The non-green effects of going green: Local environmental and economic consequences of lithium extraction in Chile *

Leonardo Peñaloza-Pacheco† Vaios Triantafyllou ‡ Gonzalo Martínez §

March 4, 2024

[THIS IS A DRAFT. PLEASE DO NOT CITE OR CIRCULATE.]

Abstract

In this paper, we analyze the local environmental and economic impacts of lithium extraction in the Atacama Salt Flat (ASF) in Chile. We use measurement well levels to estimate the effect on water availability. Also, we use satellite data to estimate the effects on vegetation at a resolution of $300m \times 300m$, the local human settlements at a resolution of $100m \times 100m$, and nighttime light density at a resolution of $500m \times 500m$ near the ASF. First, we find that during the 2013-2019 period, there was a significant reduction of up to 1 standard deviation in the groundwater levels around the ASF, compared to other wells in the north of Chile. Also, we compare changes over time in NDVI and find that an increase of 1 standard deviation in our measure of exposure to lithium extraction reduced vegetation in nearby areas by 4% relative to the vegetation levels in the baseline period (2013). Further, we show that the negative effect on NDVI was greater for those locations closer to the ASF and with particularly higher levels of vegetation at baseline. Also, human populations in the local villages were reduced by 11% relative to baseline values for each kilometer closer to the ASF. Lastly, we demonstrate a reduction of 1% in nighttime light density relative to baseline for a 1 standard deviation increase in our measure of exposure to lithium extraction.

*We appreciate the comments and suggestions of Ryan Bailey, Agustin Olivo, Nick Sanders, Sunoj Shajahan, and participants in seminars and conferences at Development Bank of Latin America and the Caribbean - CAF, Cornell University, Universidad Católica Argentina, the International Economic Association World Congress, and the Eastern Economic Association Annual Meetings.

†Cornell University and Center for Distributive, Labor and Social Studies (CEDLAS), IIE-FCE, Universidad Nacional de La Plata. E-mail: leopacheco93@gmail.com.

‡Cornell University. E-mail: vaios.tria@gmail.com.

§Université de Liege. E-mail: gonmartinez95@gmail.com

The non-green effects of "going green": Local environmental and economic consequences of lithium extraction in Chile

Abstract

In this paper, we analyze the local environmental and economic impacts of lithium extraction in the Atacama Salt Flat (ASF) in Chile. We use measurement well levels to estimate the effect on water availability. Also, we use satellite data to estimate the effects on vegetation at a resolution of $300m \times 300m$, the local human settlements at a resolution of $100m \times 100m$, and nighttime light density at a resolution of $500m \times 500m$ near the ASF. First, we find that during the 2013-2019 period, there was a significant reduction of up to 1 standard deviation in the groundwater levels around the ASF, compared to other wells in the north of Chile. Also, we compare changes over time in NDVI and find that an increase of 1 standard deviation in our measure of exposure to lithium extraction reduced vegetation in nearby areas by 4% relative to the baseline vegetation levels. Further, we show that the negative effect on NDVI was greater for those locations closer to the ASF and with particularly higher levels of vegetation at baseline. Also, human populations in the local villages were reduced by 11% relative to baseline values for each kilometer closer to the ASF. Lastly, we demonstrate a reduction of 1% in nighttime light density relative to baseline for a 1 standard deviation increase in our measure of exposure to lithium extraction.

JEL Classification: D30, F22, J61, O15 *Keywords:* Environment, Chile, Lithium.

1 Introduction

The *Clean Energy Transition* and the reduction of greenhouse gas (GHG) emissions, as agreed within the United Nations Framework Convention on Climate Change (UNFCCC), are key objectives for governments around the world. Those efforts are concentrated on transforming both the production of secondary energy, through the introduction of renewables, and the final energy used directly by consumers. The *green* transition for final energy use is largely based on the introduction of sustainable transportation. According to the U.S. Environmental Protection Agency (EPA), transportation accounts for almost 15% of GHG emissions worldwide, calling for the introduction of electric vehicles (EVs) as a key component of the transition (Environmental Protection Agency, 2023)

Over the past years, sales of EVs in the United States, Europe, and China have increased rapidly. More than 6 million EVs were registered in these economies in 2021, compared to less than 1 million in 2016 (International Energy Agency, 2022b). The projected market share of EVs is set to reach 96% by 2035 from 10% in 2020, a trend that is expected to continue beyond this date (Boston Consulting Group, 2021). Currently, half of all sales of cars in the world are "covered by zero-emission vehicle mandates", while the U.S. and the E.U. are pushing for adoption of EVs through tax incentives and financial support in the *Inflation Reduction Act* and the *Green Deal Industry Plan*, respectively (International Energy Agency, 2023). However, as is true with most *green* technologies, EVs require energy storage and, therefore, their ramp-up is coupled with the production and use of batteries. Hence, this increased demand for EVs is driving up the demand for minerals used in battery storage, with lithium seeing the largest increase (Department of Energy, 2017). In particular, according to the International Energy Agency's Sustainable Development Scenario, demand for lithium is predicted to increase by almost 40 times by 2040 (International Energy Agency, 2022a).

While the need for adoption of *green* technologies and sustainable transportation is imminent, the impacts of sourcing the needed materials remain unclear. This is especially important as the extraction of those minerals takes place in developing countries, through processes that can have adverse effects for local populations. Specifically for lithium, despite the potential positive economic and technological benefits that come with its extraction, there are environmental and socioeconomic externalities that should be considered when evaluating the full supply-chain sustainability of its end uses; its extraction is a water-intensive process, impacting the availability of water in neighboring regions and the water cycle altogether (Center for Strategic and International Studies, 2021).

Lithium is mainly sourced in Australia, Chile, and China. However, Chile, together with Argentina and Bolivia, are part of what is known as the *Lithium Triangle*, a strategic area located in South America that contains more than half of the world's lithium ore reserves (IDB, 2017). In this paper, we provide causal evidence of the local environmental and economic impacts of lithium extraction in this region. Our analysis focuses on Chile, the country with the largest reserves of *commercially viable* lithium worldwide. More specifically, we study the environmental and economic impacts of lithium extraction around the area of the Atacama Salt Flat (ASF) in the north of Chile, where the bulk of extraction operations in the country take place.

To do so, we work with four main sources of data. First, we utilize a database on groundwater levels, measured both at the wells surrounding the ASF as well as in the north of Chile overall. Second, we use data on the Normalized Difference Vegetation Index (NDVI) for the main identified vulnerable areas (IVAs)[1] around the ASF, obtained through satellite images, at a 300m×300m resolution. Third, we use data on nighttime light density around the ASF, at a 500m×500m resolution. Lastly, we use a database proxying the density of human settlements within the same vulnerable areas around the ASF, again through satellite images, at a 100m×100m resolution.

Our estimation of the effects of lithium extraction in the area around the ASF on groundwater levels relies on a comparison between wells located in the ASF and wells further away over time. On the other hand, the estimation of the effects on vegetation, human settlements, and nighttime light density relies on a measure of the exposure of each "pixel" to the extraction of lithium. We construct this measure as the ratio of the demand for EVs in Europe, the US, and China during the 2013-2020 period to the distance of each pixel from the water extraction wells around the ASF. We consider both EV sales (time variation) and the distance measure (cross-sectional variation) to be plausibly exogenous to the environmental and economic outcomes we study. Our measure of exposure is increasing in the amount of sales of EVs and decreasing in the distance from the wells. Therefore, the pixels closer to the wells and in years when EV sales are larger are more exposed to lithium extraction. Based on this, we compare changes over time for vegetation and nighttime light density over the 2013-2020 period and between pixels with close proximity to each other. For the analysis of the impact on human settlements, we only use the distance variation as we have data for 2013 and 2020 and can only perform a first difference analysis.

Four important results stem from our analysis. First, during the 2013-2019 period, there was a significant reduction of up to 1 standard deviation in the groundwater levels around the ASF, compared to other wells in the north of Chile but further away from the flat. Second, an increase of 1 standard deviation in our measure of exposure to lithium extraction reduced vegetation by 4% relative to baseline

[1] Those are the localities reported in the census, as well as the National Flamingo Reserves in the area. For more details on the identification and construction of the IVAs please see Appendix C.

vegetation levels. This effect was more severe in those areas where the level of vegetation was higher at the beginning of our period of analysis and closer to the ASF. Third, a 1-km decrease in the distance to ASF reduced human settlements by 11% relative to baseline levels. Last, but not least, an increase of 1 standard deviation in our measure of exposure reduced economic activity, as proxied by nighttime light density, by 1% relative to baseline levels.

To shed light on the mechanisms driving these results, we provide suggestive evidence of the drop in agricultural activity during the 2007-2021 time frame. Over that period, the total cultivated area in the region dropped significantly from almost 1,500 to 500 hectares. We argue that this reduction could explain the effect on vegetation found in our main results. In line with this, we demonstrate that agricultural employment was significantly reduced over the same period, potentially explaining the reduction in human settlements and economic activity.

Our results contribute to four main strands of the literature. First, we contribute to the literature on the local and regional socioeconomic impacts of natural resource extraction. Overall, the magnitude and direction of the impacts found in the literature are ambiguous (van der Ploeg, 2011). On the one hand, local communities can benefit from a boom in the extraction of natural resources in terms of employment and income; on the other hand, such activities can have adverse consequences for local populations. Aragón and Rud (2013) find a strong and positive impact on the income of communities within a 100-kilometer radius of around the Yanacocha gold mine in Peru. They attribute these positive effects to the mine's demand for local inputs. On the other hand, in a related work analyzing the case of copper mining in Zambia, Lippert (2014) finds that increases in the production of copper mines have a positive impacts on the living standards of the local communities even for households not directly employed by the new copper mines.

To the best of our knowledge, the most closely related work in the economic literature to our study is Aragón and Rud (2016), analyzing the effect of gold mining activity in Ghana on the productivity of the agricultural sector. The authors find that gold-mining activity reduces agricultural productivity and that the effect is concentrated within a 20-kilometer radius around the mines. Furthermore, using remote sensing data, the authors find suggestive evidence indicating that the gold-mining regions exhibit a significantly higher concentration of NO_2, which diminishes with distance from the sites. Hence, they point to pollution as the main driver of the drop in agricultural productivity (For a more comprehensive review of the economic literature, see, for instance, Cust and Poelhekke, 2015; Loayza and Rigolini, 2016; Corral et al., 2018; Pokorny et al., 2019; Bazillier and Girard, 2020). We show that negative environmental and economic consequences for communities around natural resource extraction sites can be present even if the pollution channel that Aragón and Rud (2016) demonstrate is not present. In the case of the ASF in Chile, management and depletion of water resources drive those effects, rather than pollution caused by the operations.

Second, we contribute to the literature on the socioeconomic impacts that changes in water availability have on local communities. Economic literature demonstrates an important impact of water availability on agricultural outcomes, although, surprisingly, the effects in terms of economic growth are ambiguous (See, for instance, Dell et al., 2012; Brown et al., 2013; Burke et al., 2015; Damania, 2020; Russ, 2020; Damania, 2020; Marbler, 2024). Related to this literature is the work of Burlig et al. (2021), who conclude that lower access to groundwater leads to a reduction in agricultural activity. However, most of these studies focus on changes in the availability of water through climate change, rainfall, or exogenous shocks such as electricity prices and their impact on the cost of groundwater extraction. Our contribution to this literature is twofold: (1) we provide evidence on how agricultural activity can be affected via anthropogenic shifts in underground water availability, and (2) we demonstrate that this depletion, which reduces agricultural activity in the area, in turn, affects migration decisions of the people in local communities.

Third, we contribute to the natural and environmental science literature by providing new causal estimates on the impact that lithium extraction in the ASF has on water availability and vegetation in the area. There is no clear consensus in this literature on the net impact that lithium extraction activities have on the region, and overall (Flexer et al., 2018). Several studies have found that there is a significant reduction in water availability, vegetation, and soil moisture in the area, as well as higher temperature and evaporation rates (Liu et al., 2019; Marazuela et al., 2019, 2020; Liu and Agusdinata, 2020; Vera et al., 2023). All these consequences, which are correlated with the extraction of lithium in the area, according to the literature, affected the abundance of wildlife in the region, particularly flamingos, which is a protected species in the region (Gutiérrez et al., 2022; Vera et al., 2023). However, other studies argue that the negative variations in the aforementioned environmental outcomes can be attributed to extreme weather phenomena in the region, and subsequently to climate change, but not to the lithium extraction operations per se (Munk et al., 2021; Moran et al., 2022).

