Environmental Justice Across the Lithium Supply Chain: A Role for Science Diplomacy in the Americas

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Executive Summary: While climate change mitigation is a global concern that all countries must play a role in curbing, the costs and benefits of various strategies across geographic boundaries must be examined from a full supply chain perspective. In countries such as the United States (US) where the transportation sector is a leading source of greenhouse gas (GHG) emissions, switching from internal combustion engine vehicles (ICEV) to electric vehicles (EV) has emerged as one strategy to combat climate change. However, these EVs rely on critical minerals in their batteries, which are sourced largely from the global south, where there are not as many environmental and social protection regulations and practices. One such mineral, Lithium is found mostly in the Lithium Triangle (LT) in the South American countries of Argentina, Bolivia, and Chile. Lithium mining is negatively affecting natural resources and ecologies in the LT, in turn creating challenges for nearby communities including indigenous people in the area. Science diplomacy could strengthen relationships and communication between Northern and Southern American countries and more equitably distribute the social and environmental costs and benefits of lithium extraction and EV sales and operations. This paper explores how science diplomacy can foster the governance processes and scientific inputs needed to support more sustainable and just supply chains. It demonstrates higher benefits at the use stage of the EV supply chain in North America, and higher costs at the raw materials extraction for lithium in the EV supply chain in South America. This paper also calls attention to standards and measures that could be applied to sustainable mining. We document best practices, lessons learned, and gaps in collaborative potential between interdisciplinary and transitional stakeholders to develop definitions, measures, and goals across the entire supply chain of lithium for EV batteries.

I. Introduction

Climate change mitigation requires reducing fossil fuel consumption, increasing renewable energy use, and overall reducing greenhouse gas emissions. This challenge is acute in the transportation sector, where electric vehicles (EVs) have emerged as a panacea for climate change mitigation.

In the United States (US), the shift to EVs is especially pronounced, as Transportation is the leading sector contributing to greenhouse gas emissions. However, EVs are powered by batteries that require rare minerals, notably lithium. The demand for EVs powered by lithium-ion batteries has rocketed in wealthy countries, including the US.

Electric Vehicle (EV) and battery technologies are quickly being developed, and critical mineral mining is tied to these developments.

High demand for EVs and their lithium-ion batteries is driving a strong pressure and economic opportunity for extracting lithium salts from brines in a region called the "Lithium Triangle" (LT) in the central Andes of South America. This region houses the Atacama Desert and is also home to indigenous peoples and unique ecologies. Transnational companies are increasingly operating in this fragile region of Chile, Bolivia, and Argentina, in a context of very incipient environmental policies and safeguards for extraction in such countries. There are few policies regulating these companies, and a notable lack of individuals with scientific or indigenous knowledge engaged in any policy-making around mining in the LT. The more robust policy sphere for EVs in the US does include considerations for climate change and other environmental and social impacts. Communication between scientists, policy-makers, and other stakeholders across American borders and various sectors involved in the lithium battery supply chain could promote policies for the more equitable distribution of costs and benefits across different countries and communities.

The uptake of EVs in North America could provide benefits to South America through climate change mitigation and economic development opportunities through greater demand for South American lithium. However, the environmental and societal impacts of lithium mining are currently unevenly distributed with disproportionate costs to the Global South due to mining activity and benefits to the Global North as with electric vehicles replacing internal combustion engine vehicles. The current state of the supply chain for EV batteries thus opens the door to opportunities in science diplomacy, which is the support of "foreign policy on bilateral and multilateral issues where science and technology are important" (Soler 2021). Science diplomacy includes intergovernmental communication and policies related to climate change and biodiversity as well as the management of shared natural resources and transboundary ecosystems, and the associated impacts on communities and their health and economic opportunity (Soler 2021).

Given the increasing demand for lithium, there is a need for transnational policy development and science diplomacy for the full supply chain. Supply-chain policies (SCP) such as certifications denoting environmentally or socially sustainable practices as part of a supply chain are well developed in the agricultural and forestry sectors, where they have reduced commodity-driven tropical deforestation. Despite the high potential for applying SCP in the mining sector in general, and the supply chain in particular, best practices are still lacking. Inserting scientific evidence into the policymaking process will identify the impacts of lithium mining and allow for better policy analysis and development.

International, collaborative scientific research can meet this need by setting sustainability standards for mining operations and developing procedures to trace the origin of salts. Science diplomacy can mitigate the costs and allow for more just distribution of benefits as demand for EV batteries continues to rise. Policies and diplomatic agreements in other sectors have set precedents that support socially and environmentally sustainable outcomes across various stages of the supply chain in countries in the North and South. Leveraging these lessons learned and existing international collaborations can lay the foundation for distributive justice for health, economic benefits, and climate impacts throughout the lithium supply chain in the Americas.

This paper addresses four goals. First, to provide background on the lithium-ion EV battery supply chain, from extraction to manufacturing and sale of EV batteries, while highlighting the imbalances of social, environmental, and economic costs and benefits most prominent in the Americas. Second, to explore policies across the Americas that influence the EV battery supply chain. Third, to learn from examples in other sectors, such as agriculture, where science and policy connect stakeholders across the Americas. And finally, to identify existing and potential opportunities for science, policy, and science diplomacy to support more equitably distributed costs and benefits across the supply chain steps and geographic regions. If national governments, private companies, local communities, and scientists work together across borders, shared information can help reach shared global goals for environmental, social, and economic sustainability.

II. Background: Supply chain policies and equity

This section reviews the full supply chain across the Americas for context. It then discusses policies in Chile, Argentina, Bolivia, and the United States that set the framework for increasing multilateral scientific and diplomatic relationships. Examples from the agricultural sector are then discussed, as there is a long history of international collaboration for agricultural resources, with transnational policies that influence supply chain impacts on the environment, society, and economy.

i. Lithium supply chain

The ultimate use of lithium in EV batteries is dependent on the entire supply chain, and each step of the supply chain presents costs and benefits to different communities.

