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ABSTRACT

Demand for clean technologies has increased global lithium (Li) production. However, the potential impacts of lithium extraction, especially on frontline communities, have not been studied holistically. This research assesses the community sustainability in Salar de Atacama, Chile. We developed a coupled natural-social systems framework to analyze the interdependencies of the lithium extraction and its impacts. Using data from the Chilean census, company sustainability reports, remote sensing, and media archives, we investigate the temporal dynamics of water availability, labor influx, employment, social activism, and corporate social responsibility. Our study finds that between 2002 and 2017, the total water storage declined at a rate of 1.16 mm/year. Compared to other uses, water consumption from Li-mining was higher by two orders of magnitude. Mining played a crucial role in creating greater migration impacts, as indicated in a high migration effectiveness index of 85% and 90%, respectively. Labor influx increased 2.3 times, whereas the role of local labor in mining decreased from 52% to 18%. Local social activism increased both in intensity and scale. Our interdependency framework and analyses show that Li-mining and local communities are closely linked at both local and regional scale through the sharing of water resources, economic opportunities, and resource governance.

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), and supports 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., 2019), 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 are 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, 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.

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(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. We assess 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?* We selected the area surrounding Salar de Atacama in Northern Chile, the current location of the world's largest brine-based lithium mines. Due to the remoteness of the area and lack of local data, we used data from diverse sources, 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). Others 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) framework (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. 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 Salar de Atacama, 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, we start by describing the social demographic and geographic characteristics of the study area. Then we introduce the coupled natural-social system framework that we applied to show the interdependency of Li-mining and local communities. Grounded in the SI framework, we illustrate the process for the impact themes selection and the diverse data source used in this study. Next, we assess each identified theme and synthesize the dynamics of impact trajectories based on the mining-community interdependencies. Subsequently, we discuss the implications for other Li-mining areas in the lithium triangle and point out directions for future research.

2. Study area

Our study area is the San Pedro de Atacama (S.P.A.) commune (Fig. 1), located in the region of Antofagasta of Northern Chile, site of the world's largest brine-based lithium extraction. This location is the site of intensive mining operations and has a relatively higher availability of preexisting data. The commune supports two major lithium mines, operated by Sociedad Quimica y Minera (S.Q.M.), a Chilean company that is the world's largest lithium producer, and Albemarle, an American company that operates worldwide. Li-mining was brought into the area during the 1980s by Rockwood, which was purchased by Albemarle in 2015. S.Q.M. began extraction in 1995 and quickly dominated the global market. In the past decade, Li-mining has expanded rapidly, quadrupling in area from 20.54 km^2 in 1997 to 80.53 km^2 in 2017 (Liu et al., 2019).

Geographically, S.P.A. is in the Atacama Desert with an average altitude of 2400m; rainfall is extremely limited. Water resources are precious and rarely renewable. Local livelihoods mostly rely on water from melting ice from the Andes Mountains that is channeled through community-built ditches and catchments. The mining operations extract groundwater for the evaporation process of lithium production. According to the 2017 national census, the commune contains 16 communities, with a total population of 10996; 50% of the residents belong to indigenous groups (INE, 2018). Local livelihoods are mostly based on the traditional agro-pastoral economy, although in recent years they have been affected by the 'extractivism-as-development' economy due to mining expansions (Babidge, 2016).

3. Methodology: Coupled natural and social system and sustainable livelihood framework

3.1. 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 our understanding of complex systems (Seiffert and Loch, 2005). Faced with a complex socio-ecological system, we develop a coupled natural-social system