Studies in the natural and environmental science literature, on both sides of the debate, run into identification issues; they rely purely on observational and correlational evidence, hence not being able to separately identify the impact of lithium extraction operations and distinguish it from the effect of other environmental phenomena in the area on the outcomes in question. In this paper, we provide, for the first time, causal evidence of the lithium extraction operations on vegetation and economic activity. We do so by exploiting arguably exogenous variation in the exposure of each location to lithium extraction, controlling for location differences across units of analysis in our sample. Hence, we are able to reach a clean identification of the estimated impact of lithium extraction on our outcome variables.

Finally, we contribute to the growing literature on the externalities of environmental regulations imposed within developed countries in developing ones. In their recent paper, Tanaka et al. (2022) demonstrate how the tightening of air regulations in the United States impacts the relocation of polluting activities to Mexico and, in turn, negatively affects birth outcomes in this developing country (For additional papers on this literature, see, for example, Copeland and Taylor, 2004; Levinson, 2010; Cherniwchan et al., 2017; Cole et al., 2017). We provide new evidence to this discussion by showing how the push for a regulatory framework fostering the adoption of EVs in the United States and Europe translates to local environmental and economic damages in a developing country like Chile. Furthermore, we show that the entirety of those damages is borne by rural and indigenous communities residing around the area where the extraction of lithium takes place.

The rest of the paper is organized as follows: Section 2 provides context about the lithium extraction process in the ASF and the potential mechanisms through which it can affect water availability and vegetation in this area. Section 3 describes the data we use for our analysis. Section 4 outlines the empirical strategy implemented in the paper to estimate the effect of lithium extraction on the outcomes of interest. Section 5 provides the main results of our estimates. Section 6 provides suggestive evidence of the mechanisms driving those results. Section 7 describes the robustness checks we run against our main specification. Finally, Section 8 places our results into the context of the overall supply chain of lithium, while Section 9 concludes.

2 Context

In this section, we provide background on lithium extraction in South America, particularly in the *Lithium Triangle*, the region enclosed by Chile, Argentina, and Bolivia. We then continue to describe the context of lithium extraction specifically in Chile and the different mechanisms through which lithium extraction can lead to lower water availability in the area of the ASF. Finally, we discuss the specifics of the process of extracting lithium from brine deposits.

2.1 Extraction of lithium in South America

Hard-rock ores and continental brines[2] are both utilized for lithium extraction, with the latter being the most prominent source. The Altiplano-Puna high plateau in South America is one of the planet's most distinctive geological formations and is renowned for its unique brine-type deposits of lithium. Consequently, the global push for significant technology advancements in energy storage, in an effort to move towards the adoption of renewable energy and sustainable transportation, has driven the Andean *lithium rush*. While lithium's end uses vary from ceramics and glass to lubricating greases and air treatment, 87% of it is used for energy storage in batteries (United States Geological Survey, 2024).

Since the beginning of the rush, more than ten years ago, the plateau area has become known as *The Lithium Triangle* (shown in the left-hand side of Figure 1). This informal term describes the region lying between Chile's ASF, Bolivia's Uyuni Salt Flat, and Argentina's Hombre Muerto Salt Flat, which constitute the most significant lithium reserves worldwide (López Steinmetz and Salvi, 2021). The two largest salt flats in Bolivia are the Uyuni and Coipasa, covering an area of about 10,000 km^2, with Uyuni being the largest salt flat in the world. However, according to López Steinmetz and Salvi (2021), as of 2021, both of the two salt flats in the Altiplano region in Bolivia were untapped. In Argentina, Hombre Muerto and Olaroz constitute the most important salt flats, and both are currently subject to lithium mining. Finally, in Chile, the most important is the ASF, which covers an area of 3,000 km^2, has the largest lithium extraction operations in the region, and will be the subject of our analysis.

According to López Steinmetz and Salvi (2021), the ASF contains the highest concentration of lithium among the salars in the *Lithium Triangle*. While the average concentration of lithium in the Altiplano Salt Flats in Bolivia is between 213 and 258 mg L^{-1}, and between 280 and 570 mg L^{-1} in the Puna Salt Flats in Argentina, the average concentration in the ASF is about 1,400 mg L^{-1}. Its particularly high levels of concentration of lithium make the ASF the most important lithium extraction operation with the richest lithium brine-type deposits in the world (López Steinmetz and Salvi, 2021). Consequently, this puts Chile in second place, after Australia, in exports of lithium worldwide.

2.2 Extraction of lithium and water depletion mechanisms in the ASF

The companies extracting lithium in the ASF in Chile have a lease agreement with the Production Development Corporation (CORFO) of the country. While there are several companies in the ASF exploiting lithium resources, such as SQM and Albemarle, the overall brine extraction is almost purely driven by the activities of SQM in the area, hence our data for water use and monitoring will come

[2] Brine refers to a solution of water with a high concentration of salts.

from the company's reporting archives (Moran et al., 2022). The agreement between CORFO and SQM has been in place since 1993 and was recently revised in 2018. These agreements stipulate lease payment rates that are tied to the final sale prices, the obligation by SQM to contribute specified amounts to research and development activities, as well as reporting and environmental audit and control obligations for the company (U.S. Securities and Exchange Commission, 2018).

Figure 1: Main lithium extraction locations in South America

(a) Lithium triangle (b) Atacama Salt Flat

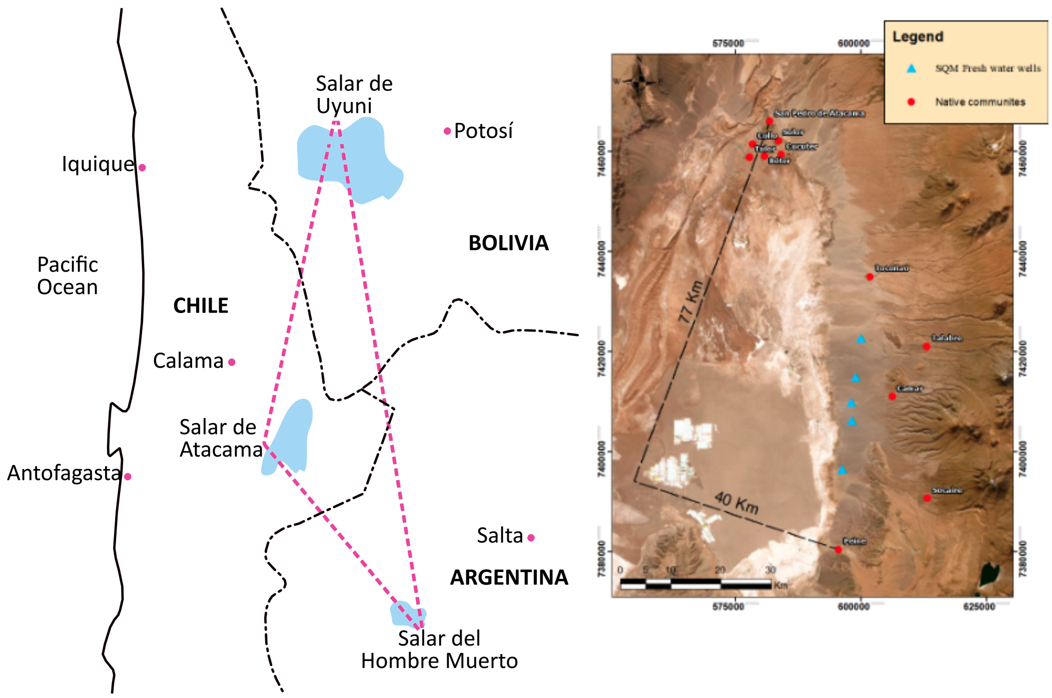


Figure 1(a) demonstrates what is known as the *Lithium Triangle*, while Figure 1(b) demonstrates the ASF area with the main IVAs that we will be studying. Source. Figure 1(a): De la Hoz et al. (2013). Figure 1(b): Own rendering

To the best of our understanding, lithium extraction from brines involves two distinct processes that could contribute to water depletion. The first such process is the direct extraction of brine, which is done through the use of pumps. The extracted brine is placed in large evaporation ponds and as the water evaporates, several salts precipitate. After the useful ones are recovered, the remaining water is re-injected into the brine. The second process is the direct extraction of freshwater, mainly used for cleaning the equipment (Vera et al., 2023). While a clear consensus on which mechanism is the dominant one concerning water availability does not seem to exist, Vera et al. (2023) argue that brine extraction can lead to a reduction in brine volume, in turn causing freshwater to permeate the mixing zone and seize to be fresh (Flexer et al., 2018; Marazuela et al., 2020). In our analysis, we remain agnostic about which mechanism is dominant. Rather, taking into account that in both cases a reduction in water levels would be observed at the points where freshwater is extracted, we use as reference the distance from SQM's freshwater wells, which, as can be seen in the right-hand side of Figure 1, are very close to the local communities.

Over the last thirty years, as groundwater exploitation for mining purposes has expanded, Dirección General de Aguas (DGA), the country's top administrative body for water management, has been responsible for monitoring the use of water in the area. As a result of the DGA allocating rights for water use, multiple groundwater extraction wells were built over this period. SQM is granted the right to extract brine at a rate of no more than 1,600 liters per second, however, its pumping activity has been historically below this threshold. In 2020, through its corporate sustainability plan, the company announced that they aim to reduce pumping rates to 50% of the stipulated threshold within a decade (Sociedad Quimica y Minera de Chile, 2021, 2022). Additionally, as far as freshwater (or industrial water) is concerned, SQM is authorized to extract at rates of up to 240 liters per second in its five freshwater wells, while for the past 4 years overall extraction rate has been less than 50% of the stipulated limit (Sociedad Quimica y Minera de Chile, 2024).

In the area of the ASF, indigenous populations have been using surface water for domestic and agricultural purposes for decades (Babidge, 2019). However, the relationship between SQM and local communities over the past years has been turbulent. In 2019, the *Atacama Indigenous Council* (CPA) sued the company for excessive pumping, with the two sides settling the dispute a year later (Reuters, 2020). In section 3.4, we will analyze in greater depth the socioeconomic characteristics of the population surrounding the Atacama Salt Flat.

2.3 The process of sourcing of lithium from brine deposits

Production of lithium carbonate (Li_2CO_3) from brines can be broken down into three key steps, namely mass reduction of brines in solar evaporation ponds, brine purification, and Li_2CO_3 precipitation. Brine is pumped from aquifers via wells located on the salar. It is subsequently transported to solar evaporation ponds through pipelines to reduce its volume. After it reaches a certain Li content, brine is delivered to a processing facility, where calcium (Ca), magnesium (Mg), and boron (B) impurities are removed from the Li-enriched brine solution. This is achieved through the use of quicklime to remove Mg, organic solvent extraction to remove B, and ion exchangers to remove Mg, Ca, and B. The methods and the sequence in which they are employed are determined by the particular brine composition at the site in question. Subsequently, Li_2CO_3 is precipitated by heating the pulp and adding soda ash. Technical grade Li_2CO_3 that has crystallized is then dissolved in cold water. Reheating the solution to 80 °C yields the precipitation of Li_2CO_3, which constitutes what is known as "battery grade" product (Garrett, D. E, 2004; Tran and Luong, 2015; Schenker et al., 2022)

Chile has long been a top producer of Li_2CO_3, with output mainly coming from brine activities at the ASF. The extraction and evaporation of brine water take place on-site at the ASF, after which the lithium concentrates are transported for processing to two Li_2CO_3 processing plants and one lithium hydroxide monohydrate ($LiOH \bullet H_2O$) processing plant in Antofagasta, Chile (Jaskula, B.W., 2018; Kelly et al., 2021).

3 Data and Descriptive Statistics

In this section, we describe the data we utilize in our analysis and provide stylized facts and descriptive statistics about the supply and demand of lithium, as well as the socioeconomic and environmental characteristics of the region we analyze.