Figure 1 shows the seven steps of the lithium supply chain in the context of EVs, from discovery of the resource to disposal or recycling. Each step is complex and many can be carried out with multiple approaches. This paper focuses on the **Discovery** and **Extraction** steps, prominent in South America, and the **Electric Vehicle Applications** step, prominent in North America. While processing and battery manufacturing – steps that occur mostly in Asia – are relevant to understanding the full supply chain, a full discussion of these steps is out of the scope of this article.

Table 1 shows the global movement of lithium through the middle five steps in the supply chain. Extraction, processing, and refining occur where lithium resources are discovered. Battery manufacturing occurs mostly where lithium is imported, and EV application occurs where electric cars are purchased by consumers. South America and Australia produce nearly all exported lithium, and the US is not able to or has not accessed their reserves. China, South Korea, and Japan import the majority of lithium for battery production; and Europe and North America put a large proportion (40%) of EVs on their roads. (Alessia et al. 2021; Jerez et al. 2021).

ii. Distribution of costs and benefits of Lithium mining

The associated costs and benefits of lithium mining are tied to supply chain steps, with South America absorbing those of lithium mining and production, and North America absorbing those of EV sales and usage. Some South American communities face negative environmental and health impacts of lithium mining, while other actors monetarily benefit from the process. The US lists EVs as a necessary component on the path towards a healthier, greener future, but often does not consider the full life cycle of all EV components (USDOT 2022).

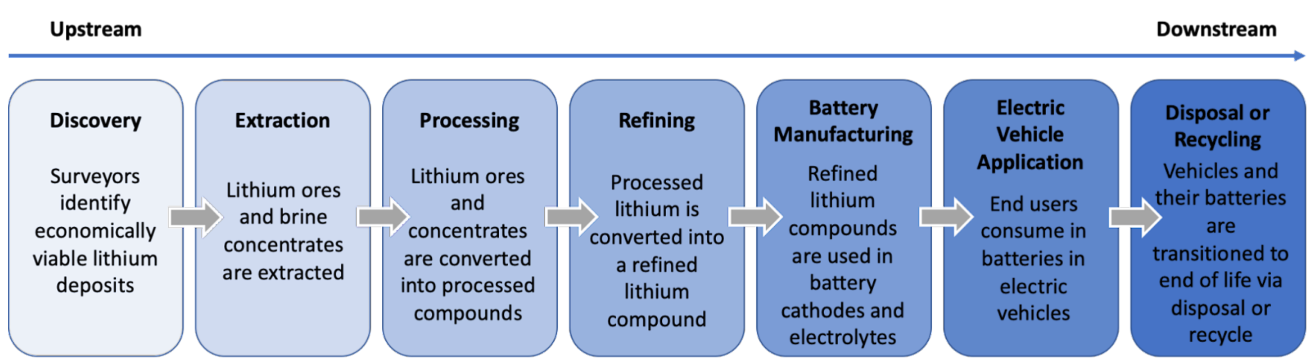

Figure 1. Lithium Supply Chain in the Context of EVs. Image based on figure from Willis et. al, "Australia's Opportunity in the Lithium Battery Boom," January 30, 2018.

Lithium resources by country (million/tons)	Lithium reserves (million/tons)	Lithium producers	Lithium importers	Electric car consumers
Bolivia: 73	Chile: 8.6	Australia: 54.5%	China: 24%	China: 56%
Argentina: 17	Australia: 2.8	Chile: 23.6%	South Korea: 20%	Europe*: 23%
Chile: 9	Argentina: 1.7	China: 9.7%	Japan: 16%	USA & Canada: 17%
USA: 6.8	Others: 1.1	Argentina: 8.3%	USA: 10%	Rest of the world: 4%
Australia: 6.3	China: 1	Zimbabwe: 2.07%	Belgium: 10%	
China: 4.5	USA: 0.63			

* Includes only Norway, Germany, France, Netherlands & the United Kingdom.

Source: Jerez et al., 2021, edited by the authors.

Table 1: Global chain of lithium resources for EV applications by country.

Addressing these imbalances through science diplomacy between the American North and South could minimize overall costs and maximize benefits, while more equitably distributing both across stakeholders throughout the Americas. Historically, science diplomacy between North and South America has also spurred increased collaboration between different stakeholders and sectors within countries in South America (Soler 2014), which could benefit Chile, Argentina, and Bolivia as all three countries are at different stages of lithium production and policy development.

It is not entirely clear that the potential environmental benefits of EVs outweigh the environmental degradation necessary to meet consumer demand, given current technologies for battery production, mining, and energy production (Riofrancos et al. 2023). The distribution of costs and benefits lies at the core of these discrepancies with most of the environmental costs borne by populations close to mining sites and manufacturers, and the social and environmental benefits going to consumers of EVs.

Lithium extraction imposes costs on the local population in the form of environmental degradation. In particular, the competition for water in lithium mining areas is so high that it could threaten the livelihoods of nearby communities, including indigenous communities (Romero et al. 2012) who are already marginalized. In fact, lithium mining leads to water scarcity not only in the immediate mining areas, but also in adjacent areas (Liu and Agusdinata 2020).

However, there might also be significant benefits to local populations. These benefits depend largely on the local management of the lithium industry through indirect job creation and the redistribution of royalties and taxes. In the case of Argentina, the lithium industry employs 37,794 people in the mining industry, with recent increases in jobs (9.8% from November 2021 to November 2022; MEA 2022). In Chile, the revenues generated by the lithium industry are among the largest of Chilean export commodities (Cochilco 2020). Benefits might reach workers through wages, the government through royalties, and adjacent populations indirectly through overall increased economic activity. Mining companies benefit through revenue, but it is worth noting that these firms are not all South American-owned. The extraction of lithium by foreign-owned firms amounts to an extraction of profits from South America (see Espina 2022; Ibarra 2022; Reuters 2023).