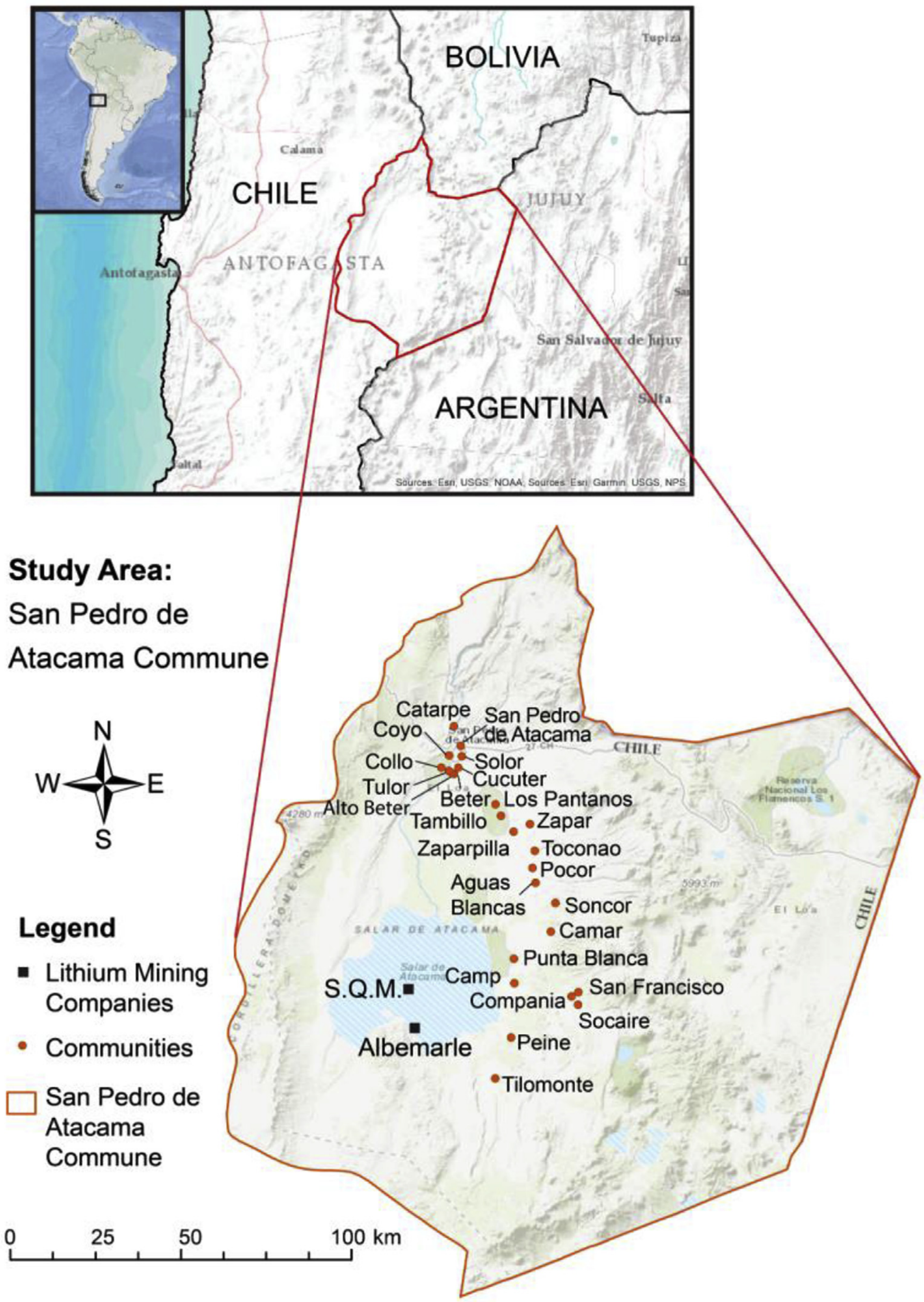


Fig. 1. Case study area: San Pedro de Atacama (S.P.A), Chile.

framework to integrate the examined impact categories into a more holistic picture by uncovering interdependencies between the expanding lithium industry and local communities (Fig. 2).

The coupled natural and social system is shown in Fig. 2. The natural system is comprised of the large endorheic salares (i.e. salt flats and associated wetland systems); the social systems consist of socio-economic activities and lithium governance. Water provided by the natural system is the key constrained resource for livelihoods and economic activities in the area. Socio-economic activities incorporate local livelihoods and their economic activities, which are categorized into four subgroups: mining, mining-induced, ecotourism, and other economic activities since local economic structure depends heavily on Li-mining and ecotourism industry. 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. Governance systems refer to decision-making actors and mechanisms that directly and indirectly govern lithium-related activities and impacts at both local and regional level through laws, procedures, and norms.

The social actors that are involved include national and multinational mining companies, local communities, tourism