3.1 Data

We utilize seven main sources of data in our analysis, namely groundwater levels, vegetation index, agricultural production and livestock, human settlement estimates, nighttime light radiance, elevation levels, and EV sales. The sources are as follows:

Groundwater levels: The first source of data concerns the levels of groundwater in the area of the ASF. These are obtained through public measurements of well levels available on the website of SQM, the predominant lithium extraction company in the ASF. As part of their hydrological monitoring, SQM reports values for 196 wells, which we have downloaded and used in our analysis. Additionally, we use data from monitoring wells in the North of Chile obtained through DGA. More specifically, we use measurements for a total of 109 monitoring wells between 2010 and 2019, within the regions of Antofagasta, Arica and Parinacota, and Tarapacá, which serve as a comparison group. In both cases we use the mean groundwater level over each year in this period.

Vegetation Index: Measurements for vegetation are obtained through the API provided by the Earth Engine Data Catalog. More specifically, we obtain the Landsat 8 Collection 1 Tier 1 Annual NDVI Composite measure. We identify a radius of interest, split it into 300m×300m pixels, and recover the average NDVI values for each pixel and year between 2013 and 2020 within the locations around the

ASF. The NDVI is a vegetation index that ranges from -1 to 1, where greener areas take values closer to 1.

Agricultural production and livestock: This data is available through the National Agricultural and Forestry Census carried out by the National Institute of Statistics of Chile (INE, by its acronym in Spanish) at the comuna level (which is equivalent to a county in the U.S.). More specifically, the available data shows the national planted area, production, and annual yields for vegetables and agricultural products for the 2007 and 2021 years.

Human Settlements: To estimate the effects on local population settlements, we utilize the Global Human Settlement Layer (GHSL) dataset provided by the European Union through Copernicus. More specifically, we use the spatial raster product, a dataset that deduces the spatial distribution of human settlements based on satellite images from Sentinel-1 and 2. The population distribution is expressed as the number of people in each 100mx100m cell.

Nighttime light radiance: The data on nighttime lights are values of radiant flux from the API provided by the Earth Engine Data Catalog. We utilize the VIIRS Nighttime Day/Night Annual Band Composites through the joint NASA/NOAA Suomi NPP satellite at a 500mx500m resolution, using the average Day/Night Band (DNB) for each pixel in each year between 2013 and 2020.

Elevation: For each centroid of each pixel in our analysis, we control for elevation, as we expect pixels with higher elevation to be less affected than pixels with lower elevation. We download the 30-meter Shuttle Radar Topography Mission (SRTM) Digital Elevation Model (DEM) files through the NASA Earthdata platform.

EV sales: As part of our empirical strategy we utilize the number of sales of EVs in the United States, Europe, and China. The data is obtained through the International Energy Agency (IEA) and contains information on the annual sales of electric vehicles between 2010 and 2021. The sales data is provided by vehicle type for Battery Electric Vehicles (BEVs) and Plug-in Hybrid Electric Vehicles (PHEVs).

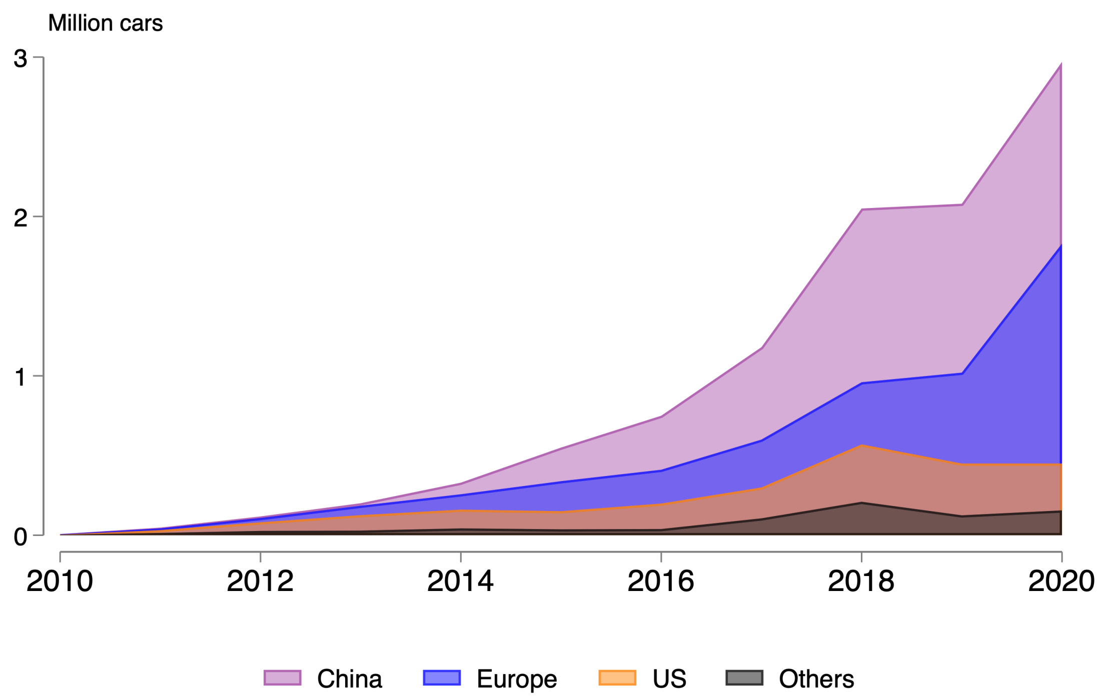
3.2 Descriptive Statistics

In this section we provide statistics on the evolution of supply and demand for lithium around the world and in Chile, as well as on the sociodemographic characteristics of the populations residing around the ASF. Finally, we demonstrate statistics on the evolution of underground water levels and vegetation levels in the area during the period under study to motivate the main empirical strategy and results presented in or analysis.

3.3 Lithium supply and demand

As can be seen in Figure 2, there has been a significant increase in the demand for EVs worldwide since 2010. Over the previous decade, EV sales skyrocketed from 7.5 thousand in 2010 to 3 Million in 2020. The demand for EVs is driven by three regions, namely China, Europe, and the U.S. By 2020, these three regions represented about 95% of total EV sales globally. While China has historically been the main EV market, Figure 2 shows that Europe has gained a lot of momentum, representing 46% of the global demand by 2020.

Figure 2: EV Sales by Destination, 2010-2020

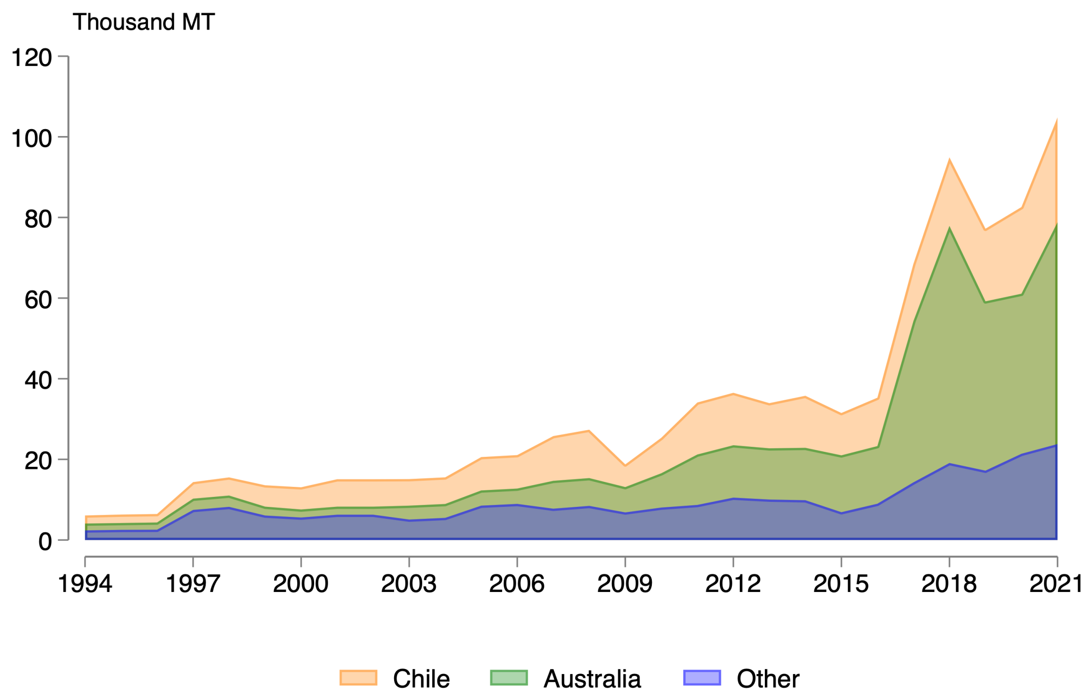


Notes. Overall EV sales in Million cars for the U.S., Europe, China, and the rest of the world. Source: Own rendering based on data from the IEA.

On the other hand, Figure 3 shows the mine production of lithium in Thousand Metric Tons (MT) between 1994 and 2021 by producer country. Two main takeaways emerge from this figure. First, the mine production of lithium worldwide has increased significantly, particularly after 2016. Second, most of the production of lithium has been concentrated in Chile and Australia, although in recent years Australia seems to have become the leader, representing about 48% of the worldwide production, with Chile in second place contributing to 26% of production as of 2021.

Finally, a key observation from Figures 2 and 3 is that the production of lithium, and its increase in recent years, seem to be strongly correlated with the demand for electric vehicles and lithium batteries in Europe, the U.S. and China. This fact will be crucial in the design and implementation of our empirical strategy and, therefore, in our identification.

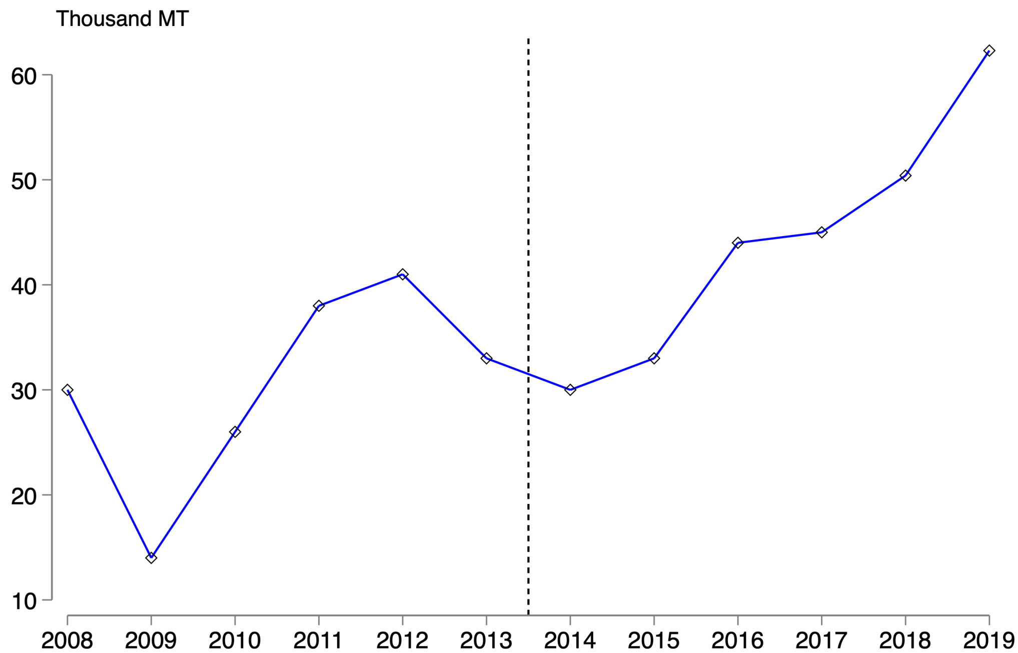
Figure 3: Mine Production of Lithium by Origin, 1994-2021



Notes. Mine production of lithium over time in thousand MT of contained lithium per year for Chile, Australia, and the rest of the world. Source: Own rendering based on data from the Mineral Commodity Summaries from the US Department of the Interior and the US Geological Survey.

In Figure 4, we zoom into the production of lithium in Chile, particularly in the ASF, and the extraction carried out by SQM. As can be seen, the aforementioned ramp-up in production coincides with an increase in the lithium extraction activity in the ASF. There seems to be a significant increase in the amount of lithium produced in the ASF by SQM from 30,000 MT in 2013 to 60,000 MT in 2019, according to the company's annual reports.

Figure 4: Production of Lithium in the ASF by SQM, 2008-2019



Notes. Production of lithium over time in Thousand Metric Tons by SQM in the area of the ASF. Source: own elaboration based on data from the SQM's annual reports.