Evidence from other mining industries shows that populations close to mining sites can benefit from resource exploitation. For example, Aragon and Rud (2013) found that in a gold mine in Peru, the increase in the demand for local inputs, like labor or other local purchases, led to an increase in real and nominal income, an increase in consumption, and a decrease in poverty for nearby households. However, to the best of our knowledge, there has not been an effort to quantify or identify these potential effects for any lithium mine in the LT.

Moreover, the benefits of the mining industry might not be homogeneously distributed between the three countries of the LT. For instance, the 2021 Infrastructure Investment and Jobs Act in the US incentivizes trade with the country's commercial partners. Here, Argentina and Chile are most advantaged. However, the US market is not the only available one. In fact, Bolivia has partnered with a Chinese company, which could open up Chinese markets for Bolivian lithium.

The transition from internal combustion engine vehicles (ICEVs) to EVs can bring significant benefits to places that adopt EVs. For instance, EVs emit less heat than ICEVs, thus reducing the intensity and number of heat islands in urban settings (Li et al. 2015). Perhaps the most discussed and evident benefit is the lower carbon emission of EVs, which depends on the specific power sources available to charge the vehicles. However, even when power plants used to charge EVs burn coal, gas, or other "dirty" fuels, EVs still provide emissions reductions due to higher overall efficiency than ICEVs (Requia et al. 2017). Beyond this, there is an array of local benefits that EVs could provide, such as a decrease in local pollutants and noise pollution (Noel et al. 2018).

Table 2 summarizes some of these costs and benefits, focusing on social, environmental, and economic impacts in South America and North America.

	South America		North America	
Supply Chain Step	Costs	Benefits	Costs	Benefits
Extraction	Water scarcity, environmental degradation, Societal health and quality of life degradation due to water shortages - especially among indigenous populations	Local investment, wages, job creation, royalties	Import cost of raw materials, supply chain uncertainty with changing geopolitics	Revenues from Foreign Direct Investments, lower material cost due to lower wages and less environmental regulation, short-term availability of materials
End use in batteries in vehicles		Climate change mitigation	High priced vehicles decrease society's access to driving	Climate change mitigation, reduced air and noise pollution for better health,

Table 2: Social and environmental costs and benefits of current lithium supply chain for EV applications distribution across the Americas

While there might be some other indirect costs to lithium-consuming areas, like those brought about by competition in the automobile market or the energy sector, here we focus on the particular environmental and social benefits that come directly from production and consumption.

The costs in South American countries fall largely on the local environment and communities, many of whom are indigenous populations. The current state of lithium mining leads to water scarcity and environmental degradation, which, in turn, lead to quality of life degradation including health impacts due to clean water shortages. Some of the most impacted groups are indigenous populations who live near the LT, who will not benefit as much from the overall potential mitigation of climate change due to EV use if they are ultimately forced to relocate due to mining activity taking over the land or depleting water access. Meanwhile, populations in the US experience direct benefits due to cleaner air from lower EV emissions and less noise pollution due to quieter power sources in EVs, both of which contribute to better health outcomes (Khreis et al. 2023).

While countries in the LT invest in mining companies, there is also foreign direct investment from the US, leading to economic benefits flowing to both the North and South. Furthermore, auto manufacturers selling EVs in the US benefit from the lower cost of lithium extraction associated with lower wages and fewer environmental protections present in the LT as compared to domestically or from other major sources such as Australia.

iii. Current policies in the Lithium Triangle and the United States

This section discusses existing policies and areas for growth across governments and private consortia in the Lithium Triangle and the US. Figure 2 shows the concentrated location of known lithium reserves in the LT, spanning Chile, Argentina, and Bolivia. Importantly, not all reserves are easily accessible for lithium extraction, and not all locations are actively mined.

Figure 2: Lithium Ore Reserves in the Lithium Triangle (LT). Adapted from: Inter-American Development Bank, from the US Geological Service (IDB 2022)

Chile policy background

Lithium has been an essential metal on Chile's political agenda for the last decade. In1979, it was declared a non-concessional resource of national interest, and its extraction and commercialization was reserved for the State. Under this condition, the right to exploit lithium could be carried out or granted by the State to companies with special lithium operation contracts or administrative concessions licenses (Cochilco 2009). For decades, Chile has only given extraction permission to two firms: Chilean giant SQM (Sociedad Química y Minera), which is one of the world's biggest lithium producers, and US firm Rockwood Lithium/Albemarle. In June 2023, the Chilean government released a new National Lithium, which creates national opportunities for stakeholder engagement, lithium discovery, studies of salt flats and lithium, and a state-owned lithium company that can also partner with other companies (Gobierno de Chile 2023).

Since 2014, the Chilean government has promoted a series of institutional arrangements, such as the creation of the National Lithium Commission (CNL), an interdisciplinary group of experts from public and private sectors, with the purpose of advising the government on sustainable national lithium policy (Poveda 2020). CNL´s first report highlights lithium's potential environmental impacts on the complex and fragile of brine ecosystem, incorporates a vision of local community rights for the use of public water and land, advocates for adequate compensation for negative impacts that the projects may generate, and recognizes the need for public policies that promote research and technology development to improve capacity and increase competitiveness. Additionally, they recommended the renegotiation of contractual conditions with SQM and Alembarle, which partners with the Chilean Production Development Corporation (CORFO), the Chilean government agency that is in charge of lithium mining (CNL 2015). The 2023 National Lithium Plan aligns with these recommendations (Gobierno de Chile 2023).

The contract negotiation process allows the Chilean government to increase lithium production in the country while redistributing the income from exploitation among the companies, the State, and the local communities. In addition, the public policies surrounding research, development, innovation, and added value in the Lithium supply chain have been promoted to the public. The policies establish a commitment for companies to make direct financial contributions in favor of plans and programs designed to fulfill these purposes (Poveda 2020).

