to drag and drop each statement onto the board according to their perceived level of agreement or disagreement. In each sorting process, participants were free to move the statements until they were satisfied with the ranking. After sorting, each participant's final sorting was automatically collected (q-sort) and then exported for final analysis and interpretation.

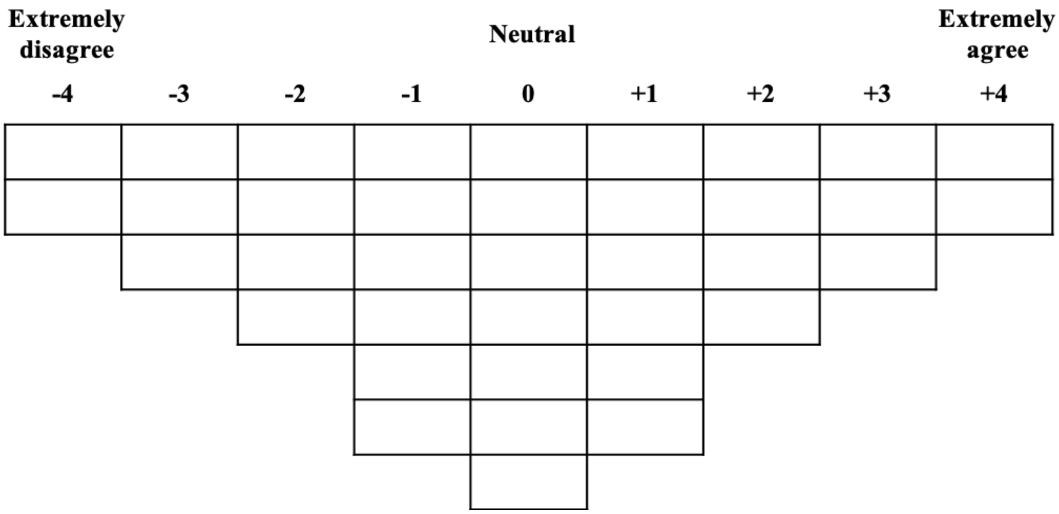


Figure 22. The Quasi-normal Distributed Sorting Board Used in the Q-sorting Procedure

6.2.1.5 Data analysis and interpretation

Data analysis of the collected q-sorts mainly involves the statistical techniques of correlation and factor analysis, which reduces the complexity in correlated variables and highlights patterns of similarities and distinctions among the viewpoints (Hothorn and Everitt, 2014; Watts and Stenner, 2012). This study employed the '*qmethod*' package (Zabala, 2014) in the R environment, which calculates the correlation matrix, performs a principal component analysis (PCA) to extract common factors, uses a varimax rotation to maximize the variance explained by each factor, and also automatically flags q-sorts significantly loading on a factor. A "factor" is used as a technical term for a shared perspective (Raadgever et al., 2008). Using this package, three groups of q-sorts (i.e., *Tech*, *Fin*, and *Env*) were analyzed individually to extract shared perspectives, and then interpreted and compared across groups.

Four factors were selected for the *Tech* group, three factors for the *Fin* group, and four factors for the *Env* group, based on commonly employed factor selection criteria including Eigenvalue (Watts and Stenner 2012), loadings of q-sorts (Brown, 1980), total variance explained (Kline, 1994), and feasibility in the interpretation. Eigenvalue >1 or significant loadings of q-sorts ≥2 indicates a satisfied statistical strength and explanatory power of extracted factors, while they also result in an overly large number of factors (Watts and Stenner 2012). Thereby, the final selection is based on the empirical rule (i.e., 1 factor for 6-8 participants; Watts and Stenner, 2012) and feasibility of interpretation. Details of selection criteria are in Table B4. The characteristics of selected factors are shown in Table 9, and the detailed interpretation of each factor is explained in the result section. The total explained variance in each group meets the empirical range of a satisfactory explanatory variance (34–40%) by Kline (1994). The composite reliability of each factor is high (e.g., >0.95), indicating the strength of the extracted factors (Brown, 1980; Zabala and Pascual, 2016). This research also examined the correlation between factors and found the correlation is fairly low between factors within each group (e.g., abs. of correlation coefficient <0.3) while some correlations exist between factors of different groups (see Table B5), which indicates potential agreements between groups.

Table 9. Summary of the Selected Factors

	Tech				*Fin*			*Env*			
	F1	F2	F3	F4	F1	F2	F3	F1	F2	F3	F4
Loadings of Q-sorts	7	7	13	5	5	5	6	9	6	7	4
Eigenvalues	6.2	4.26	3.2	2.78	2.35	2.3	2.31	3.35	3.03	2.86	2.37
% of variance explained	15.89	10.93	8.21	7.12	13.84	13.56	13.01	10.46	9.47	8.93	7.4
Composite reliability	0.97	0.97	0.98	0.95	0.95	0.95	0.96	0.97	0.96	0.97	0.94
SE of factor scores	0.19	0.19	0.14	0.22	0.22	0.22	0.2	0.16	0.2	0.19	0.24

6.3 Results and analysis

6.3.1 Consumer awareness of mineral extraction impacts

The data collected from pre-sorting surveys are analyzed by each owner group (based on purchase intention: *Env, Tech, Fin*) and shown in Figure 23. Prior to the Q-sort, most respondents did not have a strong awareness of the externalities of EV minerals, although there were differences across the groups. On average, environment-driven owners generally agree with mining-related impacts on local water systems, ecosystem, and social livelihoods, indicating their relatively strong awareness of mining externalities compared to other groups. Technology-driven owners on average are more aware of issues of the water consumption caused by mineral extractions, but slightly disagree with other socio-ecological impacts. Financial factors-driven owners on average have the lowest knowledge of mining-related impacts. Their perceptions are also largely varied, especially in terms of impacts on water systems (Q1, Q4) and social tensions (Q5), indicating a general confusion and lack of awareness of such impacts.

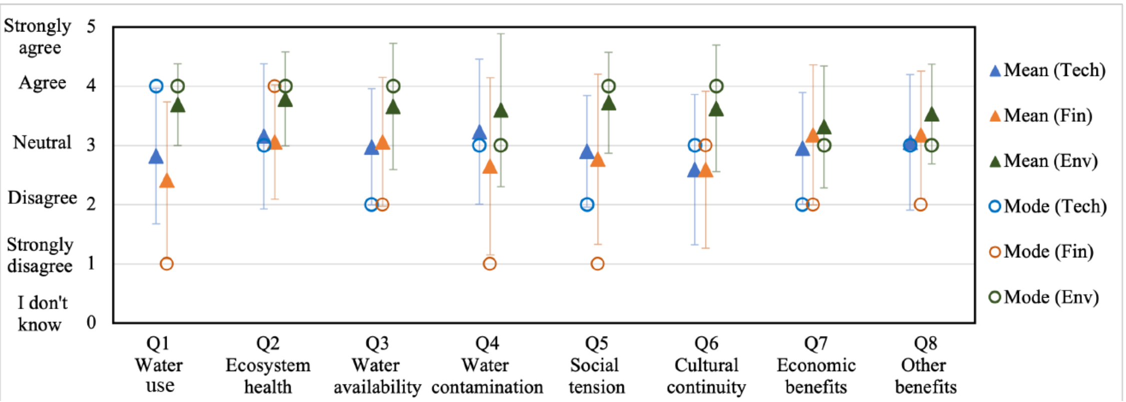


Figure 23. Summary of Consumer Awareness of Mineral Extraction Impacts among Different EV Owner Groups

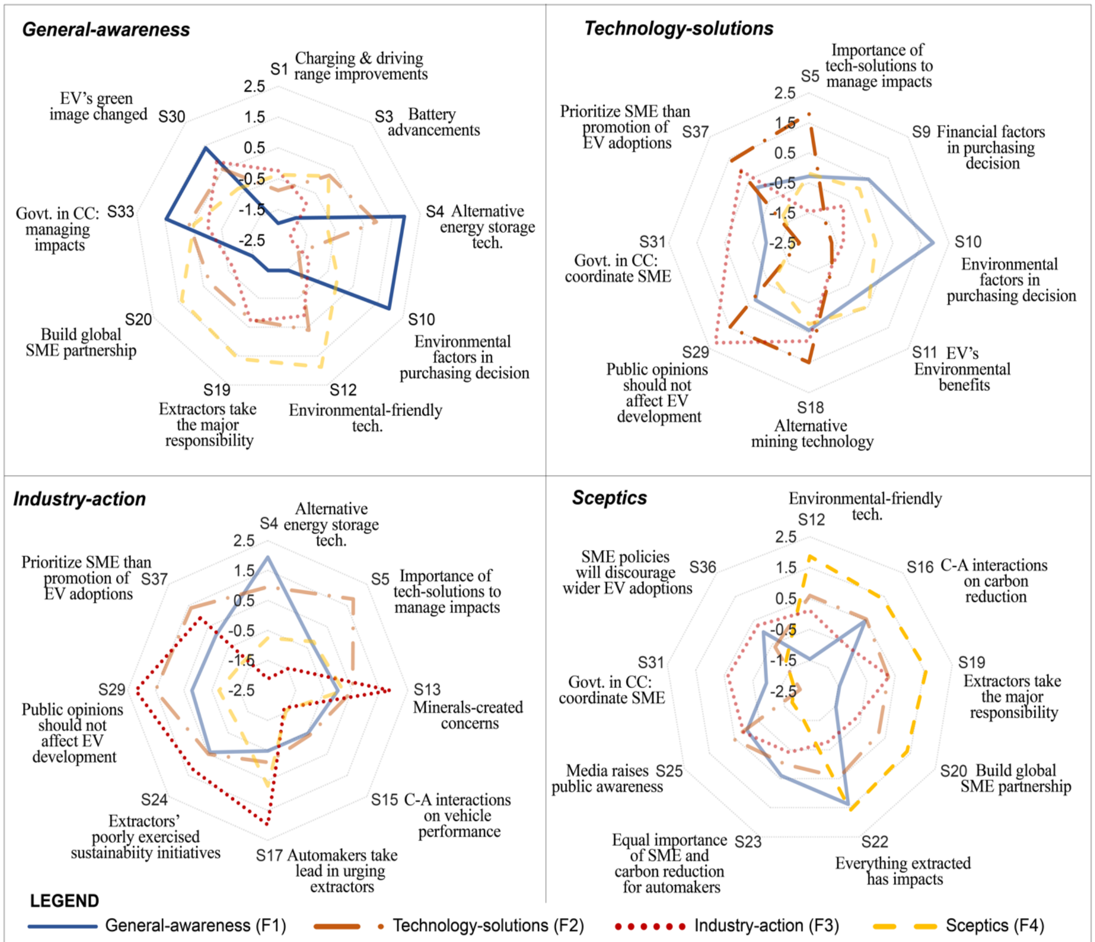
6.3.1.1 Factor interpretation

The extracted factors represent the shared perspectives about governing EV minerals in each participant group. The factor scores and z-scores were calculated (Table B6-B7), which represent the optimal distribution of Q-sort for a given factor and the weighted average scores of respondents who define that factor, respectively (Van Exel and de Graaf, 2005). Statements identified as distinguishing for each factor are marked with an asterisk ($p < 0.05$). The interpretation of these perspectives is based on distinguishing statements and the selected disagree/agree statements for each factor, and a descriptive label for each factor is created to represent its major characteristics. In the next section, it identified and elucidated these shared perspectives among each participant group. In each perspective, the analysis includes the distinguishing Q-set (S1 to S37) and associated z-scores.

6.3.1.2 Technology-driven owners (Tech)

Each perspective identified in the *Tech* group is labeled with a descriptive form: *General-awareness* (F1), *Technology-solutions* (F2), *Industry-action* (F3), and *Sceptics* (F4), and their most distinguishing statements are mapped in Figure 24.

The ***General-awareness*** perspective indicates a pro-environment attitude (S10, 1.94) and disagreement with EV's environmental benefits. Respondents indicate that EVs are not environmentally friendly (S12, -1.46) and their marketed green image could be deceptive (S30, 1.42). However, they doubt the importance of addressing mining impacts driven by EV minerals (S13, 0; S14, -0.97). As for future technology development, they strongly support developing alternative energy storage technologies than Li-ion batteries with lower impacts (S4, 1.94), and don't prioritize developments related to vehicle performance (S1, -1.95; S3, -1.56). The most distinctive characteristic of this perspective is its stance on SME governance. Respondents feel SC actors should not take the major responsibility in managing mining impacts (S19, -1.46; S20, -1.46). Instead, they anticipate national governments in consuming countries to take the lead (S33, 1.45), while not prioritizing any governmental actions (funding, frameworks, etc.) for impact management (S31, -0.98; S32, -0.97; S35, 0; S37, 0.11).



Note: C-A interactions: Consumer-Automaker interactions; SME: Sustainable Mineral Extraction; Govt. in C-C: Governments in EV-consuming countries

Figure 24. Distribution of Z-Scores for Factors' Distinguishing Statements in the Tech Group

The ***Technology-solutions*** perspective emphasizes the role of technology in consumer preference and mineral governance solutions. Distinctively, it firmly advocates the importance of technical solutions in managing mining externalities (S5, 1.81), manifested in its support for lower-impact energy storage technologies (S4, 0.95) and alternative mining technology (S18, 1.49). This perspective shows some awareness for its questioning stance of EVs as cleaner technologies (S11, -1.34). Respondents strongly relate themselves to technology-driven buyers (S8, 1.2) and exclude environmental (S10, -1.69) and financial factors (S9, -1.63) in their purchase decision. They recognize the role of media in raising awareness and spreading knowledge of EV minerals (S26, 0.72; S25, 0.57), but strongly oppose social participation in shaping the future of EV transitions (S29, 1.5). As for mineral governance, they are not inclined to prioritize any actors or institutional tools to manage mineral extraction impacts, but they support prioritizing SME in global politicians' agenda (S37, 1.38).

The ***Industry-action*** perspective shows the strongest awareness of the concerns created by EV minerals (S13, 1.87) in the *Tech* group, and it anticipates industrial actors to lead the SME governance (S17, 1.98). It firmly opposes any further technology development related to EV performance (S3, -0.97; S4, -2.11). Respondents believe the current sustainability practices in the SC are insufficient (S23, -0.41; S24, 1.25), thus more industrial measures should be taken and led by EV companies (S17, 1.98) and mining companies (S18, 0.78). Institutional solutions are generally welcomed by this perspective. It primarily supports the priority of SME governance in global policy agenda (S37, 0.91), and generally agree with various policy tools (funding, frameworks, etc) that could be exercised by governments in both consuming and producing sides (S31, 0.37; S32, 0.37; S34, 0.41; S35, 0.6).

The ***Sceptics*** perspective questions the issue created by EV minerals and its importance (S13, 0.19; S14, -0.02). It firmly believes EV is environmentally friendly (S12, 1.87) and its carbon reduction benefits outweigh the externalities created by extracting EV minerals (S16, 1.41). Respondents are in favor of more technological developments around EV batteries as to end-of-life management (S7, 1.09) and impact reduction (S6, 1.35). Distinctively, they distrust the role of media in raising public awareness and pressuring industrial actors (S25, -1.79). Actions from the SC are preferred to government agencies in this perspective. Mineral extractors are identified as the most appropriate actor to manage mining externalities (S19, 1.59). They also expect global partnerships (S20, 1.38) and automakers to bring transparency to mineral sourcing (S17, 0.68), while such actions should not be obliged (S22, 1.59). In alignment with their strong belief in EVs as green-tech, they think politicians should keep expanding EV acceptance rather than prioritizing SME (S37, -1.2).

Consensus exists for the *Tech* group as to alternative mining technology (S18) and the objection to consumer-automaker interactions on vehicle performance improvements (S15). In addition, EV-owners represented by factor 1, 2, 3 are dissatisfied with extractor's sustainability practices (S24) and feel the marketed green images of EVs could be deceptive (S30). The need for consumer pressure on SME (S27) is agreed by EV-owners represented by factor 1, 3, 4. EV-owners represented by factor 1, 2, 4 reach a consensus on the role of governments in consuming countries, agreeing that they should primarily manage externalities of mineral extraction rather than just be a coordinator for sustainable mineral sourcing (S31, S33).

6.3.2 Financial factors-driven owners (Fin)

Three identified common perspectives, labeled as *Conservatives* (F1), *Collaborative-management* (F2), and *Unoriented strong awareness* (F3), are shown in Figure 25.