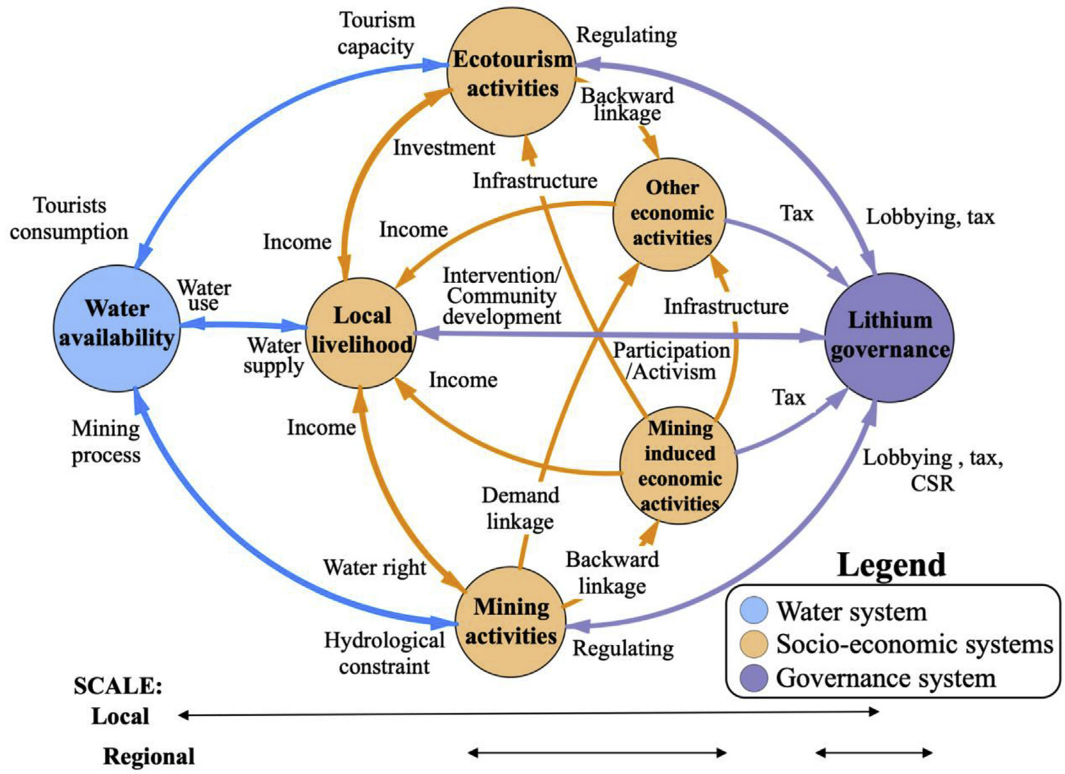


Fig. 2. Coupled natural and social system of lithium mining-community interdependency.

enterprises, and regional and national policymakers. Mining companies and local communities are economically interdependent, providing each other with employment and labor, respectively. Tourist operators offer ecotourism activities that bring outside dollars into the local economy. Information flows among these groups culminate in social mobilization and collective actions, which becomes one of the main feedback mechanisms that mobilize the governing of resource use (water) and extraction (lithium).

In the study area, 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. The governance system regulates the water use of each socio-economic subsystem through permit issuing and environmental inspections, thereby governing the total water availability in the natural system. The governance system also receives tax revenues and social investment from local industry, which may then be used for community development. Sometimes, the governance system serves as an intermediator to resolve conflicts between the communities and mining companies.

Socio-economic subsystems are also closely linked by mining and tourism. The mining industry attracts a distant workforce who could foster local economy by demand linkage, and also stimulate economic prosperity in relevant industries (e.g. construction and services) through backward linkage. Similar to mining, other subsystems also interact through economic linkages. For example, mining-induced activities provide infrastructure that is shared by all industries. Each subsystem provides incomes to support local livelihoods. In return, the locals invest in tourism businesses and sometimes illegally trade a part of their water rights with mining companies in exchange for monetary gains or job opportunities.

3.2. The sustainable livelihoods (SI) framework 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.

Grounded on the SI framework, we held stakeholder meetings to select impact categories perceived as the most relevant to Li-mining activities. We conducted three sets of meetings 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.

We grouped the highlighted themes into five impact categories, each reflecting one or more capital assets (Table 1): (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,

Table 1
Impact categories most concerned by communities in S.P.A.

Impact categories	Capital assets	S.P.A. 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 S.P.A
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

representing grass-root 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.

3.3. Data and material processing

Since hydrological records are either unavailable or highly inconsistent, we 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, we acquired the data 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, we selected the USGS Level 2 river basin dataset 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. We estimate 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, we 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 S.P.A from Chilean tourism yearbook (https://www.ine.cl/estadisticas/economicas/turismo). Third, domestic water use is estimated by the projected annual population in S.P.A (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, we use 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. We also use the CHIM (CHilean Internal Migration) database, developed by Rowe (2017), to extract data on spatial labor mobility in S.P.A. during 1997–2002 based on the 2002 census. We then followed the same method in CHIM database construction (Rowe, 2013) and developed the labor mobility in S.P.A. 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, we selected the Migration Effectiveness Index (MEI), 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 (1), as (Shryock and Siegel, 1976):

$$MEI = \frac{\sum_i |D_i - O_i|}{\sum_i |D_i + O_i|} \times 100 \quad (1)$$

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. We 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*'. We then examined events directly relevant to Li-extraction in S.P.A. We also verified and incorporated events data from the Mineral Extraction Conflict database (https://mapa.conflictosmineros.net/ocmal_db-v2/), which is compiled by a local NGO, Observation of mineral conflicts in Latin America.