However, these policies have not achieved their stated goals of economic growth and redistribution. Recent debates in Chile regarding the receipt or lack of receipt of royalties from lithium extraction point to political concerns of resource redistribution matching the above stated goals. Critical environmental and social impacts of lithium extraction include a growing scarcity of water resources, the existence of indigenous communities and the sensitivity, and the overall fragility of the Salar of Atacama ecosystem. Extraction affects flora, soil, biodiversity, and climate, all of which are costly or impossible to revive. Additionally, one of the most complex issues linked to lithium extraction is the impact on the hydrogeological balance in wetlands, alluvial mud, lagoons, and other water sources (Lunde Seefeldt 2022). It is possible that the newly announced government interest in stakeholder engagement and research could help address these concerns, especially if scientific and indigenous knowledge are sought and applied to the policies and actions that will stem from the new strategy.

Argentina policy background

Argentina has no unified, clear public policy regarding lithium extraction. National, state, and federal provinces share responsibilities regarding resources, making policy-making highly complex (see López Steinmetz & Bing Fong, 2019). Pronounced political changes also complicate the implementation of long-term strategies. The result is a fuzzy setting characterized by great interest from multinational companies in lithium mining, high public-private interaction, and uncertainty of the local population.

Policies at the provincial level are diverse. The provinces of Salta and Catamarca are dominated by a pro-mining policy, where the state acts as a facilitator for private companies (Fornillo 2015a, p. 75). In contrast, the province of Jujuy takes a more active role to maximize benefits from resource extraction. In 2011, Jujuy declared lithium a strategic mineral, a revenue-generating asset based on the implementation of value-added processes and the creation of local jobs (Barandiarán 2019). Aiming sustainable growth and socio-economic development, the provincial government and the Universidad Nacional de Jujuy participate in several research and development initiatives with the collaboration of the Argentinian National Scientific and Technical Research Council (CONICET) and other national public universities.

In the 1990s, the policies of neoliberal President Carlos Menem led to a "business-friendly" mining policy for the Argentine national government. This policy continued during the 2003-2015 Kirchner Era (Hafner et al. 2016, 31) and was consolidated under the presidency of Mauricio Macri (2015-2019). With this background, it is unsurprising that the Argentine Mining Secretariat limits itself to promoting resource extraction without further industrialization processes such as refinement and battery manufacturing within the country (Fornillo 2015, 76). Therefore, the three provinces often find themselves in a "war for lithium" (Dinatale 2016), trying to win the race for attracting investors. There have been recent efforts to unite the three provinces in their efforts to manage and control production in the region under the Regional Lithium Committee, but no tangible results have emerged so far. With the new government of Alberto Fernández, the pressure to extract natural resources had increased even more, as shown by his announcements regarding Vaca Muerta, the huge deposit of shale oil and shale gas in Northern Patagonia (Ocvirk 2019).

Bolivia policy background

Despite having the world's largest known quantity of lithium reserves, Bolivia is not a major producer of the mineral (see Table 1). Bolivia's state ownership of lithium extraction is nearly absolute. This has been regarded by some scholars as one of the country's main barriers to attracting private investments into the sector (see, for example, Mares 2022; Martin 2022). Besides these institutional barriers, some point to geography and infrastructure as hurdles for the development of the industry. The lack of roads and relative inaccessibility of deposits has prevented the lithium industry from flourishing in Bolivia (Martin 2022).

The country recently launched a call for proposals for private investors to develop lithium extraction in the country. The Chinese battery company CATL won the bid for the contract (Reuters 2023), but the exact terms of the extraction sites have not yet been publicized. This constitutes a break in the country's previous approach to the sector, in which the state primarily extracted and processed materials (Revette 2017). But, despite having one of the largest lithium deposits in the triangle, no private firm has tried to exploit this resource in the country.

US policy background

Policies in the Global North can have effects close to home as well on the Global South. In the context of lithium mining, large government incentives and investment in vehicle electrification lead to a quick increase in demand for battery components, including lithium. Recent federal legislation in the United States, namely the Infrastructure Investment and Jobs Act, incentivizes electric vehicle sales through tax credits, funding for research and development, as well as a publicly-funded national EV charging network (Public Law 117-58, 2021). Automakers have aligned with the new policies, announcing goals to shift manufacturing and sales in the US to majority or a high proportion of EVs by 2035 (IEA 2022). However, the raw materials needed in EV components, namely lithium for batteries, are still not being produced in the US at a scale to even come close to meeting this projected demand.

The US is dependent on products made with imported lithium due to minimal domestic access. As of April 2023, there is only one lithium mine in the entire country. However, there are more lithium reserves in the US, including near the border with Mexico. There are domestic lithium mines in the works in the US, but timing for operations and lithium production is still unclear (CRS 2022). Policy and technology will shape how quickly the US can ramp up its domestic lithium supply. However, setting up new mining operations is not a fast process, especially in the context of a mineral such as lithium with only one existing facility to reference. In the overall mining sector in the US, it takes an average of two years, and up to 11, for the required Mine Plan approval process, excluding the time to develop the plan or set up operations after plans are approved (GAO 2016). There are domestic lithium mines in the works in the US, but timing for operations and lithium production is still unclear (CRS 2022).

Under the recent Inflation Reduction Act (Public Law 117–169 2022), final assembly of EVs and sourcing of critical minerals used in EV batteries must take place in North America to receive tax credits. In order to qualify for these subsidies, critical minerals including lithium have to be sourced from the US or qualifying Trading Partners. This requirement is being phased in, allowing for time to adjust to the new incentives. Starting in 2024, the requirement applies to only 40% of critical minerals found in batteries, and by 2028, the sourcing requirement climbs to 100% (PL 117-169, sec. 13401).