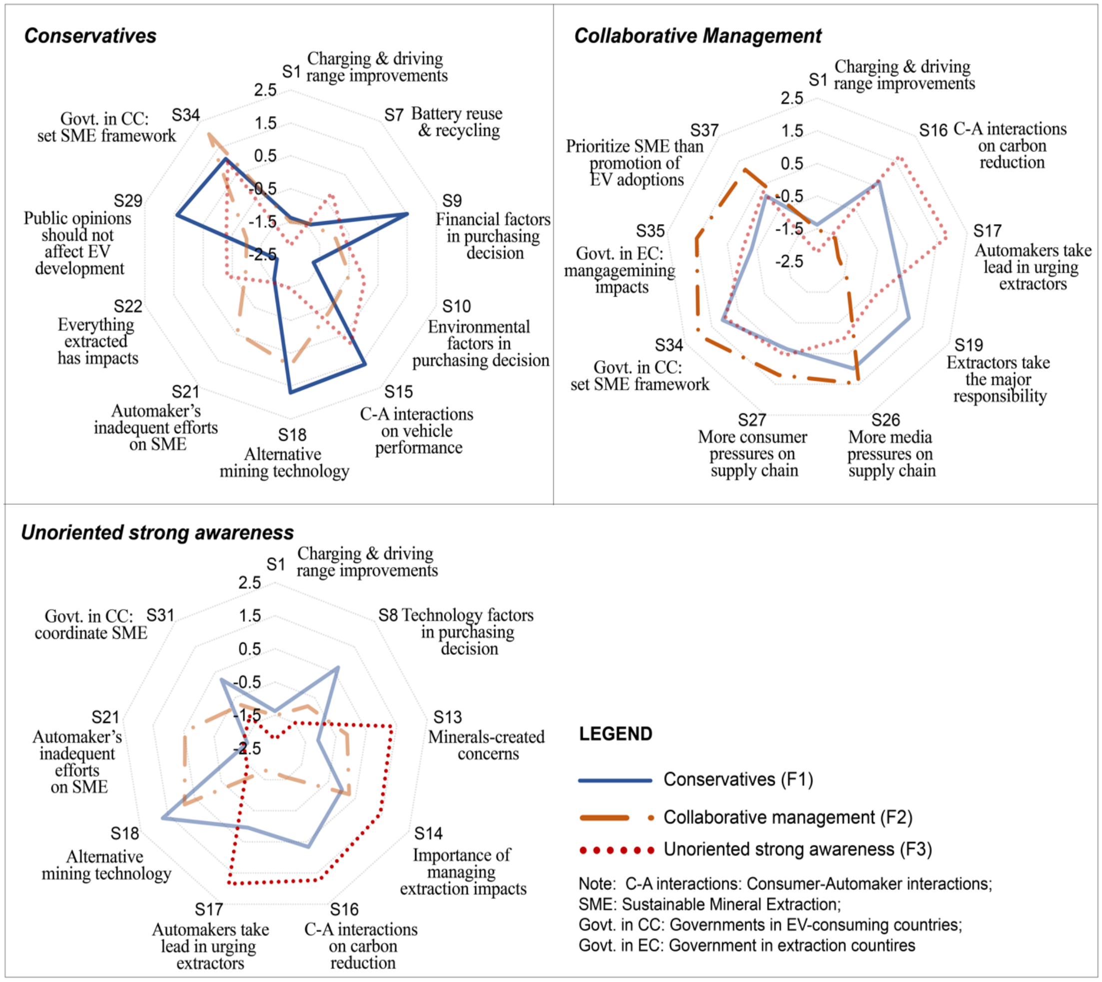
The ***Conservatives*** **perspective** is neutral about the overall sustainability of EVs and conservative about mineral governance. Respondents confirm that they are driven by financial factors (S9, 1.5) and do not factor in EV's environmental attributes (S10, -1.71). They care about further developments in vehicle performance more than other aspects, as reflected in their agreement with improvements on driving experience (S2, 0.88), alternative power storage methods (S4, 0.89), and consumer-producer interactions on vehicle improvements (S15, 1.63). They acknowledge the role of media and consumers in raising awareness and pressuring sustainability practices but believe public opinions should not affect the direction of EV developments (S29, 1.39). They generally don't think EV minerals are creating new concerns (S13, -1.09). Mining impacts should be majorly managed by extractors (S19, 0.98), with the help of alternative mining techniques (S18, 1.7) and automakers (S22, -2.04). Top-down instruments are not preferred here, but frameworks led by consuming countries to facilitate SME partnerships are prioritized (S34, 1.09).

The ***Collaborative-management*** perspective prioritizes the SME governance and emphasizes collaborations among all actors: consumers, media, governments, and SC. Respondents show awareness of the issue and recognize the need to shift the focus from

EV adoptions to SME (S37, 1.17). It strongly advocates for policy interventions in both extraction and consuming countries. Managing mining externalities should be led by governments in extraction countries (S35, 1.52), and consuming countries should lend help and build mineral sourcing partnerships (S34, 2.02; S33, 1.13). Respondents largely recognize and value social participation from media and consumers, calling for more pressure on industrial actors for SME (S26, 1.49; S27, 1.2). Current sustainability efforts are perceived as insufficient in the SC (S24, 1.15; S21, 0.45). They firmly oppose passing on the responsibility of SME to any single actor in the SC (S19, -1.35; S17, -1.8). Instead, they believe building global partnerships is needed (S20, 1.06).

The ***Unoriented strong awareness*** perspective has a strongly raised awareness of the mineral extraction issues and the importance of managing these externalities (S13, 1.34; S14, 1.44). However, it is unoriented as to various schemes to govern mineral extraction/sourcing sustainably. Respondents understand the role of media in raising public awareness (S25, 1.1) while not in facilitating mineral governance (S26, 0.03). They specify automakers, rather than mining companies, to take the lead in urging SME (S17, 1.85; S18, -1.47). Policy-wise, they are concerned that more SME policies could discourage EV developments and adoptions (S36, 1.2), but they slightly agree with institutional support from consuming countries, such as regulatory frameworks (S34, 0.98) and subsidies (S32, 0.71).

In general, participants in the *Fin* group believe further technology development should not be prioritized for EVs, especially as to driving range and charging techniques (S1). Notably, they reach a consensus on the consumer participation in pressuring automakers for SME (S27) and the role of governments in consuming countries in setting regulatory frameworks (S34). However, the potential discouraging effects of SME-related policies are of concern within this group (S36).



Note: C-A interactions: Consumer-Automaker interactions; SME: Sustainable Mineral Extraction; Govt. in CC: Governments in EV-consuming countries; Govt. in EC: Government in extraction countires

Figure 25. Distribution of Z-Scores for Factors' Distinguishing Statements in the Fin Group

6.3.2.1 Environment-Driven Owners (Env)

In the *Env* group, four perspectives are labeled as: *Green-tech defender* (F1), *Collaborative-management oriented* (F2), *EV-adoption supporter* (F3), and *Extractor-focused* (F4). Their most relevant statements are mapped in Figure 26.

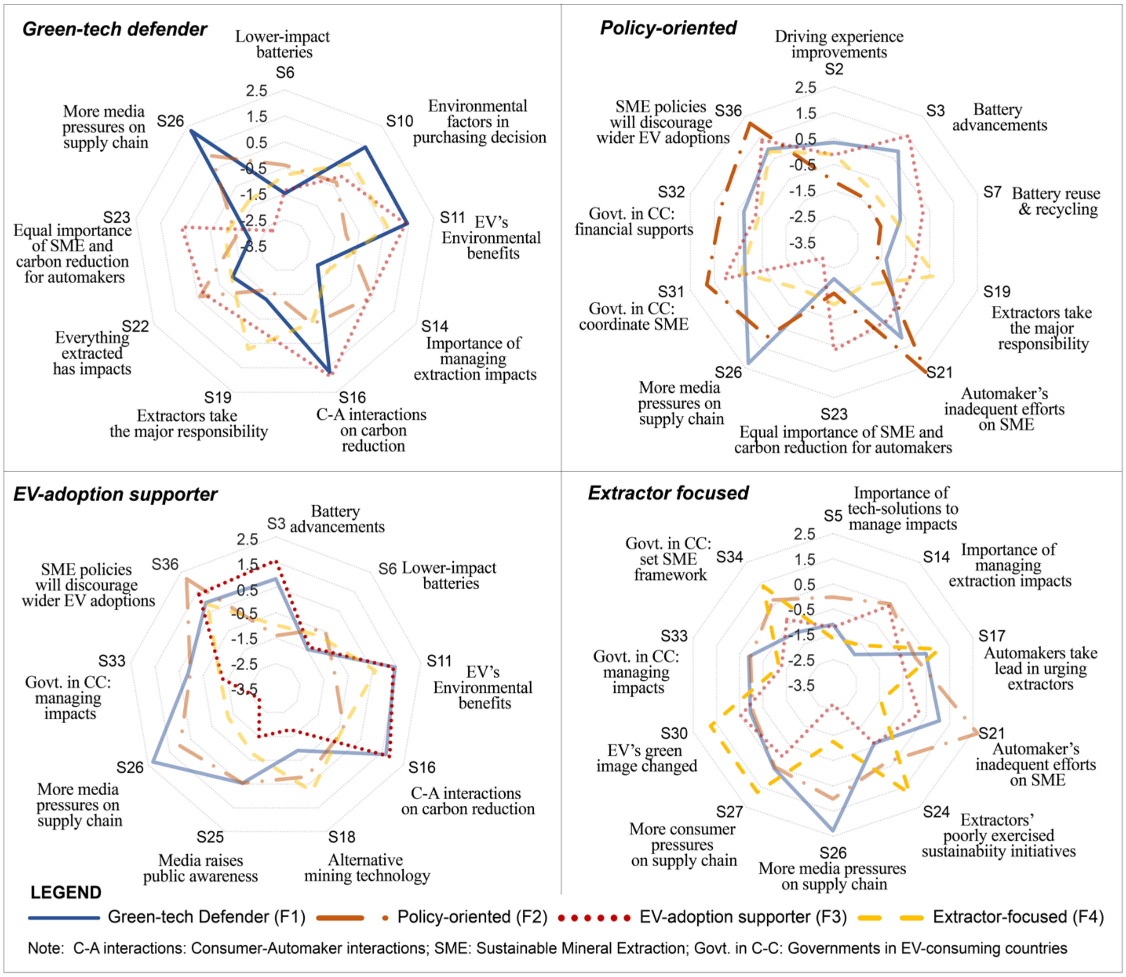
The ***Green-tech defender*** perspective has a strong belief in EV's environmental benefits while neglecting the related mineral extraction externalities. Respondents show a strong pro-environment attitude (S10, 1.46) and a strong intention to defend the green aspect of EVs (e.g., carbon reduction; S11, 1.43; S12, 0.61; S16, 1.68). They disagree with the importance of addressing mining impacts (S14, -2.01; S5, -1.1). Institutional interventions are therefore not welcomed and even concerned (S36, 0.94). However, respondents expect SC actors to lead SME governance. Automakers, rather than extractors, are expected to lead industrial actions and prioritize the importance of responsible battery sourcing (S19, -1.31; S21, 1.07; S22, -1.11; S23, -2.09;). This perspective understands the role of social participation in resource governance, and highly advocates for increased pressure from the media on automakers and suppliers (S26, +4).

The ***Policy-oriented*** perspective slightly recognizes the need for and importance of governing mineral extraction impacts (S14, 0.46) and tends to support policies and government-led initiatives to achieve SME. It doesn't prioritize any further technology development of EVs (S2, -1.15; S3, -1.41; S7, -1.54). Respondents think the sustainability efforts in the SC are poorly exercised (S21, 2.71; S23, -1.53; S24, 0.27). They don't expect industrial actors to lead mineral governance actions but firmly call for more serious commitments and investments from automakers (S21, 2.71). Pressure from consumers and the media in industrial changes is perceived as crucial to achieving SME (S26, 1.01; S27, 0.53). Government-led initiatives from consuming countries are largely supported, including coordinating sustainable mineral sourcing (S31, 1.82), funding supports (S32, 1.19), regulatory frameworks (S34, 0.66), and prioritizing SME over EV adoption in policy agenda (S37, 0.52). However, they also show strong concerns if SME policies will discourage the wider adoption of EVs (S36, 2.17).

The ***EV-adoption supporter*** perspective emphasizes EV's environmental benefits (S11, 1.36; S12, 0.77; S16, 1.86) even indicating a slight awareness of related mining externalities (S13, 0.49; S14, 0.37). Respondents highly prioritize the need for wider adoption of EVs over addressing mineral extraction issues (S3, 1.57; S37, -0.54). They are concerned that policy interventions would discourage the wider EV adoptions (S36, 1.37). They are generally satisfied with the current sustainability practices by industrial actors (S23, 0.67; S24, -0.62). They agree that SC partnerships, rather than individual actions, should be established to bring more transparency to mineral extractions (S20, 1.12; S18, -1.78). This perspective is also characterized by strong disbelief in the media's influence, particularly in the role of raising awareness and pressuring governance changes (S25, -1.49; S26, -2.73). Governmental actions are mostly expected from mineral extraction countries (S35, 1.03), while consuming countries are merely expected to be a coordinator (S31, 1.09; S33, -1.29; S32, -0.22; S34, -0.29).

The ***Extractor-focused*** perspective is characterized by a strong dissatisfaction with mining companies' current sustainability practices (S24, 1.82). Respondents recognize the adverse impacts from mineral extractions and the marketed green image of EVs could be deceptive (S13, 0.93; S30, 1.75), but they firmly disagree with the importance of addressing such impacts (S14, -1.56; S5, -1.67). They are of the opinion that extractors should extract resources more sustainably and actively manage associated impacts (S18, 0.81; S19, 0.74). Urging mineral suppliers for sustainable extraction is perceived as critical and should be initiated by automakers (S17, 1.06). Distinctively, respondents highly value the need for consumer participation in pressuring and precipitating changes in the SC (S27, 1.76), while largely oppose the participation from the media (S26, -1.26). Government-led actions are largely undesired with some concerns on the discouraging effects of policies (S33, -1.19; S32, -0.36; S36, 0.84), but regulatory frameworks led by consuming countries to facilitate SME partnerships are supported (S34, 1.34).

In the *Env* group, there is some consensus in terms of a relatively strong concern that SME-related policies might discourage wider adoptions of EVs (S36). The importance of developing lower-impact batteries is also not supported by this group. Their opinions largely differ in terms of consumption impacts and governmental actions, but some of them reach agreements over SC practices and public opinions. Global mineral sourcing partnerships are perceived as necessary (S20) by participants represented by factor 1, 3, 4. The importance of social participation is well understood (29) by participants represented by factor 1, 2, 3, and consumer participation in pressuring sustainable practices (S27) is supported by participants represented by factor 1, 2, 4, highlighting the higher awareness of social participation in shaping the better governance of EV minerals.



Note: C-A interactions: Consumer-Automaker interactions; SME: Sustainable Mineral Extraction; Govt. in C-C: Governments in EV-consuming countries

Figure 26. Distribution of Z-Scores for Factors' Distinguishing Statements in the Env Group

6.4 Discussion

6.4.1 Consumer awareness and perceptions

6.4.1.1 General lack of awareness

The result from the pre-sorting survey indicates that there is a general lack of awareness among consumers about the impacts of EV-minerals extraction, even though consumers with pro-environment motivations have a slightly stronger cognizance of these impacts. This finding is consistent with the notion that end-users remain poorly informed about the impacts of their purchasing decisions (IRP, 2020), which poses a governance challenge in the telecoupled system. The fact that most EV-minerals are extracted in places (e.g., South America, DRC, and Southeast Asia.) distant from where EVs are adopted (e.g., North America and Europe) largely contributes to the lack of awareness. These distant impacts are usually not evident to the consumer since they do not face the direct consequences of their purchase choices (Balvanera et al., 2017). The spatial disconnect also impedes information sharing and creates imbalances in access to information between consumers and the resource-host communities (Brondizio et al. 2009; Eakin et al. 2014). Although recent efforts start to relate the impacts of mineral extraction to the rise of low-carbon technologies (Ali et al., 2017; Agusdinata et al., 2018), relevant news coverage on impacts is still relatively rare compared with those on aspects of technology and finance, adding to the limited access to mining-related information.

6.4.1.2 Evidence of telecoupling components and mechanisms

Having presented the information about mineral extraction impacts, some consumers have started to question the marketed green images of EVs. It appears that these consumers were sensitive to the presented information, and it motivated them to start to recognize such impacts and change their perceptions about EV's overall sustainability. This result indicates the influential role of information that makes the telecoupling and mining outcomes visible to distant consumers, providing evidence of feedback mechanism as suggested by the telecoupling framework (Eakin et al., 2014). These consumers may be more likely to be motivated to respond through change in purchasing behavior or demand changes in policy and supply chain practice, creating important feedback and opportunities for mineral governance. Information dissemination thus is crucial, calling for broad efforts to raise consumer awareness of EV minerals, trade flows, and associated socio-environmental outcomes.