As for CSR initiatives, we 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). We 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, we tracked the disclosures of social initiatives and investments contributing to S.P.A. since 2002, and evaluated how their scope, reporting style, and content have evolved.

4. Results and discussion

In the following sub-sections, we assess the sustainability of communities and their interdependent linkages with Li-mining activities in S.P.A. Thereby, we start with an assessment of community sustainability in water availability, labor influx, employment and displacement, social activism, and long-term sustainability. Next, we provide a holistic analysis of mining-community interdependencies to reveal significant impact feedbacks on their interactions. Furthermore, we discuss the ongoing lithium boom in other lithium triangle countries, as well as the applicability of our coupled natural and social framework in these cases.

4.1. Sustainability of local communities

4.1.1. Water availability

The changes in total stored water (i.e. surface water, soil moisture, and groundwater) from GRACE are shown in Fig. 3. The period before 2004 is the model initialization period and the years 2004–2009 serve as the baseline. Thus, for trend detection we consider only the total water storage anomalies after 2010. 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 S.P.A. is estimated to decrease by 1.16 mm compared to the previous year .

Water consumption continuously increased from 2002 to 2017 due to expanded mining production, increased local inhabitants, and increased tourism (Fig. 4). Astoundingly, estimated water consumed for mining processes was approximately 50 times the estimated domestic use, and hundreds of times the estimated tourists' consumption. 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.

4.1.2. Long-distance labor influx

To compare the labor influx between the two census periods, we mapped the influx to show the spatial mobility of the long-distance labor to S.P.A. (Fig. 5). 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 S.P.A. 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 S.P.A. in the period.

The spatial impact of migration flows during the two census periods show the imbalances between in-and-out flows by industrial sectors (Fig. 6). In general, most 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 S.P.A., 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 inflows. 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 S.P.A. Another possible reason could be the growing popularity of S.P.A. as an ecotourism destination, driving more investments in infrastructure and utility, and thereby attracting more laborers. The overall migration impact in S.P.A. 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.

The labor influx increased in most industries between the two periods, with mining and manufacturing increasing at the fastest rate (Table 2). 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

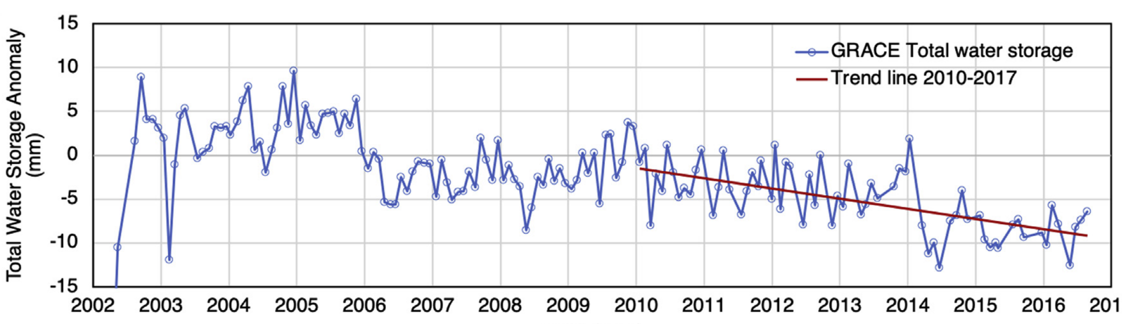


Fig. 3. Total water storage in the study area from 2002 to 2017.