Countries with free trade agreements with the US include Chile as well as Australia, the leading producer of lithium outside of South America (USTR 2023). Due to the lack of a free trade agreement with the US, both Argentina and Bolivia would face additional barriers to contributing to the lithium market associated with demand from electric vehicles sold in the United States. Either way, EV prices for US consumers would likely rise, either due to manufacturers sourcing minerals from Australia, a country with higher wages and more stringent labor laws, in order to meet requirements, or due to manufacturers not meeting the requirements for government subsidies.

The US is already ramping up battery production and, by 2020, 70% of battery cells and 87% of battery packs for EVs sold in the US were produced in the US (Gohlke and Zhou 2020). However, lithium mining within the US would take more time to set up than the policy-makers wish to wait before accelerating EV consumption. Creating a secure, sustainable supply chain across the Americas with policies that allow for imported lithium from South American countries could allow the US to remain competitive in the EV market and supply chain while minimizing reliance on countries like China with more national security and sustainability risks and concerns. Decision-makers in the US are aware of these opportunities, with non-partisan reports to Congress including recommendations for "diplomacy initiatives'' alongside increased data and mapping initiatives, tax incentives, and other policies (CRS,2022).

iv. How supply chain injustice has been addressed in agriculture and minerals

Threats to sustainability and justice along other commodity supply chains have been tackled through a variety of governance arrangements. Among these, supply chain policies (SCPs) encompass a wide array of initiatives that share three main features: 1) they are usually initiated by private actors, such as multinational firms and corporations, that have control over several stages of the supply chain, 2) they involve agreements between multiple stakeholders, usually including NGOs, civil society, and state actors, and 3) they are based on market mechanisms driven by consumers and retailers in distant markets.

The effectiveness, legitimacy, and equity of these policies has been evaluated in several cases involving the regulation of agricultural and forestry supply chains that threaten biodiversity and ecosystems—mostly forests—in the tropics and subtropics (e.g., Lambin et al. 2014). Policy evaluations of these regulatory regimes in other, non-agricultural supply chains, such as those of minerals, are scarcer.

Existing evaluations in agricultural supply chains show that the success of SCPs depends on the type of policy instrument and the context of its implementation. One of the most cited success cases is the Brazilian Soy Moratorium, which substantially reduced deforestation rates in the Amazon driven by the expansion of soybean cultivation into tropical forests. In response to pressure from retailers in soy-importing countries and NGOs, major soybean traders signed a moratorium agreeing not to purchase soybeans grown on lands deforested after July 2006 in the Brazilian Amazon (Gibbs et al. 2015). Recent studies have found that the soy moratorium reduced deforestation rates by 35% on average (Heilmayr et al. 2020). In Chile, with the Joint Solutions Project, the three largest forestry companies agreed to stop clearing native forests for plantation expansion (Lambin et al. 2018). After adoption of this zero native deforestation standard, properties controlled by these companies experienced a significant reduction in deforestation in comparison to other forestry properties in Chile that amounted to as much as 23% reduction in annual deforestation rates (Heilmayr and Lambin 2016). So far, this market exclusion mechanism has been limited to single commodities and regions.

Private sector standards have also been established to provide incentives (rather than sanctions used by market exclusion mechanisms) to those producers adopting "good" practices. Among these, a variety of certification schemes have been designed and implemented to accredit goods and services that have met defined production standards meant to protect the environment and social welfare in the places of origin (Blackman and Rivera 2011). Evaluations of certification schemes show mixed evidence for reducing environmental and social impacts. For example, a major forestry certification had no or minimal effect on deforestation in Mexico, Cameroon, and Peru, but reduced deforestation in certified forests in Chile and Indonesia (Lambin et al. 2018). For minerals, certification schemes for responsible sourcing (influenced by EU and US legislations) perform differently depending on the commodity supply chain involved, and are more developed for conflict minerals (tin, tungsten tantalum and gold) than for minerals needed for renewable energy technologies (cobalt, graphite, lithium, manganese and nickel) (Deberdt and Le Billon 2021).

Compliance under these certification schemes varies for elements used in specialized energy storage and electric contexts, such as tantalum and gold. Tantalum has been most successful, as about 95% of producers are compliant. However, gold in particular, has experienced challenges reaching high levels of compliance (Young 2018). Whether and how these sectoral policies and standards (either based on sanctions or incentives) can be successfully emulated to increase sustainability and equity in other emerging commodity supply chains (e.g., lithium) remains an open question. These and additional examples of SCPs can be examined to see what outcomes may look like in different cultural, geographic, and political contexts.

v. How has science contributed to policies in the lithium supply chain?

There is a lack of studies on the fragility of the LT ecosystem in Chile (CChEN 2016) or the sustainability of lithium extraction. However, the regulation of mining as a sector in Chile is extensive. In particular, in Chile the Environmental Evaluation Service (Servicio de Evaluación Ambiental, or SEA) is in charge of environmental impact assessments before the start of any mining project in Chile. The agency's complete guide to conducting an environmental study must be submitted to start operations in the lithium mining areas, which is a similar process to the US National Environmental Protection Act requirements for environmental impact assessments (EIS) (Public Law 91–190 1970).

However, no clear guidelines or thresholds for sustainable use are provided in these guidance documents. Water resource evaluations are required for EISs in the US as well as under the SEA guide, but even if negative impact is shown, mining may still be allowed if mitigation strategies are put in place and the overall benefit of the project is determined to outweigh the costs. In fact, some disagreements persist between mining companies and regulatory agencies in Chile regarding the extent and actual environmental consequences of lithium mining in the region (Houmann 2019), even when scientific evidence shows the significant negative impacts it has had over the past 20 years (Liu et al. 2019).