The recognition among the respondents of the complexity in the SC of EV-minerals and its governance suggests that the telecoupling framework is an effective approach to uncover this issue. The results suggest that the sending system and flows are more visible to the consumer. Most respondents understand the role of actors spanning the value-chain of EVs and even multiple stakeholders beyond the direct supply chain (consumers, the media, governments), suggesting the need for a telecoupling view in mineral governance. The importance of collaborative governance is also recognized among respondents. They care about the sustainability practices of automakers and mineral extractors, reflecting the trend of increasing consumer demand for sustainability in SCs (Nichols et al., 2019). Notably, the role of consumer advocacy and social pressure in influencing the performance of the overall SC is well understood among respondents, which may be related to the increasing media scrutiny that has spurred attention to the producer's accountability (Guo et al., 2016). Consumer-driven pressure may play an increasingly important role in catalyzing changes for sustainable mineral governance.

6.4.1.3 Contradictions and cognitive dissonance

Contradictory opinions are found among respondents: the adverse mining impacts were well recognized while at the same time the importance of addressing them was not given a high priority; consumer-producer interactions were not preferred but more consumer pressures on producers for SC sustainability were demanded; policy interventions were anticipated but their potential negative effects on EV adoptions were of a major concern. These contradictions represent some of the hard trade-offs respondents faced, and reflect the tensions and conflicts between energy transition and adverse impacts of mineral extraction. Consumers, informed of the distant mining externalities while also facing the direct air pollution from gas-powered vehicles, are making distinct trade-offs and their priorities may differ from the local communities hosting the mineral mines. The differences in cultural, value, and economic conditions of actors in the telecoupled systems adds to the complexity and challenge for mineral governance (Eakin et al., 2017).

Some respondents who were primarily motivated by environmental benefits of EV were found to be reluctant to acknowledge the potential adverse impacts of those purchases. This phenomenon is relevant to cognitive dissonance theory (Festinger, 1957), which describes the occurrence of dissonant relations among attitudes, beliefs, behaviors that lead to a state of psychological discomfort. A cognitive dissonance is evident when an individual’s behavior conflicts with beliefs that are integral to self-identity. In this case, knowing the adverse impacts of mining caused psychological discomfort to some pro-environment respondents (Evans, 2012), and they generated negative emotions to recognize these impacts (Trudel et al., 2016). The psychological discomfort can motivate changes in behavior and cognition to reduce the dissonance, for instance by trivializing the conflicting belief (Elliot and Devine, 1994), which explains their low ranking on the importance of addressing mining impacts. Such a dissonance has been discussed in other cases, for example, where studies found consumers regularly waste products but also have an aversion to waste (van Herpen and de Hooge, 2019).

6.4.2 Implications for mineral governance

6.4.2.1 Implications from different EV-purchase motivations

Understanding of the perceptions of consumers with different motivations may indicate how consumer groups are going to advocate for change and how improved governance should take into account these differences. Consumers primarily motivated by the technical attributes of EVs may lead the push for technological solutions to manage mining impacts. They are likely to exert pressures on mineral SCs to require more sustainably extracted and sourced minerals, and advocate for policy responses or new governance arrangements in consuming countries to address the impacts. For consumers motivated by financial factors, their awareness can be raised by exposure to information or education campaigns. With an increased information exposure, they may be motivated to exert consumer-based pressure to demand SC sustainability and support governmental actions in consuming countries to guide change.

Caution should be taken when mobilizing pro-environmental consumers, in case cognitive dissonance may generate negative emotions and reduce the perceived importance of impact management. Knowledge dissemination thus should not detract from the positive role of EVs in energy transitions and carbon reduction, but also steer viable ways to reduce or minimize dissonance, such as engaging in actions to pressure SCs for SME, establishment of schemes and responsible sourcing partnerships. Similarly, SC practices should pursue sustainability in mineral sourcing and extraction while not depreciating the positive message of EVs.

The role of consumers in influencing SC practices was widely acknowledged among the respondents, indicating that consumers today are increasingly conscious about their ability to exert pressure to influence SC practices. Sustainable consumption and consciousness can motivate changes along the whole SC, influencing the upstream producers for sustainable production (Taghikhah et al., 2019). Many certification standards are created in response to the growing social pressure to SC sustainability to provide this guarantee. On the other hand, the rise of internet and social media accelerates the information sharing about mining impact and may motivate global movements that can influence policy, consumption, and corporate behavior globally (IPR, 2020). This trend highlights the importance of consumers in stimulating changes in sustainable mineral governance, and the need for extending SC to incorporate consumers.

With the increasing media scrutiny and knowledge dissemination of mineral extraction impacts, consumers are likely to expect producers to demonstrate responsible sourcing and extraction in their SC. The results suggest the current green marketing of EVs could be counterproductive for SC actors as more consumers become informed of mining impacts. The SCs practices of SME did not satisfy respondents who perceived that many of them were exercised for public relations only, implying risks to the credibility, comprehensiveness, and effectiveness of current sustainability practices.

Existing practices of SC sustainability are mostly motivated by managing business risks and maintaining public relations, rather than improved governance for the resource (Sovacool et al., 2020b). Corporate sustainability reporting has been criticized for neglecting local sources of knowledge and practices (Bavinck & Gupta, 2014). It is clear that the social license to operate granted by governments and local communities is not all that is needed; the SC actors need to move beyond social license and encompass a global community of consumers, organizations, and the public. Sustainability practices need to shift to the broader and collaborative goal of sustainable development (IRP, 2020). Suggestions for an improved SC practice may include: context-specific initiatives considering the difference in mineral types and socio-ecological conditions in host environment (Owen & Kemp, 2013); building credible information-sharing systems; public involvement in sanctions to ensure compliance by companies (Acosta, 2013); and improving comprehensiveness rather than information generation (Darby, 2010).

6.4.3 Study caveats

The study results and implications do come with some caveats. The majority of respondents of EV-owners at the Reddit forum are from North American and European countries, which missed out on important consumers in other leading EV-consuming countries, such as China, as well as owners in mineral extraction countries, such as Australia. In addition, cultural, political, and institutional contexts in individual EV market can play a prominent role in influencing consumers' regulatory preferences (i.e., the expectations of what institutions can do) and perceived ability of different groups to react to environmental risks (Kates & Clark, 1996; Parrado, 2018), which was not examined in this study. Despite these caveats, this study still serves as a pilot study to highlight governance challenges in achieving SME and the need for a telecoupling view in mineral governance.

6.5 Conclusion

Grounded in the telecoupling framework, the study uses the Q-method combined with survey questions to reveal a complex picture of how consumers with different purchase motivations view the extraction impact of minerals and its governance for a sustainable and just transition of EVs. More nuanced categories of perceptions were identified, and their implications were discussed. This study found there is a general lack of awareness among respondents about the extraction impacts of EV-minerals, but most of them understand the complexity in the SC and the role of consumers in influencing corporate practices. Contradictory opinions are widely found, reflecting the tensions and conflicts between energy transition and the impacts of mineral extraction.

This study thereby provides some implications on improved governance of EV-minerals from a consumer perspective: (1) the differences in purchase motivations should be considered in deciding what consumer groups are going to be advocates for change, (2) cautions should be taken in mobilizing pro-environmental consumers to minimize the negative effects of cognitive dissonance, (3) the telecoupling view is strongly suggested, (4) knowledge dissemination and pursuing sustainability in the SC should not detract from the positive roles of EVs, and (5) the SC should shift to a broader goal of sustainable development and encompass a global community of consumers, organizations, and the public.

In subsequent studies, an extension of Q-method to include major EVs markets such as China and Japan could reveal different motivations and hence drivers for supporting SME. Further considerations of political culture and institutional setting may provide more realistic insights for informing design of interventions. Lastly, existing methodologies are currently insufficient in capturing the full suite of social, environmental, and governance concerns as well as the full interdependencies among actors across EV supply chain, consumers, and policies (Bazilian, 2018). In this context, although the rights and interests of indigenous communities affected by mining have been duly acknowledged (Agusdinata et al., 2018), their involvement and inputs in the process are still lacking in a meaningful and systematic way.

CHAPTER 7

CONCLUSION

7.1 Summary of Findings

To better understand the telecoupled impact of critical mineral extractions on local socio-ecological systems and its governance, this study sought to meet three specific objectives, using the case of Li-mining in Salar de Atacama (SdA), Chile:

1. To understand the telecoupled impacts of Li-mining activities on the local socio-ecological systems, as well as the relevant interdependencies occurring at multiple temporal and spatial scales.
2. To investigate the role of uncertainties in the focal resource in affecting the emergence of threshold that makes telecoupling visible to decision-makers.
3. To explore perceptions of end-users who own minerals-enabled green-tech products about their awareness of minerals extraction impacts and possible governance actions to regulate extraction towards sustainability.

In addressing the first objective, based on empirical studies, the analysis established a systematic representation of interdependency between social and natural systems around Li-mining in SdA, and then tested these interdependencies using various data and tools. It revealed that local livelihoods become closely connected to the Li-mining operations through three major mechanisms: (1) shared water system, (2) linkage of local economy (income, jobs, other economic opportunities), and (3) the governance of common resources. Through sharing the water system, local livelihoods are closely tied to the water use behaviors of Li-mining due to the ecological significance and scarcity of water resources in this place. The excessive water consumption by the mining industry, therefore, raises the most concerns as to their livelihood sustainability. From the aspect of economic linkage, local livelihoods are also tied to the migrant laborers in other regions. The expanding mining industry has brought a vast array of commuting laborers, who have limited contributions to the local economy, causing imbalanced migration flows. Meanwhile, the increased job opportunities were not assigned to the locals but raised the living expense for local residents. In terms of resource governance, companies' sustainability reporting has increased and diversified in recent years, driven by the pressure from global investors and end-users. However, relevant anti-mining social movements have also increased in intensity and scale, reflecting the governance challenges as to the lack of trust, opaque and untransparent information, and poor implementation of CSR efforts.

The second objective was set on the basis of the findings in the first aim, focusing on the most concerning water resources, to identify the root cause of governance challenges in the case of Li-mining. The modeling and analyses revealed that material uncertainty of the groundwater causes a time delay for the local communities to get timely feedback on the state of the resource, leading to a mismatched evolution of dynamics in both social and ecological systems. Such material uncertainty can lead to contested views and confusions on the dynamics of subterranean water flows and how they respond to disturbances, which may obscure the emergence of a threshold that makes telecoupling visible to decision-makers. Currently, the locals have been overwhelmed by the currently increasing social consultations for new mining projects. Without properly managing the uncertainty of water resources, governance efforts (e.g., social consultation) can be counterproductive and even enhance concerns on the extent and exact impact of water extraction on unseen aquifers and pastures in their territory.

Supplementing the analyses of governing telecoupled impacts of Li-mining, the final analyses sought to identify governance opportunities from the end-users of green technologies in the sending system considering the growing trend of sustainable consumption. It revealed a general lack of awareness among consumers about the mineral mining impacts embodied in their green-tech products, as well as the tensions and conflicts between the imperative of energy transitions and the reality of adverse mining impacts. The analyses identified the wide acknowledgment of sustainable consumption and consciousness among consumers, implying opportunities to motivate changes along the whole mineral supply chain. While the differences in purchase motivations should be considered in deciding what consumer groups are going to be advocates for change. Moreover, the analyses also justified the influential role of information that makes the telecoupling and mining outcomes visible to distant consumers, calling on the need for a telecoupling view in sustainable mineral extraction governance.

7.2 Significance of Research

7.2.1 Contributions and implications

This dissertation integrates knowledge from several disciplines and brings several approaches to bear, including sustainability, social science, remote sensing, environmental studies, socio-ecological systems, and system dynamics. The issue of mineral extraction is a complex problem, especially when it links to low-carbon policies and clean technologies. It requires an interdisciplinary investigation to understand its comprehensive implications from a system view. Results from this study contribute to filling the research gap that the social and ecological implications of the anticipated growth in Li-extractions have not been acknowledged and systematically studied in academia. Specifically, this dissertation has made contributions that have implications in substantive knowledge, theory, methodology, and policy, as summarized in Table 10.

Table 10. Summary of Knowledge Contributions

Domains	Contribution of this dissertation
Substantive knowledge	• Holistic understanding of Li-mining impacts • Consumer perceptions of mining impacts embodied in green-tech products
Theory	• Telecoupling framework for critical minerals • Add to the telecoupling framework by exploring how the uncertainty of focal resource affects the emergence of governance threshold
System modeling method	• An agent-based model for mining-community-aquifer interactions
Policy and governance	• Benchmark of Li-mining impacts in the Salar de Atacama • Management of uncertainties in groundwater and building resilience of SES • Which consumer groups are going to be advocates for changes for improved governance

In substantive knowledge domain, this research contributes to the few comprehensive studies examining the socio-ecological impacts of Li-mining. It identified that the local livelihoods are interdependent with Li-mining activities through the shared water resources, linkage of local economy, and the common governance of resources. These findings are consistent with the contested water use among mining, ecosystem, and livelihoods in Romero et al. (2012) and the complex 'partnership' between mining companies and the local communities in Babidge (2016). This study moves beyond the traditional and separate impact assessment of a social system or natural system through the life cycle approach (e.g., Stamp et al., 2012; Egbue 2012). It not only explores the impacts on social and natural systems but also identifies the linkages and feedback between systems to offer a holistic and systematic understanding of impacts.

In addition, this research also sheds light on consumer perceptions about the upstream impacts of green-tech products. Adequate academic interests have been devoted to the promotion of sustainable consumption or green-tech adoption, such as studies about consumer traits of sustainable consumption (e.g., Qu et al., 2015) and adoption behaviors of green-tech products (e.g., Liao et al., 2016). However, to date, understanding perceptions about the externalities of green-tech products has not attracted enough attention. This research found that consumers today are increasingly conscious about the footprints of a product as well as their ability to influence supply chain performance and policy, calling for more extensive research efforts for more grounded insights for informing the design of policy interventions.

In terms of theory contribution, telecoupling framework has been applied to a broad set of studies across spatial scales, including land-use and land-change science (Eakin et al. 2014; Friis et al., 2015; Friis and Nielson 2017), animal migration (Hulina et al. 2017), species invasion (Liu et al. 2013), and renewable energy system (Rulli et al. 2019). This research contributes a telecoupling framework for critical minerals and provides evidence of telecoupling components and feedback mechanisms as suggested by the telecoupling framework (Eakin et al., 2014). Additionally, this research adds to Eakin et al.'s (2014, 2017) studies about thresholds in telecoupled systems, which once is crossed, telecoupling can become visible to actors as a potential governance concern. This study explores a special case where the contested focal resource is groundwater, which is inherently different from land resources that are directly visible as largely studied in previous works. The main finding is that the material uncertainty of focal resource may obscure the emergence of threshold and thereby delays feedbacks to governance changes to occur.

In system modeling method, this research developed an agent-based model (ABM) for mining-community-aquifer interactions, which allows the prediction of social and ecological responses under multiple future mining scenarios. The ABM developed in this dissertation is publicly available[15] and can be adapted to other brined-based Li-mining operations in other sites by entering site-specific social and hydrological inputs. The model also has the potential for coupling with more complex climate models, such as CMIP6 (https://pcmdi.llnl.gov/CMIP6/) and incorporating new components, such as an early warning mechanism or a social network typology, to test the efficiency of various pathways to build resilience of SES in SdA.

The results of this research are also envisaged to have three major policy implications. First, governance authorities in Chile recently have shown a growing interest in regulating the hydrological balance and the mining-associated impacts in the SdA basin. However, these efforts have been hampered by the lack of reliable data and information of impacts (DGA, 2012). This dissertation provides a benchmark for the socio-ecological impacts of Li-mining in SdA which can facilitate the decision-making for new mining projects, environmental inspection, mining concession, and permit issues. The second implication highlights the urgency of managing groundwater uncertainties and building system resilience in mining governance practices. It suggests the need for a

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[15] Model of this study is accessible from: https://www.comses.net/codebases/553e8c66-1a3f-48f6-9420-be80c66e0398/releases/1.1.1/

more extensive impact monitoring and disclosure system, community involvements with accessible technical assistance, and resilience development pathways customized to fit with the local culture. Lastly, the third implication relates to consumer advocacy for changes in mineral governance. It recommends that the differences in purchase motivations should be considered in deciding what consumer groups are going to be advocates for change, and knowledge dissemination about externalities should not detract from the positive roles of green-tech products.

7.2.2 Societal significance

This study anticipates achieving broader impacts by examining the new socio-ecological challenges brought by low-carbon technological development, which may help provide a scientific basis for global decision-makers in the lithium and battery-related industries, national policymakers, and international organizations. It is crucial to address the interlinkage between sustainability policies being promoted and their potential impacts in geographically distant areas. Neglecting this intercorrelation could lead to significant socio-ecological costs that may offset the benefits gained through policy mandates. Such policies promoting Li-based clean technologies have been implemented globally. For example, relevant policies of EVs include subsidies or rebates for consumer's purchase as tax credits, mandates in the governmental purchase of EV, tightened fuel economy standard, the national target of EV purchase, and other incentives like access to HOV lane. These policies have quadrupled the Li-mining scale in the SdA, but the consequential negative impacts have not been understood, let alone put on policymakers' managerial agenda. This study contributes to filling this important gap, and the resulting assessment can shed light on the adverse impacts that global policymakers should consider in managing battery-based clean technologies to be truly sustainable.