3.4 Socioeconomic characteristics of the Atacama Salt Flat

The ASF and the region where the lithium extraction operations take place is located in the municipality of San Pedro de Atacama (SPdA), in the north of the country (in the region of Antofagasta). This region, and particularly the SPdA municipality, is characterized by arid desert conditions. Hence, vegetation is scarce and population density is low compared to other regions of the country.

In this subsection, we characterize the population residing in the SPdA municipality, using the 2002 and 2017 Chilean national censuses.[3] As can be seen in Table 1, while in 2002 roughly five thousand people resided in SPdA, 15 years later that number more than doubled. These people, who are exposed to the lithium extraction activity in the region, have a similar age distribution to the population in the Antofagasta region and Chile overall. However, the population in SPdA is particularly overrepresented by male individuals, relative to the whole country, and this is true for both years. The

[3] The 2002 census is the only reliable Chilean census before the 2017 one. While in 2012 a census was carried out, the results are not considered reliable due to the disruptions caused by an earthquake that took place in the same year.

same is true for educational attainment.

Table 1: Population characteristics, 2002 - 2017

	SPDA		Antofagasta		Chile	
	2002	2017	2002	2017	2002	2017
Panel A: Demographic characteristics						
Head of household	0.27	0.27	0.25	0.29	0.27	0.32
	(0.44)	(0.45)	(0.43)	(0.45)	(0.45)	(0.47)
Age	31.75	34.38	29.96	33.39	31.60	35.83
	(20.24)	(18.75)	(19.73)	(20.35)	(20.81)	(21.97)
Male	0.59	0.56	0.52	0.52	0.49	0.49
	(0.49)	(0.50)	(0.50)	(0.50)	(0.50)	(0.50)
Secondary Education	0.82	0.63	0.79	0.66	0.82	0.68
	(0.38)	(0.48)	(0.41)	(0.47)	(0.38)	(0.47)
Post-secondary Education	0.18	0.27	0.20	0.24	0.16	0.23
	(0.38)	(0.45)	(0.40)	(0.43)	(0.37)	(0.42)
Indigenous	0.61	0.50	0.05	0.14	0.05	0.12
	(0.49)	(0.50)	(0.21)	(0.34)	(0.21)	(0.33)
Observations	4,969	10,996	493,984	607,534	15,116,435	17,574,003
Panel B: Labor Force characteristics						
Labor force	0.59	0.79	0.55	0.65	0.52	0.61
	(0.49)	(0.41)	(0.50)	(0.48)	(0.50)	(0.49)
Employed	0.58	0.76	0.54	0.60	0.51	0.56
	(0.49)	(0.43)	(0.50)	(0.49)	(0.50)	(0.50)
Unemployed	0.01	0.03	0.02	0.08	0.02	0.07
	(0.11)	(0.18)	(0.12)	(0.27)	(0.14)	(0.26)
Primary sector	0.05	0.03	0.02	0.01	0.11	0.06
	(0.22)	(0.16)	(0.14)	(0.10)	(0.31)	(0.24)
Mining	0.12	0.11	0.12	0.12	0.01	0.02
	(0.32)	(0.31)	(0.32)	(0.33)	(0.12)	(0.13)
Manufacturing	0.03	0.03	0.08	0.05	0.12	0.06
	(0.18)	(0.18)	(0.27)	(0.22)	(0.33)	(0.24)
Commerce	0.10	0.07	0.18	0.13	0.19	0.16
	(0.30)	(0.25)	(0.38)	(0.34)	(0.39)	(0.36)
Hotels and Restaurants	0.15	0.17	0.03	0.05	0.03	0.04
	(0.35)	(0.38)	(0.18)	(0.21)	(0.17)	(0.20)
Other economic activity	0.55	0.59	0.57	0.64	0.53	0.66
	(0.50)	(0.49)	(0.50)	(0.48)	(0.50)	(0.47)
Observations	3,961	9,197	361,138	479,672	11,226,309	14,050,253

Notes. Demographic and labor force characterization of the population around SPdA, relative to the Antofagasta region and Chile as a whole. Source: Own elaboration based on data from the Chilean censuses.

Furthermore, the population of SPdA is particularly represented by indigenous individuals, relative to both the region of Antofagasta, but also Chile as a whole. Our estimates indicate that, while in

2002 about 61% of the population in SPdA self-identified as indigenous, this proportion was only 5% for the entire country. This is especially important since indigenous people have a special legal status in the country, whereby public authorities ought to protect and ensure their protection and development.[4]

In Panel B of Table 1 we show demographic characteristics of the population in SPdA, the region of Antofagasta, and the rest of Chile, as well as statistics on the labor market participation for each of the three groups. As can be seen, in terms of labor force participation and employment overall, individuals in SPdA seem to do better compared to people in the region and the rest of Chile, which might partially be explained by the overrepresentation of male individuals in the municipality. Additionally, the participation of individuals working in mining, hotels, and restaurant sectors is greater compared to Chile as a whole. This result is expected, given that the economic activity in the north of Chile, particularly the area of SPdA, revolves around extracting natural resources and tourism.

Next, we analyze the dwelling conditions under which individuals in the SPdA municipality live. In Table 2 we show descriptive statistics of each of the variables, using individual observations. We use individual observations rather than dwelling units as observations in SPdA are more likely to have a greater number of people per dwelling and we aim to avoid underestimating the magnitude of the descriptive statistics for the region.

The first characteristic that we observe in Table 2 is that individuals in SPdA are more likely to live under precarious and vulnerable conditions compared to the rest of Chileans. As can be seen, while the proportion of individuals living in dwellings with precarious walls, ceilings, and floors in SPdA is about 20%, 6%, and 2% in 2017, these figures are only 3%, 1%, and 0%, respectively, for the whole country. Moreover, in terms of water access, only 60% of individuals in SPdA have access to a public network of potable water, compared to 86% in the entire country. This is evidence that access to potable water, either for consumption or for any other activity that the community carries out in the municipality, seems to be a crucial consideration when analyzing any potential impact of the mining activity in the region.

[4] According to the Law 19.253 sanctioned in 1993 *"It is the duty of society in general and of the State in particular, through its institutions, to respect, protect and promote the development of indigenous peoples, their cultures, families and communities, adopting appropriate measures for such purposes, and to protect indigenous lands, ensure their adequate exploitation, their ecological balance and promote their expansion."*

Table 2: Dwelling characteristics, 2002 - 2017

	SPDA		Antofagasta		Chile	
	2002	2017	2002	2017	2002	2017
Number of rooms	3.13	2.40	4.82	3.01	4.80	2.75
	(2.54)	(1.31)	(2.14)	(1.26)	(1.81)	(1.07)
Precarious walls	0.32	0.20	0.04	0.02	0.05	0.03
	(0.47)	(0.40)	(0.20)	(0.15)	(0.23)	(0.16)
Precarious ceiling	0.01	0.06	0.00	0.01	0.00	0.01
	(0.10)	(0.24)	(0.06)	(0.11)	(0.05)	(0.08)
Floor material: earth	0.02	0.02	0.01	0.01	0.00	0.00
	(0.12)	(0.15)	(0.08)	(0.09)	(0.07)	(0.05)
Water from public network	0.69	0.57	0.94	0.85	0.90	0.86
	(0.46)	(0.50)	(0.24)	(0.35)	(0.30)	(0.34)
Water from wells	0.01	0.01	0.00	0.00	0.05	0.04
	(0.09)	(0.09)	(0.04)	(0.04)	(0.23)	(0.18)
Water from river/creek/stream	0.06	0.03	0.01	0.00	0.03	0.01
	(0.23)	(0.16)	(0.08)	(0.06)	(0.16)	(0.12)
Water from other	0.24	0.40	0.05	0.14	0.02	0.09
	(0.43)	(0.49)	(0.23)	(0.35)	(0.14)	(0.28)
Observations	4,969	12,108	493,984	638,464	15,116,435	18,552,095

Notes. Dwelling characterization of the population around SPdA, relative to the Antofagasta region and Chile as a whole. Source: Own elaboration based on data from the Chilean censuses.

In Table 3 we show descriptive statistics in terms of the NDVI for each location and the distance to the industrial water extraction wells of SQM in the ASF. We calculate the mean, standard deviation, minimum, and maximum values of each variable for all the 300m$\times$300m pixels of each location. Given that the nature of potential impacts is local, we only utilize the locations that are enclosed within a minimum distance of a 50 km radius of the location of the industrial water extraction wells and only present descriptive statistics for those.

Table 3: Vegetation and Distances to the Atacama Salt Flat

	Mean	SD	Min	Max
Panel A - NDVI				
Valle de la Luna	0.081	0.041	0.046	0.397
Tabmillo	0.097	0.042	0.031	0.366
Tebenquiche	0.095	0.085	-0.411	0.366
Soncor	0.066	0.067	-0.823	0.228
Quelana	0.071	0.027	0.015	0.316
Science preserve	0.075	0.035	-0.032	0.179
Miscanti and Miñiques	0.050	0.095	-0.535	0.178
Laguna Lejia	0.059	0.099	-0.692	0.122
Salar de Pujsa	0.070	0.028	-0.048	0.167
San Pedro de Atacama	0.109	0.077	0.041	0.472
Toconao	0.093	0.044	0.047	0.352
Camar	0.044	0.023	0.025	0.199
Socaire	0.108	0.028	0.043	0.248
Peine	0.075	0.043	0.025	0.297
Zapar	0.096	0.032	0.045	0.181
Pocor	0.068	0.005	0.062	0.085
Talabre	0.076	0.025	0.037	0.179
Tilomonte	0.074	0.019	0.054	0.182
	Mean	SD	Min	Max
Panel B - Distances				
Valle de la Luna	45.96	2.13	40.95	49.99
Tabmillo	26.61	4.63	17.27	35.67
Tebenquiche	30.30	1.30	27.41	33.15
Soncor	12.07	2.63	6.70	17.51
Quelana	5.79	1.60	2.46	9.02
Science preserve	41.75	4.94	28.64	50.00
Miscanti and Miñiques	40.40	4.95	27.90	50.00
Laguna Lejia	37.10	2.50	32.41	41.85
Salar de Pujsa	47.05	1.87	42.57	50.00
San Pedro de Atacama	43.70	3.61	35.81	49.98
Toconao	12.76	0.79	11.25	14.28
Camar	7.75	1.04	5.96	9.54
Socaire	18.65	4.12	10.18	26.89
Peine	15.55	0.79	14.22	17.03
Zapar	20.29	0.71	19.11	21.46
Pocor	7.95	0.34	7.45	8.46
Talabre	13.09	1.57	10.27	15.87
Tilomonte	28.53	0.72	27.21	29.96

Notes. NDVI data was obtained from Landsat 8 Collection 1 Tier 1 Annual NDVI Composite measure. We show the average of the NDVI for each Identified Vulnerable (AREA). Source: Own elaboration based on data from LANDSAT and our estimates.

As can be seen, these locations are characterized by low levels of vegetation measured by the NDVI, with Camar being the location with the lowest average NDVI (0.044). Some of these NDVI values are negative indicating the presence of some water bodies in the area. In Panel B we can see the same statistics for the distance of each location to the Atacama Flat. As can be seen, there is a significant dispersion and variability in terms of the distance of each location from the extraction points. For instance, the closest pixel to the SQM industrial water extraction wells located in the Atacama Flat is located at 2.46 kilometers in Quelana, whereas the location with the average largest distance is the Salar de Pujsa with an average figure of 47.05 Km.

In Table 4 we show additional descriptive statistics in terms of the population for each of the nine locations that are human settlements, or villages. As can be seen, on average the densest is Toconao with 0.563 people per cell, while the one with the cell containing the most people is San Pedro de Atacama with almost 69 people in a $100m \times 100m$ cell. Lastly, Socaire is the one with the lowest number of people per cell on average.