The Chilean Nuclear Energy Commission (CChEn) also regulates the lithium sector in Chile, requiring specific data from mining operations. However, it is unclear how those data are used and what standards or thresholds must be met, if any. The data include but are not limited to: number of wells drilled, brine flows by well, water table, evaporation measures, and potassium and lithium concentrations (CChEN 2016).

In Argentina, the Regional Lithium Committee is in charge of coordinating efforts between the provinces and the national government on research, production, and trade in the lithium sector. As such, the Ministry of Science and Technology of Argentina had been invited to be part of the committee. Nevertheless, as of April 2023, there is no clear documentation on specific measures or thresholds the committee will focus on, nor of its current status.

Governments can design guidelines and regulations based on existing studies done on the environmental impacts of mining. For example, a 2019 study by Liu et al. looks at whether there is any evidence of environmental degradation in areas around lithium mining activities. In particular, the study uses five environmental indicators measured using satellite imagery: Normalized Difference Vegetation Index, Daytime Land Surface Temperature, Soil Moisture Index, Nighttime Land Surface Temperature, and Net Evapotranspiration. The values reported in the article could serve as a starting point for setting methods, standards, or thresholds for monitoring potential damages to the environment. Regardless, more studies are needed that use locally collected data, such as water quality and quantity, close to the mining regions.

III. Role of science diplomacy in advancing a more sustainable lithium supply chain

Science can contribute to the canon of knowledge used by lawmakers and regulators to set methods, thresholds, and standards to sustainably source lithium. This knowledge can be used both domestically for policy development, and internationally for science diplomacy in the context of the global lithium supply chain. Science diplomacy may even include international collaboration and sharing of recommendations between countries with established environmental impact policies such as the US, and countries such as Argentina, who are still developing their policies. This collaboration could not only inform policies using scientific evidence, but also facilitate strong bilateral relationships to reach economic goals and environmental protections across many stages of the supply chain. Figure 3 shows the direct connection between the supply chain steps identified in Figure 1 with extraction centered largely in South America leading to availability of EVs in North America. This bidirectional connection opens the door for science diplomacy across the supply chain.

Stakeholders along the supply chain can agree to set standards and criteria, such as those provided by interdisciplinary sciences, to define which lithium extraction operations are socially and environmentally responsible and which are not. Then, stakeholders such as policy-makers or upstream industry actors in the supply chain can develop and apply rigorous methodologies, such as those provided by geochemical sciences, to trace the origin of lithium used in electric vehicle batteries, and ensure that it is sourced from responsible operations.

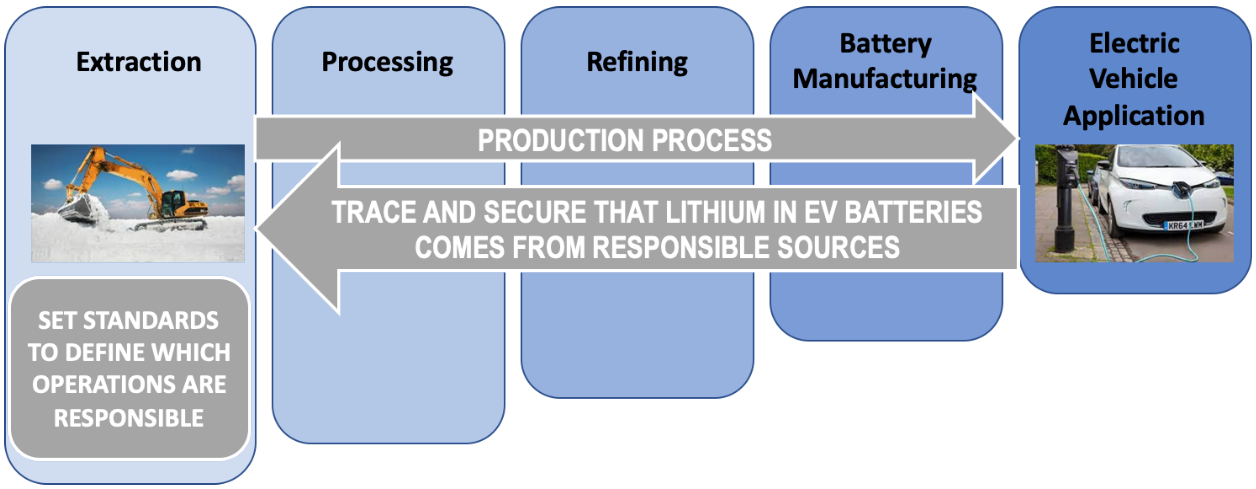

Figure 3. Supply Chain Connection Opportunities for Science Diplomacy to Foster Equitable and Sustainable Lithium Supply Chains.

i. Sustainability thresholds across borders

Given the lack of existing sustainability thresholds as discussed in Section 2, there is ample opportunity for an international approach for their development.

In response to the minimal guidance from the public sector, private sector actors in lithium mining, including some in the Lithium Triangle, have developed their own system through the membership organization, The Initiative for Responsible Mining Assurance (IRMA). IRMA is an international private company that audits and certifies lithium extraction operations according to their own standards. IRMA lists [critical requirements]() that the firms must meet in order to be certified, consisting of multiple criteria divided into four principled categories: 1) business integrity, 2) planning and managing for positive legacies, 3) social responsibility, and 4) environmental responsibility.

While these principles create a framework for social, environmental, and economic sustainability with equity considerations, some of the requirements lack specificity. For instance, one environmental responsibility requirement states "Water quality and quantity are being monitored at the mine site (4.2.4.1. a through e) and adverse impacts resulting from the mining operation are being mitigated (4.2.4.4)" (IRMA 2020). These concerns are in line with studies showing decline in fresh water availability in the region for people, plants, and animals. However, without definitions of water "quality" or measures for changes in water quality or quantity, there is no way to determine if the action supports IRMA goals. Mutually agreed-upon definitions, measures, and goals would strengthen IRMA's ability to link certification to the organization's vision that the mining group "respects the human rights and aspirations of affected communities, provides safe, healthy and supportive workplaces, minimizes harm to the environment, and leaves positive legacies" (IRMA 2022). While there is potential for non-governmental groups such as IRMA to enhance standards, existing literature also recommends government intervention to develop such frameworks (Sauer and Seuring 2017).