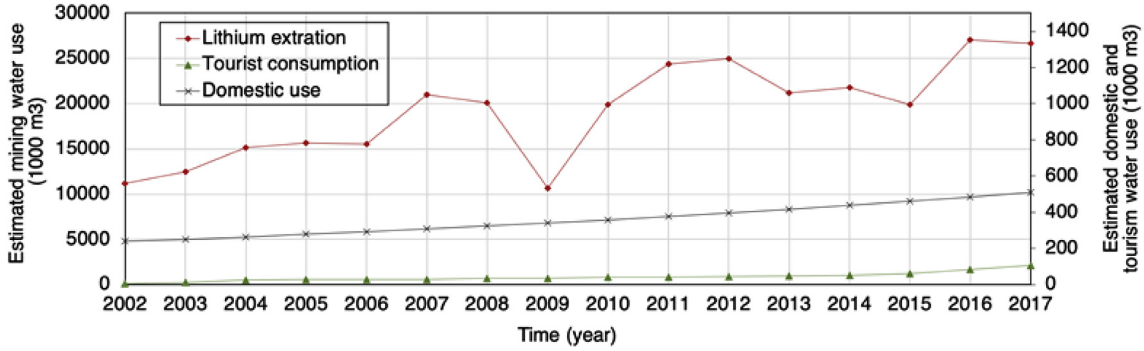


Fig. 4. Estimated water consumption of mining, domestic use and tourism in the study area from 2002 to 2017.

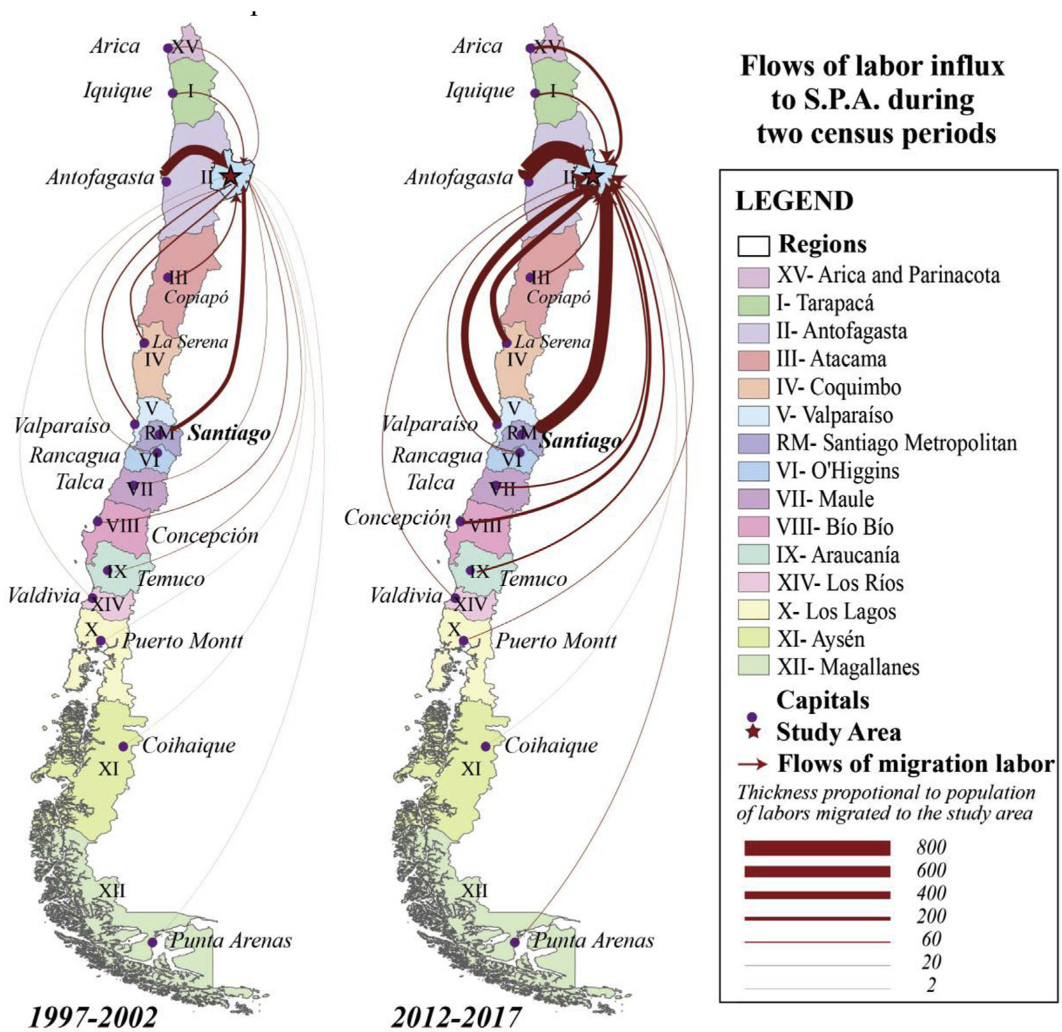


Fig. 5. Migration flows to S.P.A. during 1997–2002 and 2012–2017.