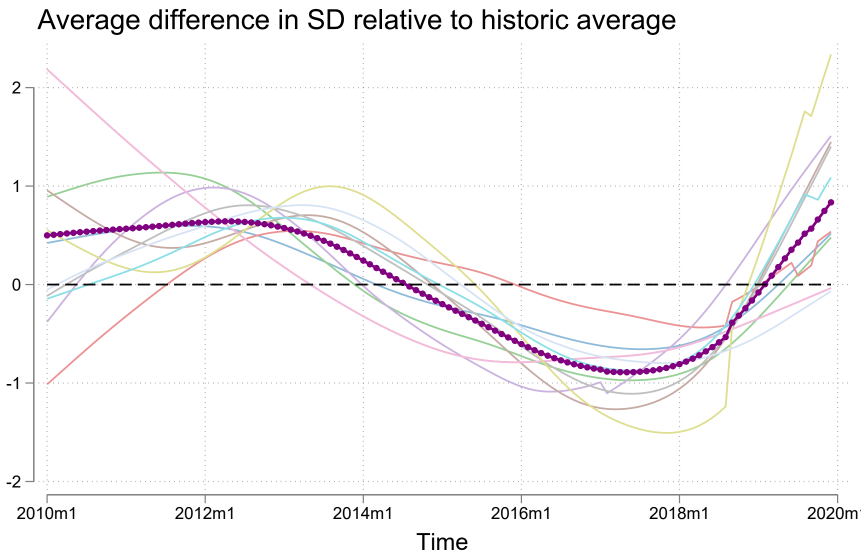
Table 4: Human Settlements of the Identified Vulnerable Areas

	Mean	SD	Min	Max
Panel A - Human settlements				
San Pedro de Atacama	0.234	1.599	0.000	68.872
Toconao	0.563	2.415	0.000	20.817
Camar	0.041	0.297	0.000	4.005
Socaire	0.010	0.245	0.000	15.844
Peine	0.220	1.105	0.000	12.132
Zapar	0.022	0.186	0.000	3.685
Pocor	0.022	0.126	0.000	1.385
Talabre	0.038	0.391	0.000	10.958
Tilomonte	0.011	0.154	0.000	3.859

Notes. Human settlements data was obtained from Global Human Settlement Layer. We show the average of the human population for each location. Source: Own elaboration based on data from Global Human Settlement Layer and our estimates.

We then analyzed the average level of fresh water measured by SQM in the ASF from 196 measurement stations that they report around the mining area in seven monitoring systems. Figure 5 shows the average deviation for each year relative to the historic average level of water in the wells from 2010 to 2020. Lighter lines show the value for each one of the seven monitoring systems, whereas the dark purple dotted line plots the average of all the systems. As can be seen, in general, since 2014 there seems to be a negative difference in the level of the wells relative to the historical average, which could be a consequence of the utilization of fresh water for the mining process. These negative values, however, went positive in approximately 2019, which could be explained by more efficient and environmentally friendly use of the water resources in the area. It is expected that, if this reduction in the levels of fresh water in the areas near the ASF had an ecological impact in terms of vegetation, then those areas closer to the ASF should be the ones that were affected the most.

Figure 5: Well levels in ASF, 2010-2020



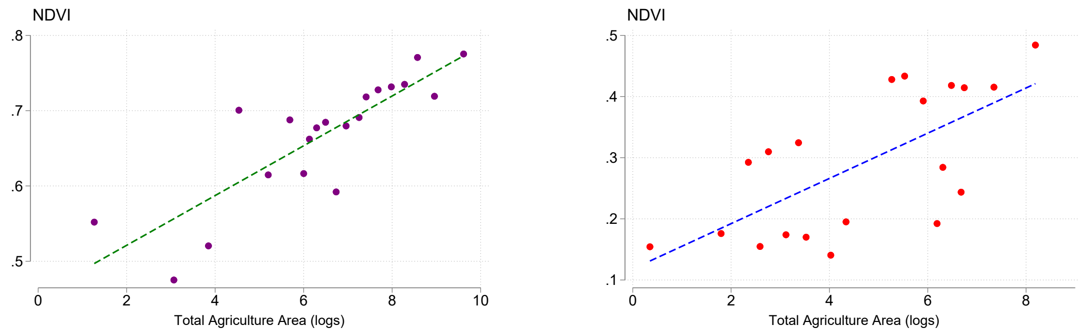
Notes. For each well we calculated the trend with a Hodrick-Prescott filter and a smoothing parameter of 14,400. We report the difference of each value relative to the historical average in the 2013-2020 period of each well in standard deviations. Each light line shows the value in standard deviations for each one of the seven SQM monitoring systems and the connected purple line is the average over time of the seven systems. Source. Own elaboration based on data from SQM.

Apart from the environmental impact of lithium extraction in the ASF in terms of vegetation, we would also like to estimate the subsequent economic impacts. We want to do this by analyzing how the levels of crops relate to agriculture and how agricultural activity in general, was affected by the intensive use of fresh water in the area. However, given the lack of granular data for the potentially affected areas, we consider the NDVI as a proxy variable for the impact on agriculture

In Figure 6 we show the relationship between the average NDVI and the total cultivated area for agriculture (in logs) in each municipality of Chile. Panel (a) shows the relationship for the whole country, whereas Panel (b) restricts the sample to municipalities located in the North Region of Chile. As can be seen, NDVI and total cultivated area for agriculture purposes seem to be positively and strongly correlated across municipalities in Chile in general, but also in the North of the country. This positive correlation provides evidence of the validity of the utilization of NDVI as a proxy measure of agricultural activity in the areas close to the ASF.

Figure 6: Relationship between NDVI (2010) and Total Cultivated Area (2007)

(a) Chile (b) North of Chile

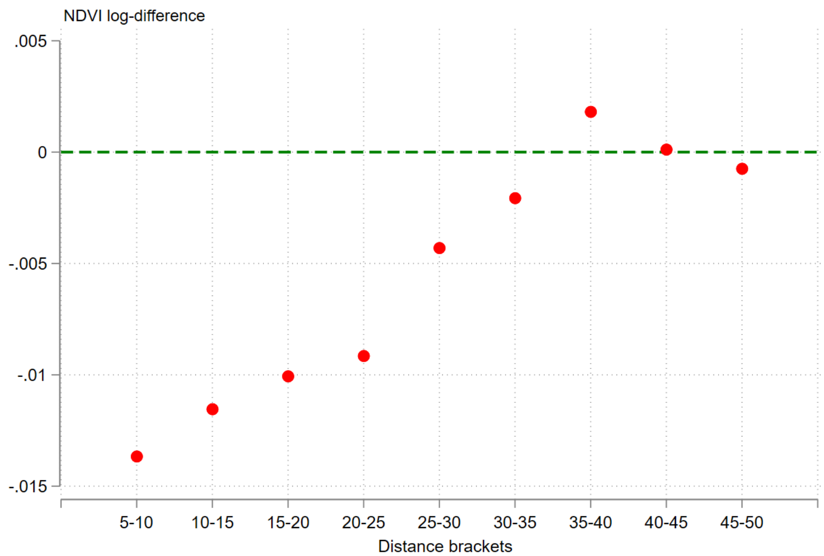


Notes. Figure (a) shows the binscatter between the average NDVI in 2010 in each one of the 287 municipalities for which there is information available in the Agricultural Census in 2007 and the total agricultural cultivated area (in logs). Figure (b) shows the same information but restricts the sample to municipalities in the North of Chile (Antofagasta Region, Arica y Parinacota Region, Atacama Region, Tarapacá Region, and Coquimbo Region). Source: Own elaboration based on data from the 2007 Agricultural Census and Landsat 8 Collection 1 Tier 1 Annual NDVI Composite measure.

A first overview of the relationship between lithium extraction in the ASF on the NDVI in the area surrounding the ASF is presented in Figure 7. In this figure, we show a non-parametric estimate of the relationship between changes in the NDVI between 2013 and 2020 for each 300m$\times$300m pixel and the distance to the ASF. It is expected that those areas located closer to the ASF are the ones in which the change in the NDVI level should be more negative. This is because fresh water utilization for the process of lithium extraction would disproportionately affect those areas.

As can be seen in Figure 7, there seems to be a significant decrease in the NDVI for those areas located in a radius of 5 to 35 kilometers to the ASF and this effect seems to be a reduction of up to 0.02 log points. In the next section, we will show our preferred empirical specification in which we will include control variables that will allow us to compare the effect between different pixels with close proximity over time. However, as we will show, results remain robust and consistent with Figure 7 shown here.

Figure 7: Non-parametric relationship between distance to ASF and NDVI change, 2013-2019



Notes. The red line shows the scatterplot smoothed relationship between the NDVI measure change over the 2013-2020 period in each 300m×300m pixel surrounding the ASF and the corresponding distance to it. Source. Own elaboration based on data from Landsat 8 Collection 1 Tier 1.

4 Empirical strategy

The empirical strategy can be divided into three parts. First, we estimate the lithium extraction impact on the underground water levels in the region surrounding the ASF. To do so, we estimate an event-study equation in which we compare the evolution of the differences in the underground levels for the measurement wells located around the SQM mine in the ASF to the measurement wells installed by the Chilean Government in the northern region of the country, before and after 2013. We use 2013 as the cutoff, as it is the year in which the lithium production activity carried out by SQM in the ASF started to significantly increase. More specifically, we estimate the following equation:

$$y_{it} = \alpha + \sum_{t=2010}^{2019} \beta_t W_i D_t + \sigma_i + \rho_t + \varepsilon_{it} \tag{1}$$

Here, y_{it} is the underground water level in each measurement well i and year t which is normalized in standard deviations to avoid problems with the differences in the measurement units across wells in our sample. W_i is a dummy variable that takes a value equal to 1 if the measurement well i is located in the ASF region and 0 otherwise; D_t is a vector of time dummies for the years between 2010 and

2019; finally, σ_i and ρ_t are well and year fixed-effects. Our event-study coefficients of interest are β_t which indicate the annual differences in groundwater levels between wells in the ASF and wells in locations far away from the lithium extraction activities. Finally, ε_{it} captures the measurement errors of our specification, which are clustered at the measurement well level.

To allow for more flexibility in our event study, we do not impose that a specific year has to be equal to 0, namely, what is commonly considered the baseline period. Instead, we impose that, on average, all coefficients β_t between 2010-2013 have to be, on average, equal to 0, which allows us to obtain less noisy estimations.

In the second part, we estimate the impact of exposure to lithium production on NDVI. To do this, we estimate the following equation:

$$NDVI_{ijt} = \alpha + \beta I_{ijt} + \Gamma[X_{ij} \times \rho_t] + [\delta_j \times \rho_t] + \phi_{ij} + \varepsilon_{ijt} \tag{2}$$

Here, $NDVI_{ijt}$ is the average annual NDVI for each 300×300 pixel i located in each location j. We define our variable of interest I_{ijt} as follows:

$$I_{ijt} = \frac{V_t}{min\{D_{ij1}, ..., D_{ij5}\}} \tag{3}$$

Where we have that $D_{ij1}...D_{ij5}$ indicates the distance between each pixel i in location j and each of the five extraction wells location in the Atacama Salt Flat that are used by SQM to extract industrial water. Hence, the denominator of I_{ijt} captures the minimum distance between each pixel and the extraction of water near the ASF. V_t is the total sales of electric vehicles in the U.S., Europe, and China, which is arguably exogenous and does not affect directly the level of vegetation in the ASF through channels other than the lithium extraction, Additionally, as we showed above, it is strongly correlated with the amount of lithium production in the area. Therefore, the variable I_{ijt} captures the exposure of each pixel i to the lithium production and demand.

Finally, $[\delta_j \times \rho_t]$ are location fixed-effects interacted with year fixed-effects, ϕ_{ij} are pixel fixed-effects and $[X_{ij} \times \rho_t]$ is a vector of controls in which we interact the latitude, longitude, and elevation of each pixel i with time fixed-effects. Therefore, in our identification strategy, we compare changes in NDVI over time with exposure to lithium extraction for pixels within the same location, with similar latitude and longitude, and with similar elevation.

Our coefficient of interest is β, which shows the effect of our measure of exposure to lithium extraction on NDVI. Our error terms are clustered on the pixel level. Considering that the vegetation of our units of observation might be spatially and serially correlated, we also show our main results by adjusting the p-values taking into account this potential spatial and serial correlation following the Conley (1999) and Hsiang (2010) approaches. In our main specifications, we consider a serial correlation with an 8-period length and a spatial correlation that follows a Bartlett kernel with a distance cutoff of 500 meters which allows us to consider a spatial correlation that vanishes as we move farther away from each pixel i. In our robustness checks, we show the sensitivity of our results to the distance cutoff for the spatial correlation.

The identification assumptions in this empirical strategy are two: on the one hand, we argue that the time-varying component of our independent variable of interest V_t is exogenous because it is driven by external factors. In short, the variation in the production of lithium in Chile is demand-driven by the consumption of EVs in Europe, US, and China, which is, in turn, exogenous to the vegetation levels in Chile. On the other hand, we control for location, elevation, and coordinates interacted with year fixed-effects. Hence, we compare changes over time in NDVI explained by the exposure to the extraction of lithium for pixels that are very close to each other and with very similar elevation characteristics.