This dissertation help explain why these impacts are not on the managerial priority of policymakers. Although the impacts of Li-extraction are creating “functional pressure” to some of the actors in the Li-extraction system in Chile, including communities, politicians, mining managers, and the general public. On the contrary, the pilot study of consumers' perceptions reveals that actors in the consuming system still have little knowledge of these impacts, leaving no incentive for the dominant actor to modify its policy priorities. Importantly, the Q-sort practices with consumers did spark some opportunities to motivate changes in resource governance. It justifies the existence and function of information as an intangible linkage in telecoupled systems, and when presented to sensitive consumer groups, it may motivate them to recognize such impacts and put pressure on private sector actors for sustainable governance of impacts. Private sector actors (e.g., automakers) nowadays, who are increasingly susceptible to such pressures in a competitive market, are likely to initiate changes in the supply chain towards sustainable governance of resources.

Meanwhile, promising efforts are made towards adding sustainable mineral extraction to the global policymakers’ agenda, despite such interests have not translated into policy. European Union, for example, is considering mandatory human rights due diligence laws to compel businesses to assess the social and human rights impacts if they’re extracting minerals (Bainton et al., 2021). Actions like this have not emerged in other sending countries (e.g., China, US). This difference might imply the variance of thresholds for different sending countries, in which they respond to the feedback flow about the mining impacts in receiving systems.

Published studies of this dissertation have already achieved some of the impacts mentioned above. The study of socio-environmental impacts of Li-mining received broad media coverage (e.g., Reuters, Mongabay, etc.), which helped put pressure on consumer-facing industry players (e.g., automakers like Daimler, Mercedes-Benz) to require its upstream suppliers showing a sustainable manner of extraction of lithium, including the Li-extraction company in SdA. Studies in this dissertation also have recently been cited in a court document in Chile to reject the compliance plan from the Li-extraction company in SdA, which led to a newly deployed online mining monitoring system and an updated sustainable mining plan.

From a localized perspective, this dissertation is also expected to achieve broader impacts for the frontline communities in the Li-extracted place. Tensions between the Li-mining company and local communities have escalated rapidly in recent years, stimulated by more mining permits issued by the regional authority. Social movements against Li-mining have mobilized from local strikes to fierce national protests. This research contributes to explaining this tension and the reason why it escalated. The model developed in this research also has the potential to serve as a participatory tool for local stakeholders to understand the various future socio-ecological outcomes of mining, thereby informing regional decision-makers to address the tension and better manage the world's largest lithium reserve with its neighbors. The results and analyses of this dissertation have also been summarized and translated into local language that are ready to share with stakeholders in SdA (see appendix C).

7.3 General Applicability of the Framework Typology

As illustrated by this dissertation, the telecoupling framework is appropriate and strongly needed to reveal the essential components, flows, actors, and feedback in the case of Li-mining in SdA. Most importantly, the framework used in this research is applicable to the existing or new Li-extraction operations in other places, and to the extraction issues of other critical minerals whose production are also largely driven by the global low-carbon transition.

Aside from the SdA in Chile, Li-mining projects are mounting up in other salt flats of the ‘lithium triangle'. Argentina, for instance, has more than 15 salares with increasingly expanding Li-mining operations, posing a great socio-ecological threat to the frontline communities. However, such telecoupled impacts have never kept up with the expansion of mining operations. These Li-mining sites and communities share similar geography, demographics, history, and culture with the case of SdA, implying the generalizability of results in this study to these sites, and the applicability of this telecoupling framework to reveal other impacts, independencies, and feedback.

The framework typology is also applicable to other critical minerals that are rapidly driven by the low-carbon policies, including lithium, nickel, cobalt, graphite, manganese, rare earths, copper, and aluminum. This dissertation conceptualizes the telecoupling components and flows in a way that is shared by other critical minerals used in green technologies. Even with the different mining impacts across minerals in the receiving system where the minerals are extracted and impacts are happening, these critical minerals share a similar sending system and the connecting flows. Despite the differences across minerals as to local contexts, policies, mining technologies, and associated mining impacts, this framework has enough flexibility to allow investigations tailored to local contexts thereby revealing the major components, flows, actors, and feedback for each case of mineral extraction, creating opportunities for innovative governance solutions.

7.4 Limitations and Future Directions

As previously discussed following the results in Chapters 4-6, this research does come with some limitations which may imply the potential directions for subsequent efforts in the future. Firstly, this study did not incorporate a full set of impacts due to the restriction of data availability and also excludes impacts that are not quantitatively measurable, such as social cohesion and indigenous culture and rights. Future efforts are needed towards enhancing the transparency and traceability of impacts disclosed by mining companies, which may include developing a consistent framework for impact disclosure along with policies or incentive mechanisms that stimulate such disclosure. Besides, future studies around the impacts of social cohesion, values, and culture and rights of indigenous people are also strongly needed. The growing extractive-based economy is gradually changing the traditional rituals, communal works, and values of indigenous people, especially the younger generation, intensifying the contested values between generations (Babidge, 2013, 2016). And the investment-focused community development efforts, exercised by mining companies to acquire social license to operate (Prno and Slocombe, 2012), can affect the locals in complicated ways such as increasing disputes among communities and weakening social linkages in some cases, raising questions around the measures of corporate social responsibility.

To incorporate a full set of impacts in future works, a combination of life cycle sustainability assessment (LCSA) (Zamagni 2012) and the sustainable development goals (SDGs) (UNDP, 2016) from the United Nations may be a promising framework to take into account the impacts of social cohesion, values, and culture and rights of indigenous people. A growing academic interest has shown attempts to integrate LCSA to SDGs to provide a comprehensive impacts assessment (e.g., Zeug et al., 2021) and even for the mining industry (e.g., Agusdinata et al., 2021). Some indicators in LCSA (e.g., respect of indigenous rights) and their links to SDGs (e.g., SDG 11.4 Strengthen efforts to protect and safeguard the world's cultural and natural heritage) could provide valuable insight on social impacts that are not quantitatively measurable.

Secondly, the agent-based model developed in this study is a high-level abstraction of the mining-community-resource interactions in the SdA basin. Other important factors, that are composed of the uncertainties of mining-community-aquifer relations, such as the cultural relations with water and pathways, are not explicitly designed or could not be translated into models, requiring future efforts with other methods or in broader disciplines. Potential efforts might be made towards including a layout of the agent's social network in the ABM to represent the ties of values within indigenous groups to understand the collective actions (e.g., mobilizations, Srbljinovic et al., 2003), or exploring the change of agent's cultural value attached to water following constructivist theory (i.e., learners construct knowledge rather than just passively take in information, Elliot et al., 2000) as seen in some ABM studies which adopted this theory to the issue of collective identify (e.g.,Lustick 2000).

Future works may also focus on incorporating some resilience-building pathways or coupling the current model with climate models. In particular, increasing early warning and awareness, for instance, could be incorporated in the future model, in which companies share their projections of impact and potential warning signs with local people, thereby altering the reference point for people's sense of change (Babidge et al., 2019). Existing early warning systems, such as FEWS on famine (https://fews.net) or flood (Perera et al., 2020) have been developed for various sustainability topics and provided decision support. Access to timely information on mining impacts could be added to reduce uncertainties, in which people are no longer subject to the changes in their location but have a broader understanding of the whole basin. Climate uncertainties could also be included by coupling our model with climate models (i.e., CMIP6, https://pcmdi.llnl.gov/CMIP6/) to understand how climate change contributes to socio-ecological changes.

Lastly, serving as a pilot study, the methodology and scope adopted in consumer perception research restrict the ability to generalize the results to a broader scale. Future works may consider use surveys to incorporate larger consumer groups with diverse profiles in major consuming countries and even extends to include users of green technologies in mineral extraction countries, such as Australia and China. Therefore, more generalizable insights and policy implications can be derived. In addition, this research majorly targets the receiving system and the component of consumers in the sending system, while not providing enough investigation on the role of other components, such as the supply chain network and players, technology producers, and global policymakers. Recently, with the increasing pressure from consumers and investors, industry-led initiatives and actions are emerging to demand a more sustainable and responsible form of extraction from upstream. Future research may also explore the role of supply chain networks and practices in shifting the critical mineral extraction towards a more sustainable future, as well as how to incentivize supply chain players.

The connection of indigenous people in the SdA (Atacameños people) to their relationship with natural resources and biodiversity, although not specifically studied in this dissertation, is important in understanding the conflicts between local communities and mining development for future research. Before mining development, Atacameños people lived predominantly as transhumant pastoralists and the salares were once their pastoral lands and the breeding site for Andean flamingos whose eggs and feathers were harvested by them (Babidge, 2016). However, afterward, the development of mining industry took away their old pastoral lands and disturbed the habitat of flamingos by production, creating discontinuity of historical livelihoods. Historically, Atacameños people value their relationship with ancestor mountains, the precious water they hold, and the wetlands fed by precious water resources (WWF, 2001). Their perception of resources, especially water, should be understood as living beings or "essence of life and livelihood" against the value of water for industry in terms of marketable commodity (Babidge, 2016). This meaning of water is consistent with the ecosystem services of natural resources proposed by TEEB (2010) (i.e., provisioning, regulating, cultural, and support services), in which cultural services take account of the spiritual, religious, inspirational, and sense of place value of resources.

Future efforts should also make towards understanding the threshold for the social-economic system in the sending systems for the emergence of governance actions.

Thresholds in environmental systems are of high-interest and frequently studied in terms of modeling and predicting tipping points and ecological regime shifts for water resources or climate (e.g., Jiang et al., 2018; Carpenter and Brock, 2006). Social tipping points (STPs), on the other hand, which is defined as “the point or threshold at which small quantitative changes in the system trigger a non-linear change process that is driven by system-internal feedback mechanisms and inevitably leads to a qualitatively different state of the system, which is often irreversible (Milkoreit, et al., 2018)”, are limitedly modeled or predicted. Castilla-Rho et al., (2021) used an ABM to model STPs in groundwater management and revealed tipping points where social norms towards groundwater conservation shift abruptly with small changes in cultural values and monitoring and enforcement provisions. Future research may explore the STPs in sending countries of this issue and how the cultural values and social, economic, and political features of each country would affect the emergence of STPs.

7.5 Reflection

This research is challenging as to the process of empirical data collection as well as the modeling method. Stakeholder meetings and unstructured interviews were conducted by Dr. Agusdinata (Chair of the committee) and Dr. Romero (member of the committee) in 2018 to understand the local concerns about impacts from Li-extraction in SdA. During the meetings and interviews, the language barrier was one of the largest challenges. The large amount of information that was communicated in Spanish was not able to be fully translated to English on-site and had to be translated later and missed the opportunity of follow-up conversations. The language barrier was also consistent throughout this study. It required me to continuously translate news, literature, website, and data from Chilean sources to English and kept a good record of them.

Collecting empirical data could be crucial to the success of this research, and another field trip was fully designed and planned in March 2020 to generate a systematic understanding of the diverse local opinions around Li-mining developments in SdA. To prepare for this trip, I am aware of the importance of building empathy with the local communities by understanding what they have been through and the difficult situation they're facing. With that in mind, research questions were designed and translated into a form that is understandable by the locals, and a presentation was also prepared in hope of acquiring permission from the local communities. However, the planned trip was canceled due to the global outbreak of COVID-19, which significantly affected the original design and structure of this dissertation. Alternative efforts were also explored to achieve the same goal to collect empirical opinions, such as using online interviews or conducting the initially planned research through online platforms. However, none of them was practical due to the remoteness of the area, the severity of the pandemic, and the high technical requirement of these alternatives. This little story only illustrates the tip of a substantial iceberg, and more complex and unique challenges could happen in the practice of conducting such a field trip.

At the method selection stage, most challenges came with the lack of data of good quality. After exploring the available methods and tools for impact assessment (e.g., life cycle approaches, multi-variate regression, etc.), I realized that generating a long-term analysis of the impacts and proving the causality of socio-environmental conditions and mining operations were not possible. This effort requires a diverse range of good-quality data on social status, economic indicators, and environmental monitoring data. However, the publicly available data was mostly patchy and inconsistent in either spatial dimension or temporal scale. Under this situation, remote sensing data, with the help of other socio-ecological data, was employed under a system approach to provide a relatively comprehensive overview of Li-extraction impacts for the period of 2002-2017. The process of research is always a trial-and-error, but the most important thing is that when you hit a roadblock, do not get discouraged. Instead, try to understand the limitations inherent in the problem, and your persistence may lead you to make a future contribution to the larger body of research.

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APPENDIX A

ODD DESCRIPTION OF ABM

1. Purpose

Global demand for lithium as a critical mineral used in low-carbon technologies (EVs, battery storage, etc.) has been largely driving the raw material extraction activities in Salar de Atacama, Chile, where most of the lithium has been mined. The Li-extraction industry's fast expansion has spurred and intensified the existing conflicts between local livelihoods and mining companies. Based on the long-term fieldworks by Babidge et al. from 2010 to 2019, this model is developed to understand how the escalating scale of Li-mining activities (brine pumping), particularly in Salar de Atacama, Chile, where drought is prevalent, depletes groundwater resources and create stresses for local livelihoods, and present potential future socio-ecological impacts from various mining projection scenarios.

The local population has been concerned with the potential impacts of extractive industries near their communities. According to Babidge et al. (2019, 2020), community members feel "overburden" about mining projects and expansions (i.e., seeing trucks transporting brines back and forth from mining sites), and perceive the drying vegetations in regular pastoral lands and increased population in their community are negative effects from the Li-mining industry. Their interactions also include financial supports from mining companies in exchange for community acquiescence to extractive activities (Babidge, 2020). The model is designed based on these interactions between Li-mining companies and the locals to explore the temporal and spatial dynamics of groundwater and social stress experienced by local residents – particularly mining-induced changes caused by aquifer depletion, population growth, and mining-related activities.

2. Agents, state variables and scales

2.1 Agents and state variables

The model has three major types of agents: (1) Community members, (2) Communities, (3) Li-mining companies. The graphic representation of agents is shown in Fig A1, and parameters related to state variables are listed in Table A1.

Community members (farmer shape, Figure A1) are characterized by five state variables: *spatial location, drought-stress, population-stress, mining-stress,* and *total stress index*. New people enter the basin each year, and community members move each day randomly (i.e., for working, herding, guiding, etc.) from their community to any location within the modeled basin with a distance smaller than 15km. *Drought-stress*, *Population-stress*, and *Mining-stress* are three experienced major changes related to Li-mining activities modeled in the area, and they are all normalized into a 0-1 range according to its initial level. *Drought-stress* represents how community members perceive the changes of vegetation health in their adjacent area. This variable is different for each community member because it depends on the largest drawdown in an area the agent visited during the daily movement. Agents start to notice the drying of vegetation when groundwater declines over 1m (Table A1), and this variable gradually increases as dryer conditions (larger drawdowns) are perceived. *Population-stress* represents the stress from an increasing population influx related to mining activities, such as contractors and miners. This variable describes how community members perceive the changes in community population compared to its initial population size, and it gradually increases as more people in the community. *Mining*-stress represents the stress caused by increasing mining activities in agents' adjacent areas, so it rises with the increase of pumping and the closeness of an agent to mining wells. This variable also captures mining-related aspect from the indigenous culture or identity in the area (i.e., knowing the fact of ongoing mining makes the agent feel stressed).

Total stress index summarizes how each agent experiences mining-induced changes differently by summing the weighted results of drought-stress, population-stress, and mining-stress. This variable also incorporates a weighted relief effect in stress brought by the company's financial compensation. The weights of stressor and the relief represent how each agent consider the importance of each source of stress and compensation differently. The values of weights are assigned randomly through a stochastic process to capture the dynamics in values of the local population.