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 S.P.A., 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 2 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 S.P.A., the share of commuting labor was still considerable and even increased from 34% to almost 79% between the time periods. In

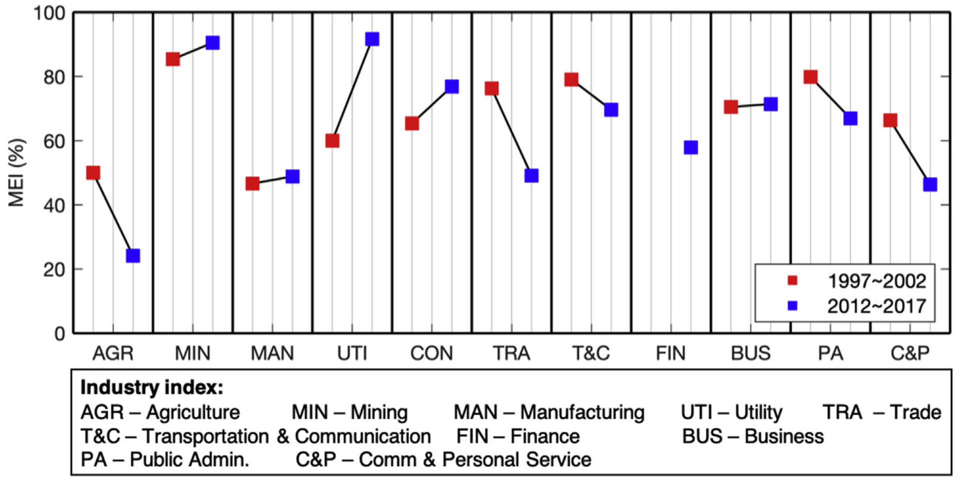


Fig. 6. Migration effectiveness of labor migration in S.P.A.

Table 2
The share of commuting labor by industry sector.

Industry Sector	Total number of long-distance labor in each industry (share of commuting labor)	
	2002	2017
AGR	24 *(17%)*	18 *(11%)*
MIN	127 *(71%)*	543 *(96%)*
MAN	22 *(27%)*	96 *(60%)*
UTI	8 *(13%)*	23 *(65%)*
CON	239 *(75%)*	314 *(74%)*
TRA	245 *(25%)*	519 *(24%)*
T&C	77 *(27%)*	162 *(59%)*
FIN	0	15 *(18%)*
BUS	133 *(69%)*	144 *(76%)*
PA	125 *(54%)*	283 *(23%)*
C&P	89 *(18%)*	349 *(32%)*

trade, most of in-migration flows were made up of permanent migration labor during both periods.

4.1.3. Employment and displacement

The employment condition of local labor is summarized in Fig. 7. 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.

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.

4.1.4. 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. We performed a timeline analysis of major activism events on Li-extractions and

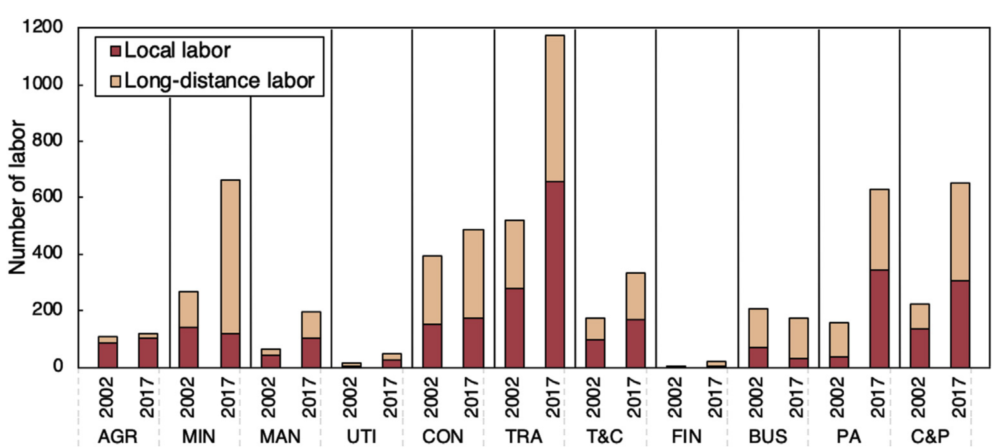


Fig. 7. Sector-wise distribution of local labor and long-distance labor in 2002 and 2017 period.

related them to major governance actions in Chile (Fig. 8). In the early 1990s, social movements related to Li-mining were rare in the S.P.A. 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.