The third part of our empirical strategy concerns the estimation of the impact of lithium extraction in the ASF on human settlements and the economic activity in the region proxied by nighttime light density. In terms of nighttime light density, we utilize an approach equivalent to that for the effect on NDVI, given by Equation 2. However, in terms of the impact on human settlements, we move from a panel data setting to a first-difference approach as the human settlement data is only available every ten years. This is mainly due to the frequency with which population censuses are carried out (and on which the human settlement data rely), giving us data for human settlements only for 2010 and for 2020. Considering this, our equation of interest is the following:

$$\triangle y_{ij} = \alpha + \beta I_{ij} + \gamma X_{ij} + \delta_j + \varepsilon_{ij} \tag{4}$$

Where $\triangle i_{ij}$ is the change in the population between 2010 and 2020 for each 100m$\times$100m pixel in the region. I_{ij} is defined as the minimum distance between each pixel i and the five extraction wells used by SQM to extract industrial water near th ASF. To have an interpretation of the coefficient similar to what we have for the NDVI and nighttime light estimates, the distance between each pixel and the ASF is multiplied by -1. X_i are latitude, longitude, and elevation controls for each pixel, δ_j are location fixed-effects, and, finally, ε_{ij} is the error term. Our coefficient of interest is β, which captures the average effect of lithium extraction exposure on human settlements. As above, we also show our p-values by considering the spatial correlation of the pixels in our sample.

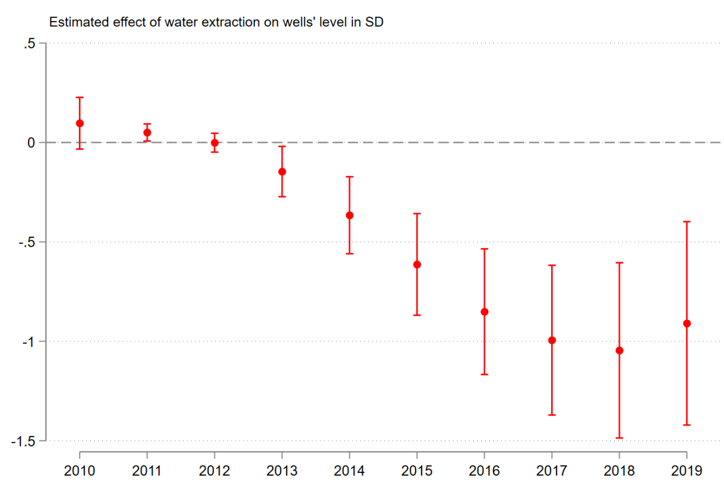
Here, our identification strategy relies on the assumption that when comparing changes in the outcome variables for each pixel very close to each other over time, any change could only be attributed to the proximity to the ASF and, therefore, to the extraction of lithium in this area. It is worth noting that, although there could exist a negative relationship between the human settlements and the distance from each point to ASF, our identification strategy is exploiting changes over time of the dependent variable in pixels close to each other, which we expect to change at similar rates.

5 Main impacts of lithium extraction

5.1 The impact on groundwater levels

Our first results are related to the effect of lithium extraction on groundwater levels in the ASF area, which is under the direct influence of the SQM mining activity. Our estimates are shown in Figure 8. As can be seen, before the ramping up in lithium production by SQM (roughly in 2013), there seems to not be any statistically significant difference in the water levels between the measurement wells located in the ASF and the ones located in other areas in the North of Chile. However, since 2013, the groundwater levels close to the ASF region seem to have been significantly reduced reaching a maximum negative impact of a reduction of 1 standard deviation in 2017.

Figure 8: Estimated effect of extraction of lithium on well levels



Notes: This figure reports coefficients of an event study regression based on Equation 1, where the dependent variable is the water levels in standard deviations. The regression controls for well and year fixed effects. Standard errors are clustered on a well level. Source: SQM measurement well reporting and DGA.

These results are in line with the descriptive evidence presented above according to which, using the SQM measurement wells in the area, the levels of groundwater in the ASF dropped below the historical averages during the 2014-2019 period, with a recovery period that seems to have started mainly in 2019.

5.2 The impact on vegetation

Our main results in terms of vegetation are shown in Table 5. In the different columns of Table 5 we sequentially include different combinations of control variables that allow us to reassure the causal interpretation of our coefficient. Our estimates indicate that those pixels that are exposed to 1 more standard deviation of our measure of lithium extraction were affected negatively by a reduction in vegetation, as proxied by NDVI, of 0.002-0.003. As can be seen in Table 5, the average NDVI in our sample was about 0.076, which would indicate a reduction in the vegetation relative to the baseline period of about 4%. These results are robust and consistent even when taking into account, not only the latitude and longitude of the different pixels in our sample but also the different shocks over time to which each pixel might have been exposed that affect them differentially according to their elevation.

To put these numbers in context, we know that one standard deviation in our outcome variable is equal to an approximate increase of 70,500 units in the raw variable. This increase can be achieved by increasing the number of electric vehicles sold over two consecutive years by 700,000, fixing a distance of 10 km relative to the ASF extraction wells. Alternatively, a one standard deviation increase in our independent variable can also be achieved by increasing the distance between two pixels by 7 Km, while fixing the number of EVs sold to 1 million, if one of the pixels is located at 5 Km from the ASF.

Table 5: Effect of Lithium extraction on NDVI

	(1)	(2)	(3)	(4)
Exposure to extraction	-0.003***	-0.002***	-0.002***	-0.002***
	(0.000)	(0.000)	(0.000)	(0.000)
Adjusted P-value	[0.000]	[0.000]	[0.000]	[0.000]
2013 NDVI Mean	0.076	0.076	0.076	0.076
Observations	199,096	199,096	199,096	199,096
Pixel FE	Yes	Yes	Yes	Yes
Year FE	Yes	No	No	No
Location FE × Year FE	No	Yes	Yes	Yes
Coordinates × Year FE	No	No	Yes	Yes
Elevation × Year FE	No	No	No	Yes

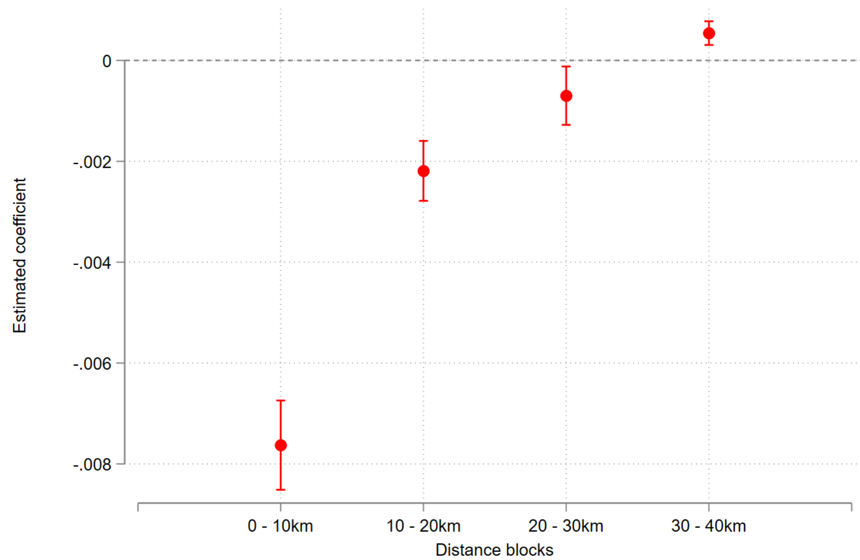
Notes: This table reports coefficients of an event study regression based on Equation 2, where the dependent variable is NDVI. Pixel FE corresponds to a dummy variable for each pixel in our sample. Location FE corresponds to a dummy for each IVA in our sample. Coordinates FE corresponds to the latitude and longitude of each pixel in our sample, while elevation FE to the elevation from sea level of each pixel. Errors are clustered on a pixel level. Also, we report p-values considering a serial correlation with an 8-period length and a spatial correlation that follows a Bartlett kernel with a distance cutoff of 500 meters. Source: Own elaboration based on data from Landsat 8 Collection 1 Tier 1 and own estimates.

Alternatively, instead of considering a pure continuous distance exposure to lithium extraction, we can also consider a measure of exposure that depends on distance blocks between the lithium extraction center of activity and the pixels in our sample. To do so, we proceed as follows: First, we split our pixels within the 50-Kilometer radius around the SQM mine in five groups of 10 km each. Second, we interact the distance dummies with total sales of electric vehicles in Europe, China, and the US (V_t in our main specification). Hence, we analyze how this exposure to the demand for lithium worldwide affects different pixel blocks based on the distance to the SQM activity in SPdA, by considering as a base level group the furthest distance block, namely those pixels between 40km and 50km away of the SQM mine. We run a regression of the NDVI over time on these interacted dummy variables by controlling for the same variables presented in our main specification (location-year fixed effects, coordinates-year, and elevation-year controls).

Our main results of this exercise are shown in Figure 9. The plotted coefficients should be interpreted as the differential effect of the exposure of each distance block to lithium extraction, relative to the effect on the block that is furthest away from the SQM mining activity. As can be seen, the closer the pixels are to the center of the mine, the more negative the impact on vegetation over the 2013-2019 period. For the closest distance block, we find a reduction in vegetation of about 0.8% relative to the

40-50km distance block.

Figure 9: Estimated effect of exposure to lithium extraction by distance blocks



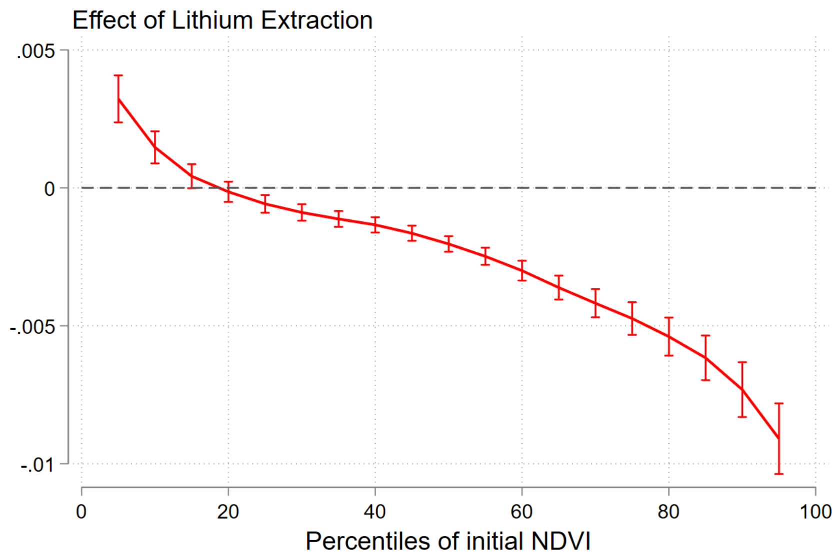
Notes This figure reports coefficients of a regression based on Equation of NDVI on distance block dummier, interracted with the sales of electric vehicles in Europe, China, and the US. The regression controls for location-year fixed effects, coordinates-year, and elevation-year controls. Standard errors are clustered on a pixel level. Source: Own elaboration based on data from Landsat 8 Collection 1 Tier 1 and own estimates.

These results are consistent with the nature of the variation considered in this paper, where we expect that the impact on vegetation will be smaller the further the pixels are located from the water extraction points. They are also consistent with the descriptive evidence presented above in Figure 7 where we showed that the negative difference in vegetation was larger particularly for the pixels between 5km and 35 km away from the center of the flat.

Additionally, we analyze whether or not the impact of lithium extraction exposure on vegetation varies according to the initial level of vegetation of the pixels in our sample in 2013. To do so, we take advantage of the panel structure of our data and interact our independent variable of interest with the NDVI of each pixel i in 2013. We show this heterogeneous effects results in Figure 10.

Our results demonstrate that the negative impact of lithium extraction on vegetation was mainly concentrated in those pixels that were greener at the beginning of our analysis period (2013). For instance, according to our estimates, the impact on the pixels located in the 80th percentile of the 2013 NDVI distribution, was almost double compared to those pixels located in the median of the 2013 NDVI distribution, and this difference seems to be statistically significant.