Once standards and thresholds are developed, there are various ways to meet environmental impact goals. Mitigating damage during the mining process is one method. Another is to replenish resources after overuse. Experts at the InterAmerican Development Bank suggest the possibility of refreshing water resources during and after mining practices that consume large amounts of water. This type of corrective action is mentioned in the IRMA standards as part of the "planning and managing for positive legacies" principle (IRMA 2022).

However, neither justifications nor corrective actions are well-defined by IRMA. In another example, IRMA states that "companies are expected to provide to auditors a reasonable science-based justification" without defining "reasonable" or "science-based" (IRMA 2022). Other standards for science-based observation for certification are also present in IRMA documentation, opening the door for communication and collaboration to further refine definitions and thresholds.

ii. Tracing materials along the supply chain

Because of its complex supply chain, ensuring that lithium comes from socially and environmentally responsible sources is complicated for consumers of EVs and their batteries. Car original equipment manufacturers (OEMs) have announced that they will increase the transparency of their supply chains for EV batteries. So far, the OEMs have employed document-based traceability systems, which can be falsified, and must be independently controlled and audited to provide credibility.

Geochemical sciences can play a role in developing procedures to facilitate more transparent and accessible tracing of lithium in EV batteries. Desaulty et al. (2022) presented an innovative geochemical approach based on analytical fingerprints of lithium isotopes of raw and processed materials to determine the origin (mine site, refining plant) of ores and products using measurable material properties. Although lithium extraction and purification processes tend to erase its geological origin, geochemical processes can differentiate lithium salts produced from ores of similar origin, but for which the extraction process may have a different environmental or social impact. It is an independent, reliable, and tamper-proof approach to auditing the document-based tracing system sought after by end users, by answering the question: "Does the lithium match its declared origin?"

Implementing a certification system for lithium will boost the development of a responsible, sustainable, and stable supply of raw materials for batteries, guaranteeing the respect and protection of human rights and the conservation of the environment along the supply chain. The development of lithium certification is of critical importance, especially in the context of the political will to re-industrialize battery production in Europe and the US, which are defending sustainable battery manufacturing projects. Northern policy goals of protecting people and the environment could be better assessed and met with certification policies, and such certification would align with the recent EU regulation for responsible and sustainable sourcing of several other raw materials, such as tin, tantalum, tungsten and gold, and the consumers' interest in sustainable products. Creating procedures to trace lithium supply could thus facilitate further international policies and agreements to uphold the social and environmental sustainability standards around which many trade policies are designed, and help highlight the Americas as leading nations meeting these standards.

IV. Incorporating science into diplomacy

Science diplomacy approaches can support global efforts to mitigate climate change while improving distributive justice across supply chains to benefit local economies and health.

i. Lessons in tracing and thresholds from agriculture and other minerals

Agricultural examples can set precedents for the use of science diplomacy to mitigate issues such as climate change, local environmental degradation, and undue burdens on specific communities.

Since the early 2000s, food companies have responded to increased information and pressure about the environmental and social outcomes of their sourcing activities by adopting a range of agricultural supply chain policies (ASPs). ASPs can be implemented through a variety of mechanisms that require cross-border coordination, such as the use of market exclusion mechanisms (excluding suppliers based on undesirable production practices, e.g., deforestation) and/or codes of conduct and certification requirements (setting criteria that farmers should meet for inclusion and/or preferred market access). If policy-makers in one country set requirements or incentives for retailers, the rest of the supply chain will be impacted. Therefore, diplomatic coordination between countries involved in every step of the supply chain can help mitigate imbalances of costs and benefits for different countries. In this case of the food supply chain, over 484 major food retailers, traders, and processors now have some form of ASP focused on forests (Rothrock et al. 2019) due to cross-boundary coordination. Yet, the degree to which these policies improve or hinder global conservation and rural livelihoods remains unclear, suggesting the need for further study and attention.

Garret et al. (2021) found evidence that ASP implementation mechanisms have improved forest conservation and livelihood outcomes in more than half of the cases where additionality was rigorously assessed, and in some cases have generated positive spillovers. Compliance does not appear to be the major challenge limiting the potential of most ASPs. Yet, even though most ASPs have dual conservation and livelihood goals, there is little evidence of win-wins across both types of outcomes, and adoption patterns give rise to equity concerns.

On the other hand, mineral supply chain policies (MSPs) have evolved significantly since the first models were adopted in the oil, diamond, and conflict minerals sectors. Investments by mining companies for environmental and social responsibility have generated new models for mining project development but have also raised questions about the real intentions behind these investments—reputational risk management, or sincere corporate social responsibility? This question is especially difficult to answer when scientists and decision-makers are not part of the process of MSP development. Leaving out scientists leads to a lack of transparency and of scientific evidence used by policymakers to assess achievement of the stated outcomes, and leaving out decision-makers leads to a lack of accountability to the public sector.

Critics have pointed out the disconnect between corporate or state actors and the benefits received by mining firms in the implementation of MSPs. Too often, unintended consequences have severely impaired the legitimacy and effectiveness of MSPs. Nevertheless, it would be wrong to assume that all MSPs are used by companies as reputational tools (Deberdt and Le Billon 2021). While slow, change seems to occur at certain levels of the supply chains and in specific commodities, especially when science diplomacy is part of the process.

ii. Need for international research collaboration in defining thresholds and allowing tracing

Efforts have emerged in both the private and public sectors to implement guidelines for lithium mining. In 2021, Chile implemented one of the first environmental guidance documents for lithium exploitation projects in salt flats using the framework of the Specific Environmental Impact Assessment for SEA, which analyzes a project's impacts on natural resources, biodiversity, cultural heritages, health, and community customs (SEA 2021). Among the private initiatives, IRMA certification also includes multiple criteria such as social and environmental responsibility (IRMA 2020). However, specific methodologies and requirements of the assessment are not clearly established in both cases.