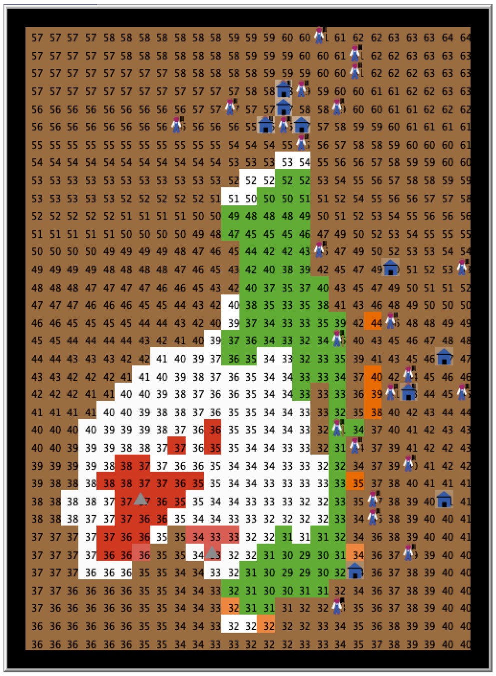


Figure A1. Model Interface View, Including Agents and Specification of Groundwater Model

Communities (house shape, Figure A1) are characterized by three state variables: *spatial location*, *community population*, and *the number of reported stresses*. Communities have a fixed spatial location based on its geographic coordinates. With new people entering the area each year, *the community population* reports the total population belonging to each community accordingly. Communities also hold monthly meetings during which the total reported cases of stress are summarized. *The number of reported cases* represents how many cases claiming stress being reported to the community in a month, which accumulates daily to the first day of the next month and then returns to zero.

Li-mining companies (grey triangle, Figure A1) are characterized by their *spatial location* and *the total pumping rate of its wells*. These agents are immobile, pump throughout the year, and also decide when to compensate communities once the social stress is high. *Pumping rate* of its wells is determined by the historical record of pumping (Table 1) with seasonality variation using a sinusoidal pumping schedule peaking at the beginning of January (southern hemisphere summer), as shown in the following equation:

$$Q = Q_{base} * (1 + \sin\left(360° * \frac{(t+81.75)}{365}\right)) \tag{A1}$$

Where Q and Q_{base} is in m^3/day and *t* is in days ($0 < t < 365$), and Q_{base} is from historical record of pumping (Marazuela et al., 2020).

Table A1. Overview of Parameters, Value, Explanation and Calibration of Parameters in the Model

Agent type	Parameter	Value	Explanation/Justification/notes
Mining companies	Annual average pumping yield (Q_{base})	Yearly values from 1994 to 2018	Extracted from Fig 4 in Marazuela et al. (2020)
	Compensation level	SQM: 2% ALB: 3.5%	Percentage of sales (mining products) invested for community development, based on SQM (2010-2019) and Albemarle (2007-2019).
	Threshold of compensation	SQM: 1/3 ALB: 2/3	SQM start to compensate when 1/3 communities are stressed.

			ALB start to compensate when 2/3 communities are stressed. These values are calibrated based on the actual year each company starts signing agreed compensations to communities (SQM starts in 2010, ALB starts in 2016).
Community members	Initial total population (modeled)	29	Total population in SdA commune is 2917 in 1994. For modeling conveniency, initial population is proportionally downscaled to 29 agents in the model (INE, 2017)
	vegetation drying depth	1m	Drawdown level that agents start to notice the drying of vegetations (e.g., defoliating, wilting, etc.). Desert shrub root depth is averagely around 0.5m (León et al., 2011); A mature Populus deltoids stand with a rapid and sustained water table decline (≥1 m) over 1 week, can cause leaf desiccation and branch dieback (Naumburg et al., 2005; Scott et al., 1999)
	Daily movement distance	15km	The distance community member agents can move each day. Estimated based on the study of community daily lives in Babidge et al. (2019)
	Threshold of stress	0.5	Threshold of total stress index for community member agents to feel stressed. This value is calibrated from 0.3, varied by 0.05 each simulation, to match the actual year when the first community (Peine) started feeling stressed.
Community	Threshold of community stress	30	The community is stressed if more than 30 times community members reporting feel stressed in each month. This value is calibrated from 5, varied by 5 each simulation, to also match the actual time when the first community started feeling stressed and the time and number of communities participated in protests in the most recent anti-mining events in October 2019 (Reuters, 2019).
	Number of communities (modeled)	9	A total of 16 communities living in the basin and 9 clusters of communities are modeled for conveniency, including town of SdA, three small communities clustered close to SdA, Toconao, Talabre, Socaire, Camar, Peine.

2.2 Environment and spatial units

This model builds on the groundwater component of the FlowLogo model using a 2D finite-difference governing equation of groundwater flow by Castilla-Rho et al.

(2015) and then parameterized and calibrated with hydrogeological inputs from a site-specific 3D-groundwater study from Marazuela et al. (2019a, 2019b), as detailed in Table A2. Model represents an unconfined aquifer bounded by no-flow boundary cells at all boundaries (*black cells, Figure A1*). The local landscape is composed of Salars, wetlands, and soils. The location and extent of Atacama salt are represented by white cells in Figure A1. Wetlands on the eastern boulder of Salar are represented by green cells with featured evapotranspiration rates. Brown cells represent soil lands surrounding the Salar. Numbers of each cell represents the initial groundwater heads in [meter]. The ariel recharge on each cell is modeled with a measured recharge map in [m/day] and is modeled with seasonality variations (peaking at southern hemisphere winter), as shown in equation (A2). Since significant rainfall events occur in March in the basin (Barrett et al., 2016), a random significant rainfall event in March is also added to model at the East or North each year. Model cells are defined primarily by one state variable: *drawdown*.

$$R = R_{base} * \sin\left(360° * \frac{(t-81.75)}{365}\right) \tag{A2}$$

Where R and R_{base} is in m/day and *t* is in days ($0 < t < 365$), and R_{base} is from the annual recharge map extracted from Marazuela et al. (2019b).

Brine pumping wells owned by Li-mining companies are represented in red for SQM and light red for Albemarle, and freshwater wells are in orange for SQM and in light orange for Albemarle (Figure A1). The well cells are featured by two state variables: pumping rate and drawdown. Pumping rate is determined by the historical record of pumping with seasonality variation as explained in Section A2.1 and Equation (A1). Drawdowns for wells at each timestep are also calculated using FlowLogo.

Table A2. Hydrogeological Inputs Used in this Model

Hydraulic parameters	Modeled name	value	Source
Hydrological conductivity (m/day)	K-input	Map of K	Fig 4 and Table S4 in Marazuela et al. (2019b)
Aquifer-thickness (m)	Aquifer-thickness	30	Fig 3 in Marazuela et al. (2019a)
Evapotranspiration rate (m/day)	ET-input	Map of ET	Table 2 in Marazuela et al. (2019b)
Initial hydraulic head (m)	Initial-head	Map of head	Fig 7 in Marazuela et al. (2019a)
Areal-recharge (m/day)	R-input	Map of ET	Table 2 in Marazuela et al. (2019b)

2.3 Spatial and temporal scales

Each grid cell represents an area of 3km * 3km, and the modeled landscape covers a 75km * 105km basin using 25 * 35 cells. The hydrogeology is composed of an unconfined aquifer with an imported map of K values for each cell and Sy= 0.1. The baseline model uses a transient one-day time step, and simulations extend for 25 years from 1994 to 2019, and future scenarios run for 10 years from 2020 to 2030. The model runs 20 times for the baseline simulation and each scenario, and results are averaged for analysis.

3. Process overview and scheduling

Model starts with only groundwater components for five years of initialization to stabilize the groundwater movements caused by natural processes. The social system is then initialized and added to the model in the fifth year (*Year = 1994*) since the mining activities are largely started in Salar de Atacama at that time. The base model simulates the interaction of mining activities with the groundwater system and local livelihoods for the period between 1994 and 2019. Scenarios of various mining projection plans are modeled from 2020 to 2030, which are elaborated in the sub-model section. More details about process and scheduling are sketched in Figure A2, which summarizes the scheduling of events and major calculations.

At the beginning of each year, new community members, proportional to the population statistics in the area, enter the basin. Meanwhile, mining companies update the pumping rate of their brine and freshwater wells. At this point, each community member agent starts the daily movement to any location within 15km from home, and stresses (*drought stress, population stress*, and *mining stress*) for each agent is assessed based on the location the agent moved. The total stress index is then assessed according to the relative importance of each stress perceived by the agent (*weight*).

On certain days of the year, environmental inspections or expansion requests by mining companies are added as exogenous events to the model. During environmental inspections, the largest drawdown in the basin is reported to all community members, thus the perceived drought stress and total stress index for each agent are changed accordingly. During the days when mining companies are requesting to expand mining quota (in [L/s]), the requested amount of quota will be reported to all community members, and the perceived mining stress is changed accordingly as well as the total stress index.

Each community member agent can report to its home community at the end of each day if the agent feels stressed by the overall impacts of mining (*Total-stress-index >= 0.5*). At the beginning of each month, each community holds monthly meetings to discuss mining-related stress reported in the last month (*count the reported case of stress*). If averagely, there were cases reported to the community every day in a month

(*Stressed-cases >= 30*), this community agent is considered as stressed and would hold a quarterly meeting with mining companies.

At the end of each quarter, mining companies hold a meeting with stressed communities (*community agent with community-stress? = True*). When there are more than three communities stressed, one company agent (SQM) will start compensating members in those stressed communities (Albemarle starts compensation when stressed community >= 6). Once the compensation starts, each community member agent's total stress index is updated accordingly to incorporate the relief effect from compensation.

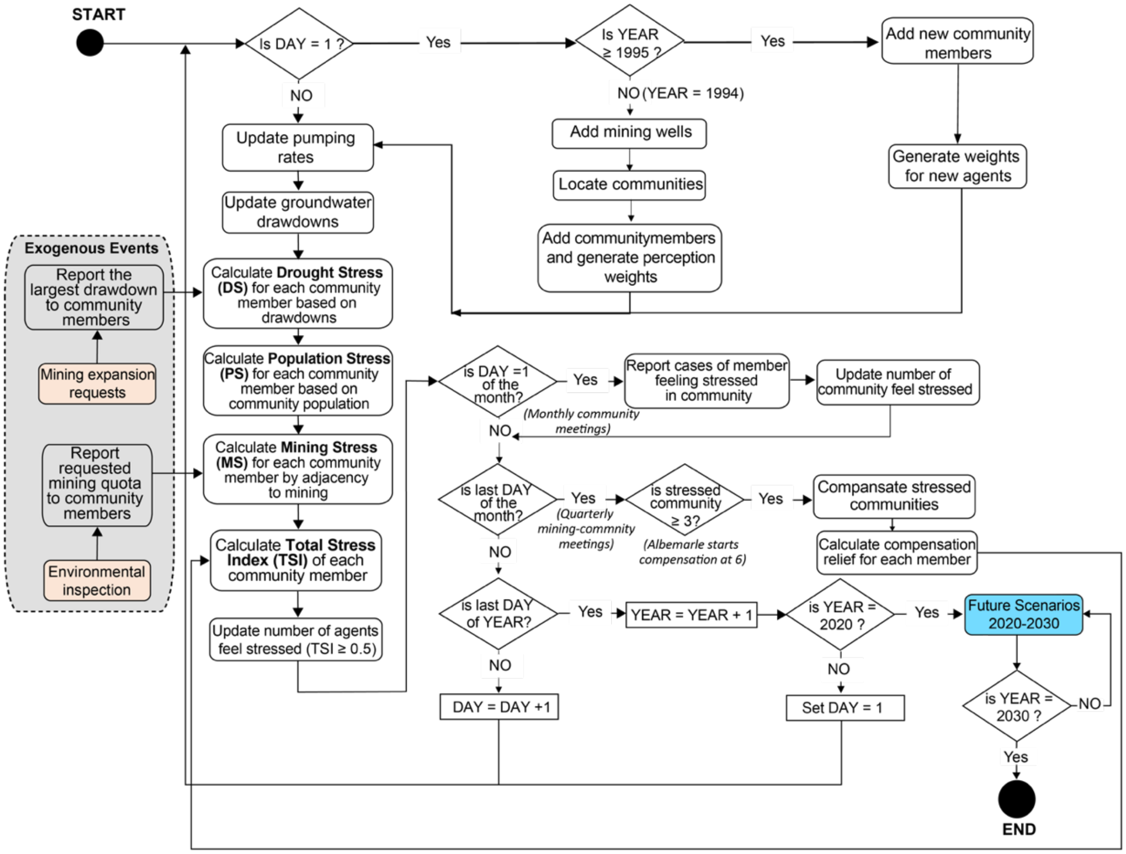


Figure A2. Flowchart of the ABM Showing the Scheduling of All Major Events and Calculations

4. Design concept

Emergence. Dynamics of stress experienced by local communities emerge from the pumping behavior of mining companies and the behavior of community individuals. Non-linear changes in mining companies' pumping rate affect the groundwater system in complex ways, generating signals on the landscape with delay, informing local individuals about the state of the system with respect to its initial state. Local individuals receive and interpret these signals differently according to the agent's behavior and value, and exogenous events added to the system also affect the interpretation of these signals, altogether generating an emergent property of the system.

Adaptation. Mining company agents have the adaptive trait of compensating stressed communities when social stress is relatively high, which directly mitigates the social costs for future mining.

Fitness. Fitness-seeking is not modeled explicitly in this model.

Prediction. Agents in this model have the memory about the initial state of system, which is used as a reference point for agents' sense of changes, but they do not have the foresight to predict future conditions.

Sensing. Community members perceive the largest drawdown among the neighbor of cells they visited, which they use to calculate drought stress. After they return home, they perceive the number of individuals in the home community, which they use to calculate population stress. They are also assumed to know the total production level by mining companies and their distance to mining facilities to calculate mining stress.

Interaction. Community members communicate directly with their home community by reporting their stress status. Communities interact with mining companies by reporting the overall status of stress in community. Mining companies interact with community members directly via compensations only when certain number of communities are in stress. Agents of the same type are assumed to have no direct interactions in the base model.

Stochasticity. Is explicitly used to model the community member agent's values on different types of stress and the effectiveness of compensation to relieve stress, thus representing variability of social values of the local population in decision-making.

Collectives. Agents in this model do not conform groups.

Observation. Groundwater drawdowns, total stress index, number of stressed individuals, and stressed communities are collected at each timestep.

5. Initialization

The groundwater model is initialized by running a steady-state flow simulation with no pumping stresses for five years. Then, 2 mining companies, 29 community member agents, and 9 communities are located at specific locations based on their actual geographic coordinates (see Figure A1). 22 cells of brine wells and 5 cells of freshwater wells are added to SQM mining company. 5 cells of brine wells and 3 cells of freshwater wells are added to ALB mining company. Location of wells is based on the area and density of actual geographic location. Initial values of pumping rate for each company are obtained from Marazuela et al. (2020) at 0.07 m^3/s in both brine and freshwater wells for SQM, and 0.05 m^3/s in brine wells and 0.01 m^3/s in freshwater wells for ALB.

6. Input

The external inputs for groundwater model primarily include model dimensions, grid spacing, and values of hydraulic parameters and ariel recharges, location of boundary conditions. Model dimension, grid spacing, and location of boundary conditions have been elaborated in previous sections (A2.2 and A2.3). Hydraulic parameters and spatial patterns of recharges are also elaborated in Section A2.2 and shown in Table A2. Data obtained is then upscaled and mapped to match the dimension of this model.

For mining companies, yearly average pumping rate is collected from Marazuela et al. (2020) and serve as model input for mining wells. Compensation level for each company is collected from companies' sustainability reports to calculate the amount of financial supports issued to communities. For community members, the threshold for observable vegetation drying (1m) is used in this model with reference to empirical studies on desert shrubs and trees (León et al., 2011; Naumburg et al., 2005; Scott et al., 1999).

7. Sub-models

7.1 Community member decision-making:

The decision-making process is based on an empirical study of the interactions between Li-mining companies and local communities in Salar de Atacama. According to Babidge et al. (2019), community members perceive mining activities are negatively affecting their lives because they observed drying vegetations in regular pastoral lands, increased population in hometown (i.e., contractors, miners), and drastically increased pumping and transporting mining products (brines) back and forth from mining sites. On the other side, when the level of stress perceived by communities is relatively high, to appease community stress, mining companies compensate stressed communities by investing in community development.

Based on these interactions, the modeled decision-making process describes how an agent perceives mining-induced changes referring to the initial state. The total stress index (TSI), interpreted as the agent's personal experience on overall mining impacts each day, is affected by the agent's location, water table changes, and mining rates. As elaborated in Section A2.1, agents assess the mining-induced changes through personal experiences on three major stressors, partially relieved by the mining compensations. For each agent, the personal experience is translated into the weight of each stressor. Following the assessment method widely used in agent-based model studies (Li & Liu, 2008; Murray-Rust et al., 2013), the overall stress that an agent *r* perceives in day *t* is computed as below,

$$TSI_{r,t} = \sum \left(Sw_{\ r,i} \times\ S_{r,i,t} \right) - Cw_r\ \times C_{r,t} \qquad (A3)$$

Where $S_{r,i,t}$ $(Stress)$ represents normalized stress of each stressor *i* at time *t* for agent *r*; $C_{r,t}$ $(Compensation)$ is a normalized indicator of compensation for an agent *r* at time *t*; $Sw_{\ r,i}$ $(Stress\ weight)$ is interpreted as the perceived relative importance of each stressor *i* for agent *r*, and these weights are summed as 1 and assumed constant during simulation; and Cw_r $(Compensation\ weight)$ represents how effective the compensation is to relieve the stress perceived by agent *r*. The values of weights for agent *r* are assigned randomly through a stochastic process to capture the dynamics in values of the local population.