Figure 10: Estimated effect of exposure to lithium extraction by baseline level of NDVI



Notes. Each point corresponds to the estimated effect according to the 2013 distribution of NDVI across all pixels in our area of analysis. The 95% confidence intervals are also plotted. Source: Own elaboration based on data from Landsat 8 Collection 1 Tier 1 and own estimates.

Based on these results, those places where vegetation was stronger at the beginning of the period were those in which there was a greater margin for crops to be negatively affected. This points us to interpret this as an impact on agricultural activity: if water availability impact leads to a reduction in agricultural activity and the greener regions are those in which agricultural activity was more intense, we expect the agricultural activity of individuals in those places to be more affected.

5.3 The impact on human settlements

The next step in our analysis relates to the impact of lithium extraction exposure on human settlements and the population in SPdA. It is expected that the reduction in water availability might have negatively affected the living conditions of the people in the region. The results of our specification with regards to human settlements are shown in Table 7. In the first column, we do not include any control in our regression and only consider the coefficient for the model in which we regress the change in the population for each location on the negative distance to the ASF. In the second column, we estimate our preferred specification including also location fixed effects to compare changes in pixels very close to each other over time. Subsequently, we add coordinate and elevation controls.

Table 6: Effect of Lithium extraction on human settlements

	(1)	(2)	(3)	(4)
Distance (Kms)	-0.004***	-0.011***	-0.021***	-0.019***
	(0.000)	(0.001)	(0.001)	(0.001)
Adjusted P-value	[0.000]	[0.000]	[0.000]	[0.000]
2010 Dep. Var. Mean	0.162	0.162	0.162	0.162
Observations	41,964	41,964	41,964	41,964
Location FE	No	Yes	Yes	Yes
Coordinates Controls	No	No	Yes	Yes
Elevation control	No	No	No	Yes

Notes: This table reports coefficients of an event study regression based on Equation 4, where the dependent variable is the change in human settlements between 2020 and 2010. Location FE corresponds to a dummy for each IVA in our sample. Coordinates controls correspond to the latitude and longitude of each pixel in our sample, while elevation controls to the elevation from sea level of each pixel. Also, we report p-values considering spatial correlation that follows a Bartlett kernel with a distance cutoff of 500 meters. Source: Own elaboration based on data from Global Human Settlement Layer and own estimates.

Hence, in our preferred specification, there seems to be a negative effect of 0.02 fewer people in local villages for each kilometer closer to the ASF. Taking into account that, according to Table 7, the average number of people per cell in our sample in 2010 was about 0.162, this negative effect represents a reduction relative to the baseline population per cell of about 11%.

5.4 The impact on economic activity

Next, we corroborate the effect on human settlements using nighttime light density data as a proxy for economic activity. The results we find are similar to the effects for human settlements, with a reduction of 0.001 in our dependent variable of nighttime light density for 1 standard deviation increase in our measure of exposure over the period in question. This reduction represents a negative effect of almost 1% relative to the baseline average nighttime light density in the cells of our sample, given an increase of one standard deviation in our independent variable.

Table 7: Effect of Lithium extraction on Nighttime Light Density

	(1)	(2)	(3)	(4)
Exposure to extraction	-0.005***	-0.003***	-0.002***	-0.001**
	(0.002)	(0.001)	(0.001)	(0.001)
Adjusted P-value	[0.003]	[0.001]	[0.008]	[0.038]
2010 Dep. Var. Mean	0.112	0.112	0.112	0.112
Observations	88,456	88,456	88,456	88,456
Pixel FE	Yes	Yes	Yes	Yes
Year FE	Yes	No	No	No
Location FE × Year FE	No	Yes	Yes	Yes
Coordinates × Year FE	No	No	Yes	Yes
Elevation × Year FE	No	No	No	Yes

Notes. This table reports coefficients of an event study regression based on Equation 2, where the dependent variable is Nighttime light density. Pixel FE corresponds to a dummy variable for each pixel in our sample. Location FE corresponds to a dummy for each IVA in our sample. Coordinates FE corresponds to the latitude and longitude of each pixel in our sample, while elevation FE to the elevation from sea level of each pixel. Errors are clustered on a pixel level. Also, we report p-values considering a serial correlation with an 8-period length and a spatial correlation that follows a Bartlett kernel with a distance cutoff of 500 meters. Source: Own elaboration based on data from VIIRS Nighttime Day/Night Annual Band Composites.

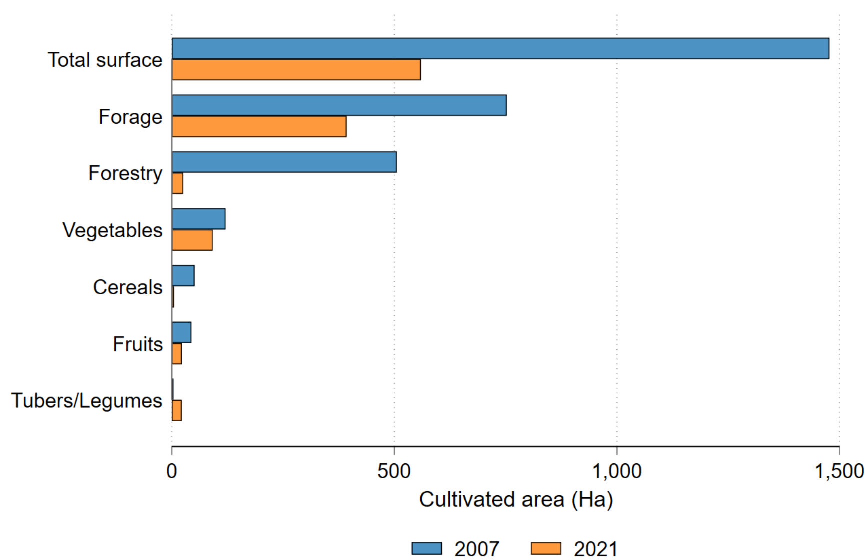
6 Mechanisms: Evolution of local agricultural activity

In this section, we present descriptive and suggestive evidence derived from the Chilean Agricultural censuses from the years 2007 and 2021. The objective is to shed light on potential mechanisms contributing to the adverse effects of lithium extraction activity on vegetation and human settlements within the region. Considering the limited granularity of available information regarding agricultural activity in the SPdA, it is not feasible to generate comparable results to those presented in the preceding section. Nevertheless, we can provide evidence of the trends in agricultural performance of individuals residing in the SPdA municipality overall.

The primary hypothesis posited in this paper asserts that the water-intensive nature of lithium extraction in the SPdA may have led to a decline in groundwater levels in the area. This, in turn, could have had adverse effects on vegetation, both on the indigenous flora of the region and on vegetation closely associated with agricultural activities. As previously demonstrated through the Agricultural Census data, the predominant vegetation in the region consists mainly of forage plants, and indigenous and endemic species, with a limited presence of vegetables.

Analyzing the changes in cultivated surface for various crops between 2007 and 2021, a period coinciding with intensified lithium extraction activities in the region, Figure 11 illustrates a significant and noteworthy reduction in the area dedicated to crops. The cultivated surface diminished substantially from approximately 1,500 hectares in 2007 to just over 500 hectares over a 15-year period. A closer examination of the primary contributors to this reduction reveals that forage and forestry played pivotal roles. The cultivated area for forage, for instance, witnessed a nearly 50% decline from 2007 to 2021. Remarkably, the forestry and endemic crops in the region experienced a drastic decline, virtually disappearing over the period between the two censuses.

Figure 11: Evolution activity in the Agriculture sector - SPdA



Notes. Own elaboration based on the 2007 and 2021 Agricultural Censuses of Chile.

Upon analyzing the crops predominantly affected by the decrease in cultivated areas within the municipality, Table 8 reveals that the decline in forage and forestry crops can be attributed primarily to the diminished presence of alfalfa and Tamarugo. Alfalfa, a distinctive crop thriving in the SPdA region, exhibits remarkable adaptation to the aridity of the desert locale. Conversely, Tamarugo, an endemic tree unique to the Atacama desert, emerges as a particularly threatened species, undergoing a significant reduction over the same period.

A distinctive feature of the Tamarugo tree is its endemic nature. Having adapted to the arid conditions of the Atacama desert, it developed extensive roots that reach phreatic levels to access underground water for survival. Per our approach, the observed decline in vegetation, particularly for Tamarugo, can be attributed to the water-intensive mining activities which, in turn, lead to a reduction in groundwater levels. This happens as those activities may impact the ability of vegetation to access sufficient water beneath the ground, consequently affecting their reproduction and diminishing green areas within the region.

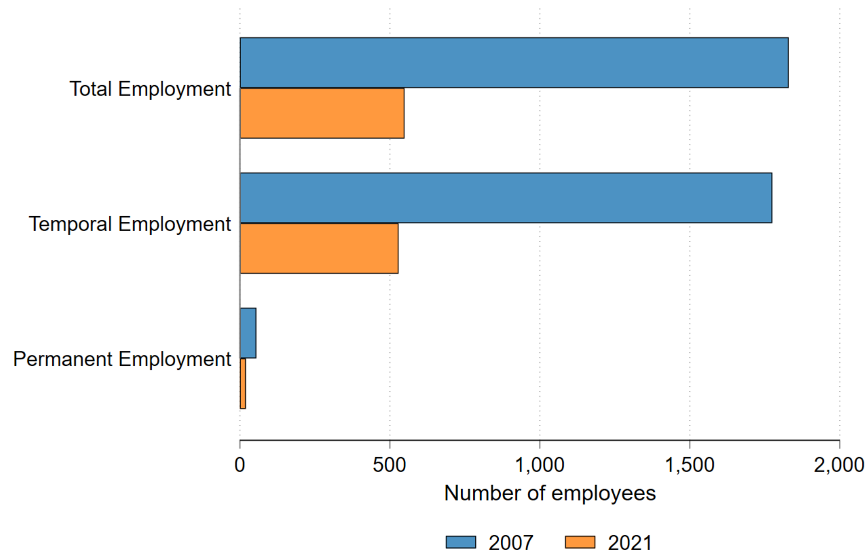
Table 8: Variation in cultivated area by main crops, 2007-2021

	2007	**2021**	**Difference**
Forage	752.43	392.58	-359.85
Alfalfa	749.94	392.08	-357.86
Forestry	505.53	25.50	-480.03
Tamarugo	505.53	11.80	-493.73
Vegetables	120.68	91.81	-28.87
Corn	82.91	69.33	-13.58
Cereals	51.09	4.67	-46.42
Corn	25.98	3.15	-22.83
Fruits	43.99	22.59	-21.40
Pear	14.89	12.82	-2.07
Tubers/Legume	3.55	22.35	18.80
Potato	3.55	16.55	13.00

Notes. Own elaboration based on the 2007 and 2021 Agricultural Censuses of Chile.

Finally, as demonstrated earlier, lithium extraction appears to have adversely affected human settlements in the region. This impact could be attributed to the challenging conditions arising from reduced water availability in the area. This is not only due to the reduction in potable water for consumption, but also due to (a) the reduction of water available for irrigation and (b) the direct influence that the reduction of groundwater might have had on vegetation. Figure 12 provides supporting evidence in this direction. It illustrates a notable decline in agricultural employment in SPdA during the 2007-2021 period, primarily driven by a decrease in temporary employment from almost 2,000 to nearly 500 employees. This decline aligns with the reduction in vegetation, the increasingly unfavorable conditions for vegetation growth, and the consequent effects on individuals residing close to the ASF. Furthermore, this reduction in agricultural employment corroborates the findings on the decline in human settlements and nighttime light density, as highlighted in the main results of the paper.

Figure 12: Evolution employment in the Agriculture sector - San Pedro de Atacama Comuna



Notes. Own elaboration based on the 2007 and 2021 Agricultural Censuses of Chile.

Our findings indicate that lithium extraction activity has a detrimental impact on water availability in the vicinity of the ASF. This adversely impacts both the vegetation and the local population in the region. This section offers suggestive evidence supporting our earlier causal findings. Specifically, during the 2007-2021 period, which is characterized by a boom in lithium extraction and an increase in water utilization by mining companies, the SPdA community experienced a significant decline in agricultural activity and crop-cultivated areas. Descriptive evidence reveals a substantial reduction in the agricultural workforce during the period in question, aligning with the results on the reduction of human settlements and nighttime light density in the region. We attribute this to presumed challenges arising from decreased water and vegetation availability.