Robust methodologies for assessing the hydrological impacts of lithium mining will be crucial for integrating scientific knowledge into regulations for the lithium supply chain. A recent study suggests that a framework that integrates remotely sensed and ground-based climate data, physical hydrological assessments, and special residence time to determine changes in water storage and fluxes in Atacama brines could be a more appropriate methodology to understand the complex hydrological system of brines and to estimate environmental impacts (Moran 2022).

Additionally, some studies have found a negative correlation between lithium mining and flamingo abundance in the Chilean Andes (Gutiérrez et al. 2022), perhaps as a result of water scarcity produced by lithium mining (Gutierrez et al. 2022; Marconi et al. 2022). Further research is needed to understand how lithium mining affects biodiversity in the LT. To a large extent, scientists can better estimate population dynamics of fauna in the LT. This is needed not only for charismatic species like the flamingo, but for all wildlife that depends on the ecosystem.

Responsible certification initiatives for conflict minerals, such as tungsten, tantalum, tin and gold, could apply to lithium mining (Van den Brink 2019). A comprehensive certification scheme designed to identify responsible sources of lithium should include mechanisms for traceability to ensure the integrity of the supply chain and verify ethical and sustainability claims. An innovative geochemical fingerprint approach based on lithium isotope analysis could be a useful tool for tracing the origin of lithium (Desaulty et al. 2022). Collaborative research could expand knowledge about brine systems in mining areas and the associated impacts on water and the natural environment, as well as develop consistent, international reference standards for environmental impact assessments. Additionally, the development of an interoperable, accessible, international system for data integration and processing would also facilitate international collaboration, benchmarking, and tracking. Furthermore, international research collaboration could increase knowledge, productivity, and creativity, leading to a more efficient use of resources in developing a sustainable lithium supply chain.

Governments, local and international research institutions, local communities, and other interested parties in the lithium extraction sector can play a role in this effort. State actors in the LT can mediate communication between international scientists and local stakeholders. Given the levels of national investment in lithium activities in the LT, state efforts to increase international collaboration may be key to establishing sustainability guidelines and traceability mechanisms. Scientists and organizations involved in these solutions will need access to reliable data and field sites to draw credible conclusions. Federal governments may play a key role in granting permits to researchers and connecting them with the local parties interested and affected by the lithium industry. Increasing diplomatic connections will benefit stakeholders across the North and South, as well as promote research to address global challenges in the lithium supply chain.

iii. The need for collaboration and communication across governments, companies, and communities

Socially responsible lithium mining requires stakeholder involvement, especially local and indigenous communities, who are most adversely affected by lithium mining. Involving local communities in setting standards can potentially allow for higher rigor in sustainability guidelines. Since local communities bear the direct costs of resource exploitation, they might bring stronger opinions to the table on the potential negative externalities of lithium extraction. Stakeholders that do not actively engage with local communities risk overlooking harder-to-measure consequences of mining activities, and even perhaps face rejection by local communities (Conde and Le Billon 2017; Majer 2013).

Communication between different stakeholders has been considered in certification processes, like IRMA, that include multinational interdisciplinary stakeholder collaboration to set standards and assess compliance. Members of this committee include NGOs, mining and mining exploration/development companies, original equipment manufacturers (OEMs), labor groups, and local communities.

V. Policy lessons and recommendations

Our analysis suggests a potential role for science in diplomacy for developing a more sustainable and equitable lithium supply chain. Governments, private companies, scientists, and local communities can work together across borders to develop achievable shared goals and standards, especially as they relate to sustainability throughout the lithium supply chain for EV batteries. This conclusion is supported by four main findings:

First, lithium supply and demand for manufacturing lithium-ion EV batteries involves many different public and private stakeholders located in different countries, with major producers and consumers in the Americas. As such, any policy aimed at regulating the lithium supply chain must include diplomatic efforts for involved countries to negotiate according to the interests of their governmental, citizen, and indigenous communities.

Second, the distribution of costs and benefits involved in the lithium supply chain is unequal among countries of the Americas, which undermines the sustainability of this economic activity. We showed that local populations in the LT of the central South American Andes disproportionately bear direct costs associated with increasing lithium extraction, while the populations in North American cities enjoy more direct benefits associated with reduced air and noise pollution due to the replacement of ICEVs with EVs.

Third, we draw some policy lessons from experiences of interventions involving multiple countries and stakeholders that were successful at reducing supply chain injustice. We show that mechanisms that exclude operations producing sustainability standards from exporting their product to overseas markets have had success with their sustainability targets. We also show that certification schemes have positive results in some mineral supply chains when preferential access to overseas markets is granted to operations that produce above sustainability standards.

Fourth, we identified at least two points in the lithium supply chain where science can produce critical inputs for policy-making and diplomacy efforts. This leads to the policy recommendations for governments and scientists working together across borders to:

1) Use concepts and tools developed by sustainability sciences to assess the environmental and social performance of economic activities, and define thresholds and set standards to identify mining operations that are producing sustainably, and those that are not.
2) Trace the origin of lithium that is used to manufacture batteries for electric vehicles with geochemical methods, thus verifying whether lithium has been sourced sustainably (as defined by policy thresholds proposed in recommendation 1) mining operation).

Integrating these scientific inputs in a diplomatic process will be critical to reduce supply chain injustice.

Multilateral opportunities and collaborations are at the core of these findings. South American countries from the LT disproportionately bear the direct costs of the EV transition, while North America is one of the main beneficiaries. Scientific evidence can help address these pressing issues in the context of the international trade for lithium.

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