Specifically, $S_{r,i,t}$ $(Stress)$ includes Drought-stress (DS), Population-stress (PS), and Mining-stress (MS). *DS* expresses the stress agent experiences while observing drying vegetations due to groundwater drawdown, that is normalized to 0-1 as:

$$DS_{r,t} = \frac{(AD_{\ r,t} - VegD)}{AD_{\ r,t}} \tag{A4}$$

Where $AD_{\ r,t}$ $(Actual\ drawdown)$ is the maximum drawdown among the cell in neighbors agent *r* visited at time *t*, and $VegD$ $(Vegetation\ drying\ depth)$ is assumed as 1m.

PS represents the stress from increased population in the home community compared to the initial population at the start of mining-era, which is normalized to 0-1 as:

$$PS_{r,t} = \frac{(Cpop_{\ r,t} - Ipop)}{Cpop_{\ r,t}} \tag{A5}$$

Where $Cpop_{\ r,t}$ $(Community\ population)$ is the current population size in agent *r*'s community at time *t*, and $Ipop$ $(Initial\ population)$ is the population at the start of simulation.

MS describes the stress from expanding Li-extractions in agent's adjacent area. It also captures the stress originated from agent's indigenous culture or identity (i.e., knowing the fact of ongoing mining makes the agent feel stressed). It's normalized between 0 and 1 as:

$$MS_{r,t} = \left. \frac{(TMY_{\ t} - IMY)}{TMY_{\ t}} \middle/ \sqrt[2]{Dist_{\ r,t}} \right. \tag{A6}$$

Where $TMY_{\ t}$ $(Total\ mining\ yield)$ is the total pumping rate of all mining wells at time *t*, and IMY $(Inital\ mining\ yield)$ is the pumping rate when mining starts.

$Dist_{\ r,t}$ $(Distance\ to\ wells)$ is the distance between agent *r* and the closest well at time t.

Similarly, $C_{r,t}$ is also normalized to represent the level of compensation compared to the maximum possible compensation:

$$C_{r,t} = \frac{(\mathrm{MaxC} - AC_{r,t})}{\mathrm{MaxC}} \tag{A7}$$

Where MaxC (Max compensation) is the level of compensation based on the mining quota of each company, while $AC_{r,t}$ $(Actual\ Compensation)$ is based on current pumping rate.

Stress threshold implies the level when an agent starts to feel stressed by mining-induced changes. This model defines this threshold as in the baseline model, which is calibrated based on the actual time when the most adjacent community (Peine) started declaring stressed about the mining industry (Babidge, 2020). Once the threshold is crossed, the agent starts reporting to its home community and potentially seeking financial compensation from companies or mobilizing social movements for improved governance. The sensitivity of stress threshold is explored in scenario analysis to understand the critical range of threshold in system, indicating possible ways to help build resilience of local livelihoods.

7.2 Mining future projections:

Future scenarios of mining plans are investigated to understand their effects on groundwater and social stress. Four mining projections are considered for the period 2020 -2030. In the Business-as-usual (BAU), both companies expand the mining business following the same trend in the past ten years until reaching the maximum allowed rate, using the equation regressed by the average pumping rate from 2010 to 2019. In the Mining-commitment (MC) scenario, companies strictly follow their sustainable development plan (SQM, 2020b), which aims to reduce consumption of freshwater by 30% and brine by 20% compared to 2019 until both reaching the goal of 50% by 2030. In the Maximum-allowed (MA) scenario, driven by booming lithium market, companies increase the pumping rate to the maximum allowed rate to seize the opportunity. Lastly, the Mining-Recession (MR) scenario represents a case where mining water use capacity is curtailed due to social and regulatory pressure, to which both companies reduce the pumping rate to the level before they were granted an expansion concession in 2006.

APPENDIX B

SUPPORTING INFORMATION OF Q-METHOD

1. Pre-sorting survey questionnaire

Lithium, as one of the most critical minerals used in the Li-ion batteries of electric cars, is primarily extracted from Li-concentrated groundwater in Latin America. Following are some statements about the potential impacts of lithium extraction activities, please choose the response that best represents how you feel about each statement, where: 0= I don't know, 1 = Strongly Disagree, 2 = Disagree, 3 = Neutral, 4 = Agree, 5 = Strongly Agree.

Table B1. Pre-sorting Survey Questionnaire

Questions	Response					
1. Lithium mining consumes a large amount of water resources.	1	2	3	4	5	0
2. Lithium mining activities have adverse impacts on the health of ecosystems (wetlands, lakes and wildlife) in the mineral extraction area.	1	2	3	4	5	0
3. Lithium mining activities reduce the amount of water available for households and their regular activities in the mineral extraction area.	1	2	3	4	5	0
4. Water resources in the lithium extraction area are contaminated by heavy metals or other contaminants due to mining activities.	1	2	3	4	5	0
5. Lithium mining activities increase social tensions and conflicts among the communities near the mineral extraction area.	1	2	3	4	5	0
6. Lithium mining activities damage the cultural continuity of indigenous people (i.e., spiritual connections to land and water) living in the mineral extraction area, through exploiting natural resources in their territory.	1	2	3	4	5	0
7. Lithium mining activities bring new business opportunities and help improve economic conditions in the mineral extraction area.	1	2	3	4	5	0
8. Lithium mining companies help improve the education, health and infrastructure conditions for communities living next to the mineral extraction area.	1	2	3	4	5	0

2. Factsheet

Based on the previous survey questions about Lithium mining for battery production used in Electric cars, here are some facts about social and environmental concerns of lithium mining.

1. The Li-mining process consumes almost 2 million L of water for 1 ton of Lithium, which puts pressures on the local water reserves in Salar de Atacama, one of the driest places on Earth. *(UNCTAD, 2020)*
2. Li-mining sites in Latin America are located in salt flats where the unique ecosystem provides crucial ecological services to lagoons and biodiversity (e.g., flamingoes). Mining activities compromise the structure and functioning of hypersaline lagoons and reduce the quality and water availability of waterbird habitats (*Gajardo and Redón, 2019*).
3. In Chile's Salar de Atacama, Lithium and other mining activities consume 65% of the water, causing groundwater depletion and forcing local communities to abandon ancestral settlements *(UNCTAD, 2020)*.
4. Li-mining activities can contaminate soil and the already limited water supply through leaking of chemicals or minerals. In Chile, for example, local inhabitants have criticized mining companies for polluting water and covering their landscapes in discarded salt *(Harvard International Review, 2020)*.
5. Social protests and riots have grown and intensified with the Li-mining expansions and public awareness. In Chile, social movements against Li-mining

have gone from local to national level and become a national concern in 2019 *(Liu and Agusdinata, 2019)*.

6. In Chile, Indigenous people claim the disappearance of streams and loss of access to old pastoral lands due to the Li-mining, causing discontinuity of spiritual connections to ancestral land and water *(Babidge et al., 2019)*.
7. Li-mining activities bring new business opportunities to mining-related industries, while also adversely affecting other local businesses, such as agriculture and tourists.
8. Li-mining companies invest in education, health and infrastructure developments for communities affected by their operations through social responsibility programs, while its actual performance is not externally audited *(Liu and Agusdinata, 2019)*.

3. Q-set statements

Table B2. Detailed Q-set of 37 Statements in Five Categories

Technology developments and impacts

1. Future developments of EVs should primarily focus on improving driving range and fast-charging innovations.
2. Future developments of EVs should primarily focus on improving driving experience (e.g., self-driving functions, In-car entertainment, etc).
3. EV companies should invest heavily in battery advancements to lower battery costs and make EVs more affordable.
4. It is necessary to develop other electricity storage technologies with lower costs and better environmental performance than lithium-ion batteries to support the global energy transition in future.
5. Developing technologies and policies to manage the social and environmental impacts from battery production is important for EVs development in the near future.
6. Developing EV batteries with lower environmental impacts of material sourcing and battery production is crucial to promote future transitions to sustainable transportation system.
7. Reuse and recycling of expired lithium-ion batteries is important for future developments of EVs.

Consumer's preference and consumption impacts

8. Technological advancements of electric vehicles (acceleration time, speed, driving range, charging speed, etc) is my primary motivation for buying an EV.
9. Financial aspects (price, policy incentives, operation costs, etc) play a critical role in my EV purchase decision.
10. Environmental benefits of carbon and pollution reductions is an important attraction for me to purchase an EV.
11. In general, EV is cleaner than gas-powered vehicles, even considering the amount of emissions from its production and manufacturing process.
12. EVs are generally environmentally friendly technologies.
13. The metals needed for EV battery production are creating other environmental and social concerns.
14. As an EV consumer, I think it is important to address the adverse impacts of EV battery production.
15. EV companies should actively interact with consumer's feedback and requests on improving vehicle performance and technological advancements.
16. EV companies should actively interact with consumer's feedback and requests on improving its energy efficiency and reduce the environmental footprint.

Supply Chain network and practices

17. EV automakers should take the major lead in urging mineral suppliers for the sustainable extraction of the materials used in their products.
18. Lithium mining companies should prioritize the need for alternative mining technologies to extract resources more efficiently and sustainably.
19. Lithium mining companies should take the major responsibility in minimizing the social and environmental impacts from mineral extraction.
20. As an EV consumer, I feel it is necessary to build a global partnership between mineral suppliers and automakers to bring transparency to the origins and process of extracting raw materials.
21. The current efforts from EV automakers on responsible battery sourcing is not sufficient, and they should make serious commitment and investment into the communities and environment overall.
22. Everything that is extracted will have certain social and environmental impacts, and EV automakers should not be obliged to manage the impacts from materials used in their products.
23. It is equally important for EV automakers to achieve responsible battery sourcing and comply with the emission regulations and standards.
24. Mining companies' sustainability initiatives on reducing environmental and social impacts are not exercised to improve resource management.

Influence of public opinion and values

25. News and social media play an important role in raising public awareness of mineral mining impacts.
26. News and social media should play a role in putting pressures on EV automakers and suppliers for building more responsible and sustainable mineral sourcing partnerships.
27. As an EV consumer, I feel it necessary to put pressure on EV automakers to urge mineral suppliers for the sustainable extraction of the materials.
28. News and reports about the mining impacts of minerals used in batteries are often unclear and have false information.

29. Public opinions should not affect the direction and priorities of future EV development.
30. Knowing the environmental and social concerns from battery mineral extraction changes my perceptions of the environmental arguments and imagery promoted by EV companies.

Policies and governance

31. The national governments in EV consuming countries should take the lead in coordinating sustainable and responsible mineral sourcing for EVs.
32. Policies in EV consuming countries should shift focus from subsidizing battery innovations to financially supporting sustainable battery mineral sourcing initiatives.
33. The national governments in EV consuming countries should take the major responsibility for managing impacts of battery mineral extractions.
34. The national governments in EV consuming countries should only play a role in setting a framework for building responsible and sustainable mineral sourcing partnerships.
35. Governments in battery mineral extraction countries should manage the social and environmental impacts of mining by themselves considering the huge tax revenue they receive from the mining industry.
36. Policies and initiatives on sustainable battery mineral sourcing will discourage the technological advancements of EVs and the wider adoption of EVs.
37. Global politicians should prioritize the promotion of sustainable mineral sourcing, rather than the promotion of EV adoptions, to achieve real sustainability of electric mobility.

4. Participant’s profile

Table B3. Participants Profile in Three Purchase Intention Groups by Occupation

Occupations	Technology-driven owners (Tech)	Financing-driven owners (Fin)	Environment-driven owners (Env)
Agriculture, food and natural resources	7	1	2
Architecture and construction	4	1	0
Education	2	1	1
Business and Finance	9	5	7
Government and Public admin	0	2	0
Information tech and communications	6	1	5
manufacturing	7	0	8
Marketing, sales, and service	1	1	3
Science, Technology, Engineering, Math	1	5	5
Transportation and Logistics	1	0	1
None of the above	1	0	0
Total	39	17	32

5. Factor selection criteria and results

Table B4. Criteria for Selecting Rotating Factors

Criteria	*Tech*	*Fin*	*Env*
Eigenvalue >1 *Note: this criterion always results in overly large number of factors	14 factors had Eigenvalue >1	12 factors had Eigenvalue >1	14 factors had Eigenvalue >1
Two or more respondents are flagged	Factor 1: 7 flags Factor 2: 7 flags Factor 3: 13 flags Factor 4: 5 flags	Factor 1: 5 flags Factor 2: 5 flags Factor 3: 6 flags	Factor 1: 9 flags Factor 2: 6 flags Factor 3: 7 flags Factor 4: 4 flags
Total variance explained meets the empirical range of a satisfactory explanatory variance (34–40%)	42.15% variance explained by four factors	40.41% variance explained by three factors	36.26% variance explained by four factors
Empirical rule: 1 factor for 6-8 participants	4-6 factors	2-3 factors	4-5 factors
Feasibility in the interpretation	Reasonable interpretation for four factors	Reasonable interpretation for three factors	Reasonable interpretation for four factors

Note: *Meeting at least one of these criteria supports the selection of the factors.*

Table B5. Factor Correlations among Three Groups

		Tech				*Fin*			*Env*			
		F1	F2	F3	F4	F1	F2	F3	F1	F2	F3	F4
Tech	F1	1	0.15	-0.11	-0.13	-0.04	0.24	0.03	0.10	0.13	-0.24	0.16
	F2	0.15	1	0.17	0.06	0.23	0.18	-0.01	-0.12	-0.16	**-0.29**	-0.001
	F3	-0.11	0.17	1	-0.05	0.04	0.02	0.02	-0.18	0.07	-0.14	**0.45**
	F4	-0.13	0.06	-0.05	1	-0.08	**-0.31**	0.13	0.05	**-0.38**	0.07	-0.04
Fin	F1	-0.04	0.23	0.04	-0.08	1	0.01	0.11	0.03	0.01	-0.15	0.21
	F2	0.24	0.18	0.02	**-0.31**	0.01	1	0.12	-0.05	**0.42**	-0.24	0.15
	F3	0.03	-0.01	0.02	0.14	0.11	0.12	1	0.22	0.06	0.19	0.12
Env	F1	0.10	-0.12	-0.18	0.05	0.03	-0.05	0.22	1	0.24	0.13	0.10
	F2	0.13	-0.16	0.07	**-0.38**	0.01	**0.42**	0.06	0.24	1	-0.13	-0.02
	F3	-0.24	**-0.29**	-0.14	0.07	-0.15	-0.24	0.19	0.13	-0.13	1	0.18
	F4	0.16	-0.001	**0.45**	-0.04	0.21	0.15	0.12	0.10	-0.02	0.18	1

Note: *Bold coefficients indicate relatively strong positive or negative correlations between factors.*

6. Factor scores

Table B6. Factor Scores for Each Statement in Three Groups

Statement	Technology-driven owners				Financing-driven owners			Environment-driven owners			
	F1	F2	F3	F4	F1	F2	F3	F1	F2	F3	F4
S1	-4*	-2	0	-1	-3	-3	-4*	1	-1	1	0
S2	2	2	-1*	2	2*	0	-1	1	-3*	0	0
S3	-4*	0	-2*	1	1*	-1	-1	2*	-3	4*	-2
S4	4*	2*	-4*	-2*	2	0*	1	-1	-2	1	1
S5	-1	4*	-3*	-1	-1	-1	-2	-2	0*	-2	-4
S6	-1*	-2*	0*	2*	0*	-1	-2	-3	-1	-3	-1
S7	-2	-3	0*	2*	-3	-3	0*	-2	-4*	0*	-1
S8	-1	3	2	0	1*	-2*	-4*	0*	-2*	1	1
S9	2	-3*	-2*	0	3*	-2	-1	2*	0	-1	0
S10	4*	-4	-3	0*	-4*	-1	0	3*	-1	0	1*
S11	0	-3	-3	1	-1	0	2*	3	-2*	3	1*
S12	-3*	1*	0*	4*	0	0	2*	2	-1	2	-1
S13	0	1	3*	0	-2*	0*	3*	0	-2*	1	2
S14	-2	-2	-1	0*	0	1	3*	-4	1	1	-4
S15	-1	-1	-4	-3	4*	-1*	1*	0	2	0	-2*
S16	1	1	-1*	3*	1*	-4*	4*	4	-1	4	-1
S17	-1	-1	4*	2*	0*	-4*	4*	1	0	-1*	3
S18	1	3*	2	1	4*	1*	-3*	-2*	0*	-4*	2*
S19	-3*	0	1	4*	2*	-3*	-1*	-3	-4	-1*	1*
S20	-3*	0*	-1*	3*	-1*	2*	1*	1	0	3	2
S21	1	-1	-1	0	-3	1*	-3	3*	4*	0*	-3*
S22	3	0*	-2*	3	-4*	-2*	0*	-3	1	0	-2
S23	1	0	-1	-3*	-2	2*	-2	-4*	-3	2*	-2
S24	1	1	3*	-2*	-2	2*	-1	-1	1*	-2	4*
S25	0	1	0	-4*	-1*	1	2	1	1	-3*	-1*
S26	1	2	-2*	-1*	2	3	0*	4*	3*	-4*	-3*
S27	2*	-1*	1	1	1	3*	1	1	2	0	4*
S28	2	-2*	1	0*	0	0	-2*	-1	1	-2	0
S29	0*	4*	4*	-2*	3*	-2*	0*	-1	-1	-2	0
S30	3*	1	2	-1*	1*	0	-1	0	0	1	3*
S31	-2*	-4	1*	-4	0*	-1	-3	0	3*	2*	0
S32	-2*	0	1	-1	-1	1	1	0*	3*	-1	-1
S33	3*	2	0	1	-2*	2*	0*	0	0	-3	-3
S34	-1	0	1	1	3	4*	2	-2*	2*	-1*	3*
S35	0	-1	2*	-1	-1	4*	0	-1*	2	2	0
S36	0	-1*	0	-3*	1	1	3	2	4*	3	2
S37	0*	3*	3*	-2*	0	3*	1	-1	1	-1	1