Social activists had distinct concerns. The objection to excessive water use 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 Salar de Atacama. 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 S.Q.M. The contract increases the production quota to 216,000 tonne/yr of Li-carbonate through 2025 in the Salar de Atacama (Reuters, 2018). After the signing, protestors rallied at the regional capital, national capital, and S.P.A. 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.

4.1.5. Corporate social responsibility initiatives

To assess the long-term sustainability of communities, we primarily analyzed the disclosures of CSR by S.Q.M., that has fairlyw 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 S.Q.M. 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 3 summarizes the appearance of S.Q.M.'s initiatives in community development in S.P.A. 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.

4.2. Li-mining and community interdependency

To investigate the impacts of Li-mining expansions on community sustainability, we explored the impact and response trajectory of Li-mining and communities based on their interdependency, and then analyzed the dynamics of these trajectories from the impact categories we examined in Table 1. We categorized these trajectories from the interdependency framework (Fig. 2) and displayed each trajectory in Fig. 9.

The most important feedback that Li-mining affects local livelihoods is through excessive water consumption (Fig. 9a). 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.

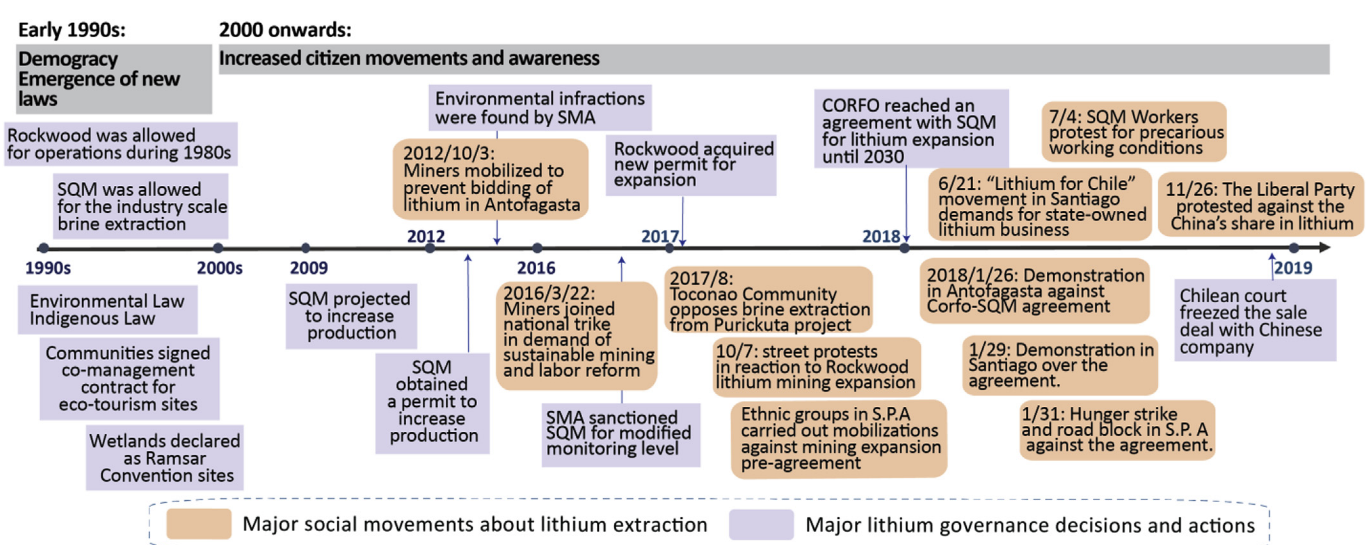


Fig. 8. Timeline of social activism events associated with the Li-mining in S.P.A.

Table 3
Disclosure of corporate initiatives for community development in S.P.A. The color-coded cells indicate reported activity in the company's annual reports.

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 Development	Micro-entrepreneurs' program						■	■	■	■	■	■	■	■	■	■	■	■
	Atacama agriculture program							■	■	■	■	■	■	■	■	■	■	■
	Emergencies restoration											■		■	■	■	■	■
	Environmental education													■	■	■	■	■
	Tourism infrastructure improvement				■	■				■					■			■
	Apprentice program									■					■	■	■	■

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 (Fig. 9b). 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.

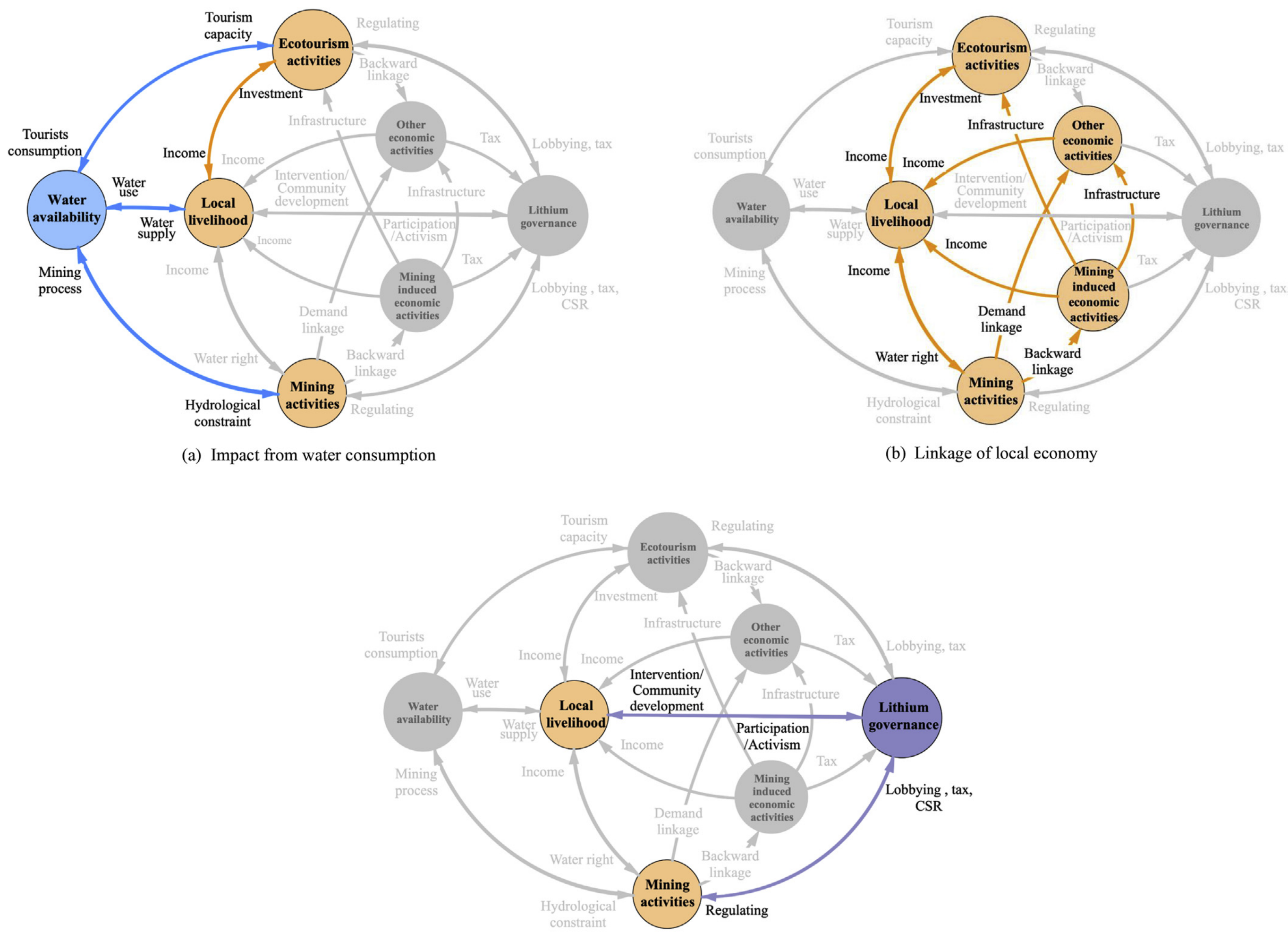
Consequently, lithium governance is increasingly important in bridging mining-community feedbacks (Fig. 9c). Generally, Li-governance receives tax revenues from local industries and regulates mining and tourism operations through permit issuance, environmental inspections, and other regulatory activities. 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 locals 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 raises 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 our 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.

4.3. 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



(a) Impact from water consumption

(b) Linkage of local economy

(c) Feedbacks through lithium governance

Fig. 9. 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.

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. Salar de Atacama 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.

5. Conclusion

This study investigated the sustainability of frontline communities near Li-mining sites in Salar de Atacama, by examining five most concerned themes derived from local stakeholder meetings: water availability, labor influx, employment, social tensions, and CSR initiatives. Our 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, our 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 S.P.A. 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.

Declaration of competing interest

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

CRediT authorship contribution statement

Wenjuan Liu: Conceptualization, Methodology, Formal analysis, Investigation, Writing - original draft, Visualization. **Datu B. Agusdinata:** Conceptualization, Methodology, Resources, Investigation, Writing - review & editing, Supervision.

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