Asterisk (*) indicates significance at p< 0.05; ranges from 4 (most agree) to -4 (most disagree)

Table B7. Z-Scores for Each Statement in Three Groups

Statement	**Technology-driven owners**				**Financing-driven owners**			**Environment-driven owners**			
	F1	F2	F3	F4	F1	F2	F3	F1	F2	F3	F4
S1	-1.95	-0.88	-0.25	-0.37	-1.38	-1.51	-2.23	0.31	-0.66	0.27	-0.22
S2	0.87	0.98	-0.3	1.2	0.88	-0.21	-0.37	0.35	-1.15	-0.13	-0.1
S3	-1.56	0.25	-0.97	0.21	0.26	-0.6	-0.65	0.84	-1.41	1.57	-0.99
S4	1.94	0.95	-2.11	-0.75	0.89	-0.1	0.54	-0.63	-0.94	0.46	0.59
S5	-0.28	1.81	-1.46	-0.19	-0.14	-0.46	-0.79	-1.1	-0.02	-1.22	-1.67
S6	-0.39	-1.03	0.13	1.35	0.21	-0.47	-0.79	-1.48	-0.39	-1.36	-0.77
S7	-1.36	-1.44	0.2	1.09	-1.38	-1.33	-0.2	-0.73	-1.54	0.22	-0.92
S8	-0.48	1.2	0.8	-0.15	0.69	-0.84	-1.5	0	-0.75	0.58	0.69
S9	0.5	-1.63	-0.76	0.05	1.5	-0.95	-0.68	0.75	-0.2	-0.52	-0.1
S10	1.94	-1.69	-1.27	-0.12	-1.71	-0.48	0.04	1.46	-0.31	-0.01	0.64
S11	-0.01	-1.34	-1.36	0.51	-0.43	-0.3	1.11	1.43	-1.03	1.36	0.62
S12	-1.46	0.6	0.11	1.87	0.02	-0.01	1.15	0.61	-0.71	0.77	-0.59
S13	0	0.53	1.87	0.19	-1.09	-0.13	1.34	0.29	-0.88	0.49	0.93
S14	-0.97	-1.29	-0.54	-0.02	0	0.27	1.44	-2.01	0.46	0.37	-1.56
S15	-0.48	-0.39	-1.67	-1.57	1.63	-0.35	0.85	0.04	0.67	0.26	-1.05
S16	0.48	0.54	-0.56	1.41	0.67	-1.59	1.72	1.68	-0.3	1.86	-0.35
S17	-0.48	-0.1	1.98	0.68	0.04	-1.8	1.85	0.49	0.02	-0.53	1.06
S18	0.42	1.49	0.78	0.21	1.7	0.88	-1.47	-0.9	0.19	-1.78	0.81
S19	-1.46	0.25	0.29	1.59	0.98	-1.35	-0.34	-1.31	-1.7	-0.15	0.74
S20	-1.46	0.25	-0.7	1.38	-0.5	1.06	0.16	0.43	0.13	1.12	1
S21	0.49	-0.33	-0.3	-0.05	-1.59	0.45	-1.45	1.07	2.71	0.2	-1.45
S22	1.38	0.46	-0.75	1.59	-2.04	-0.97	-0.33	-1.11	0.39	0.22	-1.07
S23	0.39	0	-0.41	-1.66	-1.26	1.01	-0.95	-2.09	-1.53	0.67	-1.09
S24	0.42	0.5	1.25	-0.95	-0.99	1.15	-0.57	-0.63	0.27	-0.62	1.82
S25	0	0.57	0.14	-1.79	-0.42	0.9	1.1	0.47	0.46	-1.49	-0.76
S26	0.42	0.72	-1.15	-0.16	0.99	1.49	0.03	2.28	1.01	-2.73	-1.26
S27	1.01	-0.64	0.47	0.22	0.36	1.2	0.56	0.59	0.53	0	1.76
S28	0.98	-1.02	0.55	-0.15	0.02	-0.05	-0.68	-0.21	0.3	-0.77	-0.2
S29	0.2	1.5	2.21	-0.76	1.39	-0.99	-0.3	-0.69	-0.45	-0.72	-0.27
S30	1.42	0.52	0.83	-0.32	0.5	-0.13	-0.58	0.04	-0.07	0.46	1.75
S31	-0.98	-2.16	0.37	-1.96	0.2	-0.79	-1.24	0.22	1.82	1.09	0.38
S32	-0.97	0.02	0.37	-0.27	-0.33	0.28	0.71	0.27	1.19	-0.22	-0.36
S33	1.45	0.65	-0.01	0.47	-1.25	1.13	0.09	0.12	0.04	-1.29	-1.19
S34	-0.15	-0.09	0.41	0.22	1.09	2.02	0.98	-0.94	0.66	-0.29	1.34
S35	0	-0.49	0.6	-0.56	-0.31	1.52	-0.03	-0.6	0.54	1.03	0.42
S36	0	-0.63	0.29	-1.22	0.72	0.88	1.2	0.94	2.17	1.37	0.84
S37	0.11	1.38	0.91	-1.2	0.11	1.17	0.26	-0.23	0.52	-0.54	0.57

APPENDIX C

SPANISH SUMMARY OF THIS DISSERTATION

Esta traducción es según nuestro leal saber y entender. Proporciona un breve resumen de los hallazgos y perspectivas de esta disertación, con la esperanza de brindar resultados prácticos a las partes interesadas locales en Chile.

Esta disertación tiene como objetivo comprender sistemáticamente los vínculos entre la creciente adopción de tecnologías verdes y los impactos socioambientales en lugares extraídos de Li, con el fin de ayudar a identificar posibles mecanismos o soluciones para abordar tales consecuencias. Esta disertación selecciona el Salar de Atacama en Chile como el área de estudio para proporcionar una evaluación socioambiental para sintetizar la relación de interdependencia entre las empresas mineras de Li y las comunidades anfitrionas. Luego, se desarrolló un modelo basado en agentes para demostrar las implicaciones socioambientales futuras en el área minera para varias proyecciones mineras. Por último, se recopilaron y estudiaron las percepciones de los usuarios finales de los productos de tecnología ecológica (por ejemplo, automóviles eléctricos) con respecto a la conciencia de los impactos de la minería incorporados en sus productos y cómo estos impactos deberían abordarse.

El primer estudio reveló que los medios de vida locales se conectan estrechamente con las operaciones de minería de Li a través de tres mecanismos principales: (1) sistema de agua compartido, (2) vinculación de la economía local (ingresos, empleos, otras oportunidades económicas) y (3) la gobernanza de los recursos comunes. Al compartir el sistema de agua, los medios de vida locales están estrechamente vinculados a los comportamientos de uso del agua de la minería de litio debido a la importancia ecológica y la escasez de recursos hídricos en este lugar. El consumo excesivo de agua por parte de la industria minera, por lo tanto, genera la mayor preocupación en cuanto a la sostenibilidad de sus medios de vida. Desde el punto de vista del vínculo económico, los medios de vida locales también están vinculados a los trabajadores migrantes en otras regiones. La industria minera en expansión ha traído una amplia gama de trabajadores que se desplazan al trabajo, que tienen contribuciones limitadas a la economía local, lo que ha provocado flujos migratorios desequilibrados. Mientras tanto, las mayores oportunidades laborales no se asignaron a los lugareños, sino que aumentaron los gastos de subsistencia de los residentes locales. En términos de gobernanza de recursos, los informes de sostenibilidad de las empresas han aumentado y se han diversificado en los últimos años, impulsados por la presión de los inversores globales y los usuarios finales. Sin embargo, los movimientos sociales antimineros relevantes también han aumentado en intensidad y escala, lo que refleja los desafíos de gobernabilidad en cuanto a la falta de confianza, la información opaca y poco transparente y la mala implementación de los esfuerzos de responsabilidad social empresarial.

El segundo estudio reveló que la incertidumbre material del agua subterránea (no directamente observable y menos predecible) provoca un retraso en el tiempo para que las comunidades locales obtengan retroalimentación oportuna sobre el estado del recurso, lo que lleva a una evolución desigual de las dinámicas tanto en los sistemas sociales como ambientales. Tal incertidumbre material puede conducir a puntos de vista controvertidos y confusiones sobre la dinámica de los flujos de agua subterránea y cómo responden a las perturbaciones, lo que puede oscurecer el surgimiento de un umbral que hace que el teleacoplamiento sea visible para los tomadores de decisiones (el teleacoplamiento significa que los sistemas distantes se conectan a través de políticas, acciones o comportamientos). Los impactos acumulativos y complejos de las industrias mineras existentes, sumados por consultas consistentes, han estado presionando excesivamente a la población local, lo que indica un cambio hacia la intolerancia al estrés en el sistema social. Esta intolerancia puede abrir una ventana al surgimiento de acciones colectivas o movilizaciones sociales, que pueden generar una retroalimentación efectiva de información y experiencia a las autoridades, aumentando el potencial de soluciones de gobernanza más responsable.

Sin una gestión adecuada de la incertidumbre sobre los recursos hídricos, los esfuerzos de gobernanza (por ejemplo, la consulta social) pueden generar preocupaciones sobre el alcance exacto y el impacto de la extracción de agua en los acuíferos y la vegetación invisibles. También es importante desarrollar la resiliencia del sistema socioambiental local. Pero debe estar atento a las medidas aparentemente efectivas para mejorar la tolerancia o la resistencia local porque puede resultar en el refuerzo del status quo político-económico de los impactos de la minería, socavando el potencial de una transformación sistémica más profunda. En cambio, debe incorporar la capacidad de las comunidades para movilizar recursos, formar acciones colectivas y negociar situaciones desafiantes. En particular, debe reconocer las luchas y las fortalezas de las comunidades para resistir las operaciones mineras, incluidas las confrontaciones dramáticas (por ejemplo, protestas) y las luchas en curso (por ejemplo, brechas generacionales, fracciones dentro de la comunidad). El fomento de la resiliencia debe reflejar la mejor manera de fortalecer dichas capacidades para desafiar las interrupciones mineras, creando así los mecanismos de retroalimentación instrumental para exigir responsabilidad del sector público y las autoridades mineras.

El estudio final buscó identificar oportunidades de gobernanza para los usuarios finales de tecnologías verdes considerando la tendencia creciente del consumo sostenible. Reveló una falta general de conciencia entre los consumidores sobre los impactos de la extracción de minerales relacionados con sus productos de tecnología verde, así como las tensiones y conflictos entre el imperativo de las transiciones energéticas y la realidad de los impactos mineros adversos. Los análisis identificaron el amplio reconocimiento del consumo sostenible y la conciencia entre los consumidores, lo que implica oportunidades para motivar el cambio a lo largo de toda la cadena de suministro de minerales. Si bien se deben considerar las diferencias en las motivaciones de compra al decidir qué grupos de consumidores van a abogar por el cambio. Además, los análisis también justificaron el papel influyente de la información a la hora de hacer visibles los resultados del teleacoplamiento y la minería para los consumidores distantes, y exigieron la necesidad de una visión del teleacoplamiento en la gobernanza sostenible de la extracción de minerales.

Esta disertación ayuda a explicar por qué estos impactos no están en la agenda gerencial de los formuladores de políticas. Aunque los impactos de la extracción de Li están creando una "presión funcional" para algunos de los actores del sistema de extracción de Li en Chile, incluidas las comunidades, los políticos, los administradores de la minería y el público en general. Por el contrario, el estudio piloto de las percepciones de los consumidores revela que los actores del sistema consumidor aún tienen poco conocimiento de estos impactos, lo que no deja ningún incentivo para que el actor dominante modifique sus prioridades políticas. Es importante destacar que las prácticas de Q-sort con los consumidores generaron algunas oportunidades para motivar cambios en la gobernanza de los recursos. Justifica la existencia y función de la información como un vínculo intangible en los sistemas teleacoplados, y cuando se presenta a grupos sensibles de consumidores, puede motivarlos a reconocer tales impactos y presionar a los actores del sector privado para una gobernanza sostenible de los impactos. Los actores del sector privado (por ejemplo, los fabricantes de automóviles) hoy en día, que son cada vez más susceptibles a tales presiones en un mercado competitivo, también es probable que inicien cambios en la cadena de suministro hacia una gobernanza sostenible de los recursos.

Los resultados de los impactos socioambientales en el Salar de Atacama se recopilaron como un conjunto de diapositivas, que se muestran a continuación. Algunos de los resultados que se presentan a continuación son parte de este proyecto, pero exceden el alcance de esta disertación.

Introducción e Informe a las comunidades de San Pedro de Atacama - Investigación sobre impactos de la minería de Li

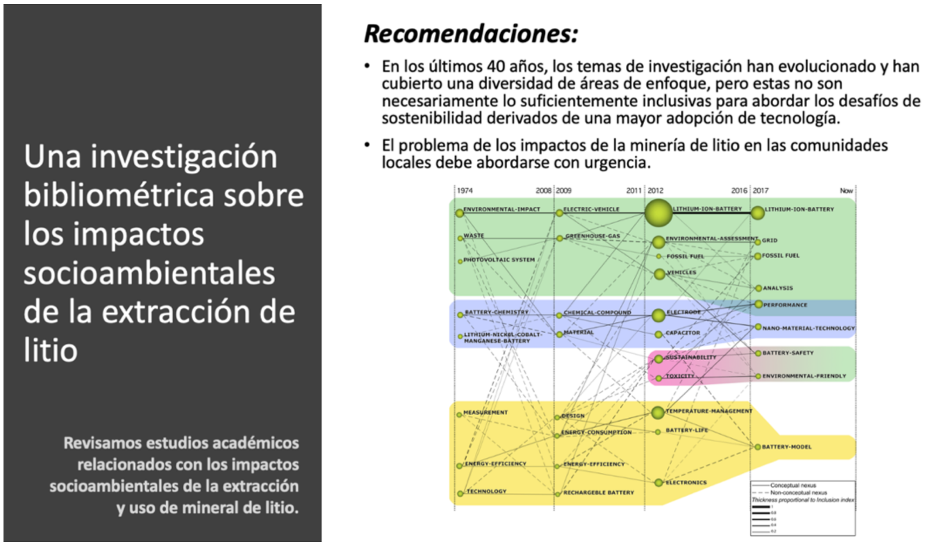
Datu Buyung Agusdinata, Arizona State University, US
Wenjuan Liu, Arizona State University, US
Hugo Remero, University of Chile

Contenido

- Nuestro equipo de investigación
- Investigaciones anteriores sobre la minería de litio
- Plan de investigación futuro

Investigaciones anteriores sobre la minería de litio

1. Una investigación bibliométrica sobre los impactos socioambientales de la extracción de litio
2. Patrones espaciales y temporales de la minería de litio y degradación ambiental en el Salar de Atacama, Chile
3. Interdependencias de la minería de litio y la sostenibilidad comunitaria en el Salar de Atacama, Chile
4. Escenarios de interacciones minería-comunidad-acuífero de litio en el Salar de Atacama, Chile



Una investigación bibliométrica sobre los impactos socioambientales de la extracción de litio

Revisamos estudios académicos relacionados con los impactos socioambientales de la extracción y uso de mineral de litio.

Recomendaciones:

- En los últimos 40 años, los temas de investigación han evolucionado y han cubierto una diversidad de áreas de enfoque, pero estas no son necesariamente lo suficientemente inclusivas para abordar los desafíos de sostenibilidad derivados de una mayor adopción de tecnología.
- El problema de los impactos de la minería de litio en las comunidades locales debe abordarse con urgencia.

Patrones espaciales y temporales de la minería de litio y degradación ambiental en el Salar de Atacama

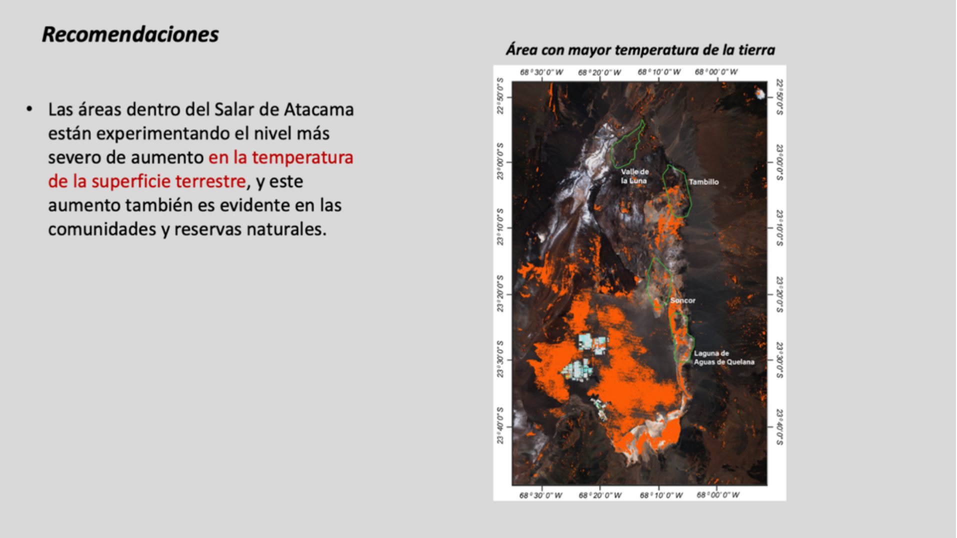
Evaluamos los cambios en el área minera, la salud de la vegetación, la temperatura de la superficie terrestre y la humedad del suelo entre 1997 y 2017.

Recomendaciones

- Entre 1997 y 2017, se estimó que las operaciones de extracción de litio se expandieron de 20,54 km² a 80,53 km² con una tasa de expansión promedio del 7,07% anual.

Área con vegetación declinada

- La disminución de la salud de la vegetación es detectable en áreas de asentamientos rurales aislados o funciones importantes del ecosistema como a lo largo de arroyos y cerca de humedales.



Recomendaciones

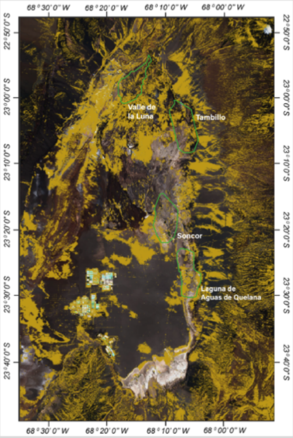
- Las áreas dentro del Salar de Atacama están experimentando el nivel más severo de aumento en la temperatura de la superficie terrestre, y este aumento también es evidente en las comunidades y reservas naturales.

Área con mayor temperatura de la tierra

Recomendaciones

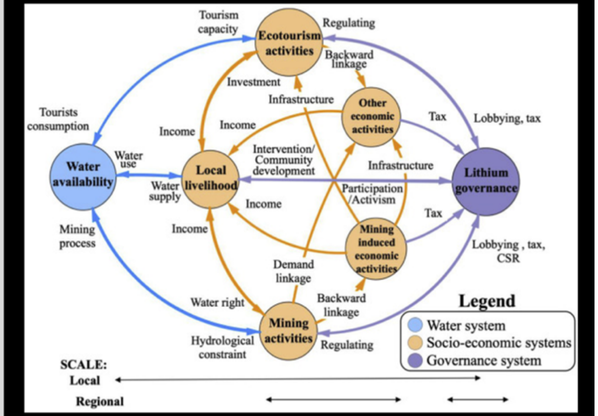
- La disminución de la humedad del suelo es frecuente en la zona. Aproximadamente 2214,5 km2 de áreas están experimentando una tendencia significativamente decreciente de humedad del suelo durante los últimos 20 años.

Área con disminución de la humedad del suelo



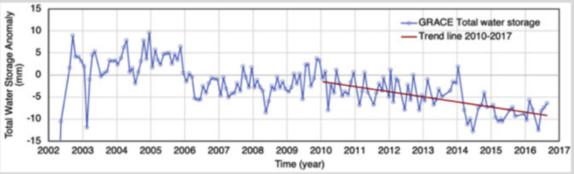
Interdependencias de la minería de litio y la sostenibilidad comunitaria en el Salar de Atacama, Chile

Investigamos la dinámica de las interdependencias entre minería y comunidad sobre la disponibilidad de agua, la afluencia laboral, el empleo, el activismo social y la responsabilidad social empresarial.



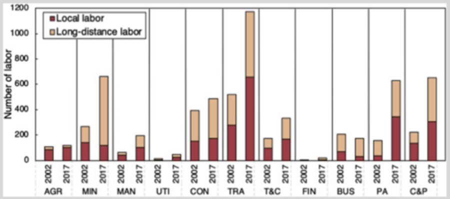
Recomendaciones

- La minería de litio es una industria intensiva en agua que afecta la disponibilidad de **agua**:



El almacenamiento total de agua se redujo a un ritmo de **1,16 mm / año**.

- La minería de litio contribuyó más a los desequilibrios **migratorios y laborales**



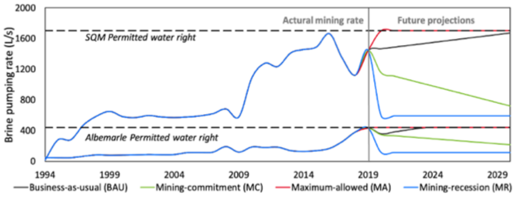
La afluencia laboral se multiplicó por 2,3, mientras que el papel de la mano de obra local en la minería disminuyó del **52% al 18%.**

- **El activismo social contra la minería de litio** ha aumentado en intensidad y escala.
- **Las iniciativas de inversión comunitaria** empresarial se percibieron como inadecuadas para compensar los impactos adversos.

Escenarios de interacciones minería-comunidad-acuífero de litio en el Salar de Atacama, Chile

Modelamos los impactos dinámicos del comportamiento de bombeo de las empresas mineras de Li en los acuíferos y las comunidades locales.

También investigamos cuatro escenarios futuros de minería:



Como siempre: bombee las salmueras con la misma velocidad que antes

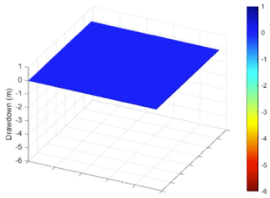
Compromiso minero: reducir el uso de agua dulce en un 30% y de salmuera en un 20% en comparación con 2019 hasta que ambos alcancen la meta del 50% para 2030.

Máximo permitido: *bombee salmueras a la velocidad máxima permitida*

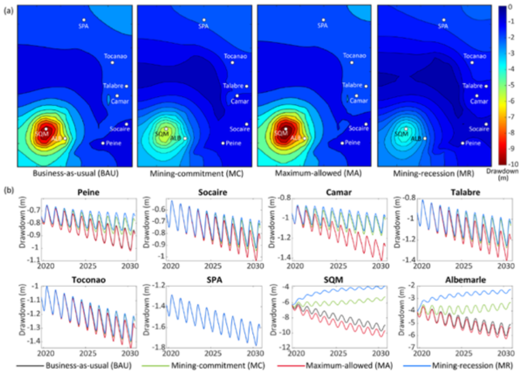
Recesión minera: reducir la tasa de bombeo al nivel anterior a que se les concediera una concesión de expansión en 2006

Recomendaciones
- Agua subterránea

- Cambios simulados de agua subterránea durante 1994-2019, en comparación con el nivel de 1994



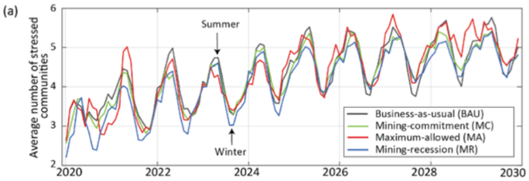
- Cambios simulados de agua subterránea durante 2020-2030 para cuatro escenarios



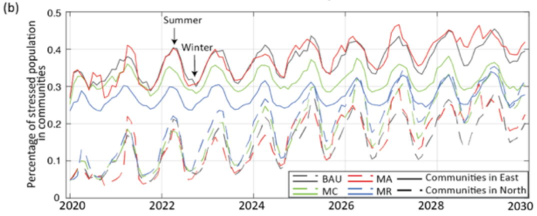
Recomendaciones – Comunidades

- Las comunidades adyacentes son más vulnerables a las operaciones mineras, pero las distantes sufren impactos duraderos.
- Las incertidumbres de las aguas subterráneas retrasan la retroalimentación a los residentes locales, provocando una evolución desigual del sistema social y del sistema de aguas subterráneas.
- Un 80% más de comunidades se verían estresadas una vez que la sociedad evolucione hacia una mayor intolerancia, mientras que las comunidades estresadas podrían mitigarse en gran medida en un 62% aumentando la capacidad de tolerancia.

❖ ***Número simulado de comunidades estresadas para cuatro escenarios futuros***

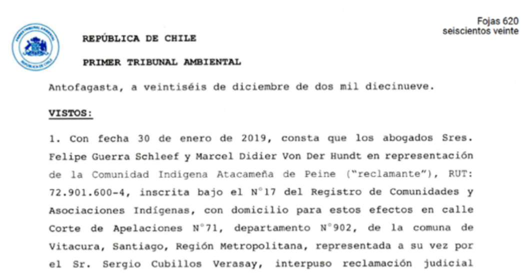


❖ ***Porcentaje simulado de residentes estresados en comunidades para cuatro escenarios futuros***



Influencia de nuestra investigación pasada

Nuestro estudio de 'Patrones espaciales y temporales de minería de Li y degradación ambiental en el Salar de Atacama' fue citado por el **Primer Tribunal Ambiental de Antofagasta** como prueba de degradación ambiental y rechazó el plan de remediación ambiental de SQM.



Fojas 620
seiscientos veinte

REPÚBLICA DE CHILE
PRIMER TRIBUNAL AMBIENTAL

Antofagasta, a veintiséis de diciembre de dos mil diecinueve.

VISTOS:

1. Con fecha 30 de enero de 2019, consta que los abogados Sres. Felipe Guerra Schleef y Marcel Didier Von Der Hundt en representación de la Comunidad Indígena Atacameña de Peine ("reclamante"), RUT: 72.901.600-4, inscrita bajo el N°17 del Registro de Comunidades y Asociaciones Indígenas, con domicilio para estos efectos en calle Corte de Apelaciones N°71, departamento N°902, de la comuna de Vitacura, Santiago, Región Metropolitana, representada a su vez por el Sr. Sergio Cubillos Verasay, interpuso reclamación judicial

Influencia de nuestra investigación pasada

Nuestros trabajos fueron citados por los nuevos medios internacionales para atraer a más investigadores a estudiar el tema de la minería de litio y ayudar a presionar los cambios en la cadena de suministro y los cambios en las políticas.

MONGABAY

El cambio a la energía renovable podría tener un costo para la biodiversidad, advierten los investigadores

Diálogo Chino

CHILE

El litio genera disputas en el desierto de Atacama en Chile

Temas ambientales han generado litigios constantes con empresas mineras en el desierto de Atacama

Lorena Guzmán

Una lucha por el agua en Atacama de Chile plantea interrogantes sobre la minería del litio

E&T ENGINEERING AND TECHNOLOGY

Exclusivo

Empresas de litio agotan suministros vitales de agua en Chile, sugiere un análisis

La evidencia descubierta por E&T parece mostrar que la empresa minera de litio SQM está jugando un papel directo en el daño al medio ambiente local en el salar de Atacama de Chile, ya que sus actividades reducen los niveles de agua en una región ya seca, con severos efectos en las comunidades locales, lagunas protegidas, y áreas de lodos aluviales.

CHILE

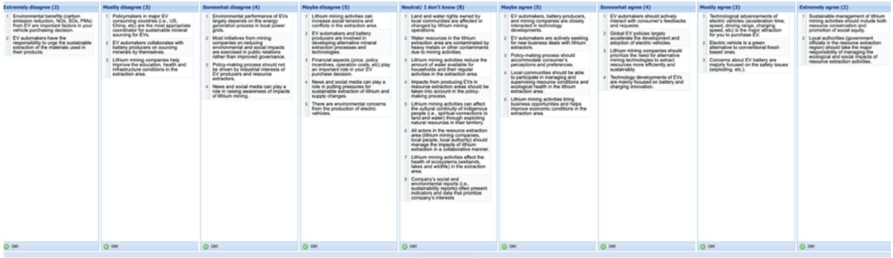
Chile: Explotación de litio deja sin agua a pobladores

LITIO: EL ORO BLANCO EN LAS ENTRAÑAS DE AMÉRICA LATINA

La demanda del litio está aumentando en todo el mundo, pero la minería está provocando diversos conflictos. En los pueblos del desierto de Atacama en Chile, el agua para las personas y los campos es cada vez más escasa.

✓ Plan de investigación futuro

- Un estudio de Q-game para comprender las percepciones de las comunidades locales sobre los impactos de las actividades mineras de litio.



Extremely disagree (2)

1. Environmental benefits (carbon emission reduction, NOx, SOx, PMs) from EV are important factors in your vehicle purchasing decision.
2. EV automakers have the responsibility to urge the sustainable extraction of the materials used in their products.

Mostly disagree (3)

1. Policymakers in major EV consuming countries (i.e., US, China, etc) are the most appropriate coordinator for sustainable mineral sourcing for EVs.
2. EV automakers collaborates with battery producers on sourcing minerals by themselves.
3. Lithium mining companies help improve the education, health and infrastructure conditions in the extraction area.

Somewhat disagree (4)

1. Environmental performance of EVs largely depends on the energy generation process in local power grids.
2. Most initiatives from mining companies on reducing environmental and social impacts are exercised in public relations rather than improved governance.
3. Policy-making process should not be driven by industrial interests of EV producers and resource extractors.
4. News and social media can play a role in raising awareness of impacts of lithium mining.

Maybe disagree (5)

1. Lithium mining activities can increase social tensions and conflicts in the extraction area.
2. EV automakers and battery producers are involved in developing alternative mineral extraction processes and technologies.
3. Financial aspects (price, policy incentives, operation costs, etc) play an important role in your EV purchase decision.
4. News and social media can play a role in putting pressures for sustainable extraction of lithium and supply changes.
5. There are environmental concerns from the production of electric vehicles.

Neutral/ I don't know (8)

1. Land and water rights owned by local communities are affected or changed by lithium mining operations.
2. Water resources in the lithium extraction area are contaminated by heavy metals or other contaminants due to mining activities.
3. Lithium mining activities reduce the amount of water available for households and their regular activities in the extraction area.
4. Impacts from producing EVs in resource extraction areas should be taken into account in the policy-making process.
5. Lithium mining activities can affect the cultural continuity of indigenous people (i.e., spiritual connections to land and water) through exploiting natural resources in their territory.
6. All actors in the resource extraction area (lithium mining companies, local people, local authority) should manage the impacts of lithium extraction in a collaborative manner.
7. Lithium mining activities affect the health of ecosystems (wetlands, lakes and wildlife) in the extraction area.
8. Company's social and environmental reports (i.e., sustainability reports) often present indicators and data that prioritize company's interests

Maybe agree (5)

1. EV automakers, battery producers, and mining companies are closely interacted in technology developments.
2. EV automakers are actively seeking for new business deals with lithium extractors.
3. Policy-making process should accommodate consumer's perceptions and preferences.
4. Local communities should be able to participate in managing and supervising resource conditions and ecological health in the lithium extraction area.
5. Lithium mining activities bring business opportunities and helps improve economic conditions in the extraction area.

Somewhat agree (4)

1. EV automakers should actively interact with consumer's feedbacks and requests.
2. Global EV policies largely accelerate the development and adoption of electric vehicles.
3. Lithium mining companies should prioritize the need for alternative mining technologies to extract resources more efficiently and sustainably.
4. Technology developments of EVs are mainly focused on battery and charging innovation.

Mostly agree (3)

1. Technological advancements of electric vehicles (acceleration time, speed, driving range, charging speed, etc) is the major attraction for you to purchase EV.
2. Electric vehicle is a green alternative to conventional fossil-based ones.
3. Concerns about EV battery are majorly focused on the safety issues (exploding, etc.).

Extremely agree (2)

1. Sustainable management of lithium mining activities should include both resource conservation and promotion of social equity.
2. Local authorities (government officials in the resource extraction region) should take the major responsibility of managing the ecological and social impacts of resource extraction activities.