7 Robustness Checks

In the Appendix, we test the robustness of the results from our main specifications. More specifically, in Appendix A we test the robustness of our event study to alternative definitions of the control group. More specifically, instead of comparing the wells around the ASF to all measurement wells of DGA in the North of Chile, we restrict the control to (a) the North of Chile without Arica and Parinacota, (b) the North without Antofagasta, and (c) the North without Tarapacá. The results remain quite robust regardless of the specification.

Furthermore, in Appendix A we test the robustness of the results on NDVI, human settlements, and nighttime density for different values of the distance cutoff in the Bartlett kernel. More specifically, we vary the distance from 500 to 1,200 meters, at increments of 100 meters and present the t-statistic. All our results remain virtually unchanged to this robustness check.

8 Discussion: Cost-Benefit of lithium extraction in Chile

The energy transition is a predominant goal for governments around the world and lithium is an important component of that transition. In the case of Chile, the production of lithium his a major export commodity and an important source of revenue for the country. According to information from the Central Bank of Chile, exports of lithium carbonate by Chile represented about 0.8% of total exports on average during the 2013-2021 period, in 2022 this share grew to about 8%. This makes lithium the second most important commodity exported by the country right after copper, which represents about 45% of Chilean exports. On the other hand, lithium extraction activity leads the mining activity in the country, representing about 3.4% of Chilean GDP and representing a real growth of 10.4% in 2022.

In this paper we demonstrate that lithium extraction activity in the country has had negative local impacts on the vegetation, population, and the ecosystem surrounding the ASF. However, at the same time, it represents a key source of revenues for the country, which could be invested in social public policies, education, and health that might contribute to the development of the Chilean population in the future. Furthermore, lithium also plays a key role in the energy transition, a process that is necessary for tackling climate change globally.

Both sides of the debate, i.e. the benefits that lithium extraction might represent and the potential environmental and economic costs for the populations surrounding the ASF must be taken into account when implementing optimal public and social policies. When approaching this matter, it is also key to consider two additional components. First, most of the people living in the ASF belong to indigenous communities that have a special and particular status under the law in the country and around the world. Therefore, when weighing the potential negative effects for these communities, it is worth considering that they must receive particular attention. Secondly, it is important to take into account the environmental value of the ASF as an ecosystem, and how any negative implications in terms of vegetation, wildlife abundance, and water availability that lithium extraction activities might entail, could be amplified.

9 Concluding Remarks

Lithium has developed into a key raw material for the Chilean economy and the creation of a future roadmap for its exploitation is at the forefront of public discussion in the country. However, the environmental and economic consequences of lithium extraction on local areas and populations are not yet clear and there is no consensus on that matter within the scientific community. It is important that relevant policymakers obtain visibility on the magnitude and extent of those consequences in order to address them moving forward.

In this paper, we aim to contribute to this debate by providing causal evidence of the impact of lithium extraction on vegetation in areas around the ASF. To do this we build on relevant environmental literature that has only provided correlational evidence between the extraction and several environmental variables. This literature guided us in identifying the relevant vulnerable areas, as well as those environmental variables that the extraction could have potentially affected. Additionally, we move one step further by attempting, for the first time, to evaluate how population changes and economic activity might have been affected.

Several important takeaways emerge from our analysis. First, we find a reduction in groundwater levels close to the ASF, compared to groundwater levels in other wells in the north of Chile. Also, in terms of NDVI, the negative effect seems to be statistically significant for all values in the initial distribution of NDVI of locations around the ASF, with pixels closer to the ASF being more severely affected. Also, the effect seems to be particularly higher the greater the NDVI index in 2013. Thirdly, in terms of human populations, our preferred specification yields a statistically significant negative result that is corroborated by the negative impact on nighttime light density.

Overall, in this study, we provide causal evidence that the extraction reduces groundwater levels and vegetation around the ASF. We also show that the vegetation index that is reduced is strongly correlated with agriculture historically in Chile. Furthermore, we causally show that populations were reduced in those same areas, positing a causal chain that reduced agriculture might have caused human flight out of the IVAs.

Our analysis sheds light on a crucial matter for Chile, however, the implications are also relevant for the other countries located in the "lithium triangle", namely Bolivia and Argentina. It is important that policymakers take into account the potential negative environmental and economic effects that might come with lithium extraction, in order to address them and compensate the affected communities

Notwithstanding the evidence we provide in this paper in terms of the environmental and economic consequences of lithium extraction, it should be stressed that a life-cycle cost-benefit analysis would also be important to complement our results. Lithium extraction has positive economic impacts for the economies that exploit this raw material, as well as for decarbonizing the economy altogether, and it is important to understand the scope and magnitude of the negative impacts in order to carry out a holistic analysis of the supply-chain of lithium.

References

Aragón, F. M. and Rud, J. P. (2013). Natural Resources and Local Communities: Evidence from a Peruvian Gold Mine. *American Economic Journal: Economic Policy*, 5(2):1–25.

Aragón, F. M. and Rud, J. P. (2016). Polluting Industries and Agricultural Productivity: Evidence from Mining in Ghana. *The Economic Journal*, 126(597):1980–2011.

Babidge, S. (2019). Sustaining Ignorance: The Uncertainties of Groundwater and its Extraction in the Salar de Atacama, Northern Chile. *Journal of the Royal Anthropological Institute*, 25(1):83–102.

Bazillier, R. and Girard, V. (2020). The Gold Digger and the Machine. Evidence on the Distributive Effect of the Artisanal and Industrial Gold Rushes in Burkina Faso. *Journal of Development Economics*, 143:102411.

Boston Consulting Group (2021). Why Electric Cars Can't Come Fast Enough. https://www.bcg.com/publications/2021/why-evs-need-to-accelerate-their-market-penetration, Last accessed on 2022-10-30.

Brown, C., Meeks, R., Ghile, Y., and Hunu, K. (2013). Is Water Security Necessary? An Empirical Analysis of the Effects of Climate Hazards on National-Level Economic Growth. *Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences*, 371(2002):20120416.

Burke, M., Hsiang, S. M., and Miguel, E. (2015). Global Non-Linear Effect of Temperature on Economic Production. *Nature*, 527(7577):235–239.

Burlig, F., Preonas, L., and Woerman, M. (2021). Energy, Groundwater, and Crop Choice. NBER Working Paper 28706, National Bureau of Economic Research. Available at SSRN: https://ssrn.com/abstract=3832203.

Center for Strategic and International Studies (2021). South America's Lithium Triangle: Opportunities for the Biden Administration. https://www.csis.org/analysis/south-americas-lithium-triangle-opportunities-biden-administration, Last accessed on 2022-10-30.

Cherniwchan, J., Copeland, B. R., and Taylor, M. S. (2017). Trade and the Environment: New Methods, Measurements, and Results. *Annual Review of Economics*, 9:59–85.

Cole, M. A., Elliott, R. J., and Zhang, L. (2017). Foreign Direct Investment and the Environment. *Annual Review of Environment and Resources*, 42:465–487.

Conley, T. G. (1999). Gmm Estimation with Cross Sectional Dependence. *Journal of econometrics*, 92(1):1–45.

Copeland, B. R. and Taylor, M. S. (2004). Trade, Growth, and the Environment. *Journal of Economic literature*, 42(1):7–71.

Corral, L. R., Schling, M., and Montiel, C. (2018). The Economic and Ecological Impact of Natural Resource Extraction: The Case of the Camisea Gas Project in Peru. Technical report, IDB Working Paper Series.

Cust, J. and Poelhekke, S. (2015). The Local Economic Impacts of Natural Resource Extraction. *Annu. Rev. Resour. Econ.*, 7(1):251–268.

Damania, R. (2020). The Economics of Water Scarcity and Variability. *Oxford Review of Economic Policy*, 36(1):24–44.

De la Hoz, G. M., Martinez, V. R., and Vedia, J. L. (2013). El Litio: Desde los Salares de la Puna a Nuestros Celulares. *Instituto de Bio y Geociencias del NOA*, 25.

Dell, M., Jones, B. F., and Olken, B. A. (2012). Temperature Shocks and Economic Growth: Evidence from the Last Half Century. *American Economic Journal: Macroeconomics*, 4(3):66–95.

Department of Energy (2017). How Does Lithium-Ion Battery Work. https://www.energy.gov/eere/articles/how-does-lithium-ion-battery-work, Last accessed on 2022-10-30.

Environmental Protection Agency (2023). Global greenhouse gas emissions data. https://www.epa.gov/ghgemissions/global-greenhouse-gas-emissions-data, Last accessed on 2024-29-01.

Flexer, V., Baspineiro, C. F., and Galli, C. I. (2018). Lithium Recovery from Brines: A Vital Raw Material for Green Energies with a Potential Environmental Impact in its Mining and Processing. *Science of the Total Environment*, 639:1188–1204.

Garrett, D. E (2004). Handbook of Lithium and Natural Calcium Chloride.

Gutiérrez, J. S., Moore, J. N., Donnelly, J. P., Dorador, C., Navedo, J. G., and Senner, N. R. (2022). Climate Change and Lithium Mining Influence Flamingo Abundance in the Lithium Triangle. *Proceedings of the Royal Society B*, 289(1970):20212388.

Hsiang, S. M. (2010). Temperatures and Cyclones Strongly Associated with Economic Production in the Caribbean and Central America. *Proceedings of the National Academy of sciences*, 107(35):15367–15372.

IDB (2017). Lithium: White Gold for a Region's Development. https://www.iadb.org/en/improvinglives/lithium-white-gold-regions-development#:~:text=The%20white%20gold%20for%20developement,to%20the%20U.S.%20Geological%20Survey, Last accessed on 2022-10-30.

International Energy Agency (2022a). The Role of Critical Minerals in Clean Energy Transitions. https://www.iea.org/reports/the-role-of-critical-minerals-in-clean-energy-transitions/, Last accessed on 2023-05-13.

International Energy Agency (2022b). Trends in Electric Light-Duty Vehicles. https://www.iea.org/reports/global-ev-outlook-2022/trends-in-electric-light-duty-vehicles, Last accessed on 2022-10-30.

International Energy Agency (2023). Gloval ev outlook 2023 policy developments. https://www.iea.org/reports/global-ev-outlook-2023/policy-developments, Last accessed on 2024-29-01.

Jaskula, B.W. (2018). U.S. Geological Survey 2016 Minerals Yearbook. U.S. Geological Survey, Lithium.

Kelly, C. J., Wang, M., Dai, Q., and Winjobi, O. (2021). Energy, Greenhouse Gas, and Water Life Cycle Analysis of Lithium Carbonate and Lithium Hydroxide Monohydrate from Brine and Ore Resources and their Use in Lithium Ion Battery Cathodes and Lithium Ion Batteries. *Resources, Conservation and Recycling*, 174:105762.

Levinson, A. (2010). Offshoring Pollution: Is the United States Increasingly Importing Polluting Goods? *Review of Environmental Economics and Policy*, 4(1):63–83.

Lippert, A. (2014). Spill-overs of a Resource Boom: Evidence from Zambian Copper Mines.

Liu, W. and Agusdinata, D. B. (2020). Interdependencies of Lithium Mining and Communities Sustainability in Salar de Atacama, Chile. *Journal of Cleaner Production*, 260:120838.

Liu, W., Agusdinata, D. B., and Myint, S. W. (2019). Spatiotemporal Patterns of Lithium Mining and Environmental Degradation in the Atacama Salt Flat, Chile. *International Journal of Applied Earth Observation and Geoinformation*, 80:145–156.

Loayza, N. and Rigolini, J. (2016). The Local Impact of Mining on Poverty and Inequality: Evidence from the Commodity Boom in Peru. *World development*, 84:219–234.

López Steinmetz, R. L. and Salvi, S. (2021). Brine Grades in Andean Salars: When Basin Size Matters. A Review of the Lithium Triangle. *Earth-Science Reviews*, 217:103615.

Marazuela, M., Vázquez-Suñé, E., Ayora, C., and Garcia-Gil, A. (2020). Towards More Sustainable Brine Extraction in Salt Flats: Learning from the Salar de Atacama. *Science of the Total Environment*, 703:135605.

Marazuela, M., Vázquez-Suñé, E., Ayora, C., García-Gil, A., and Palma, T. (2019). The Effect of Brine Pumping on the Natural Hydrodynamics of the Salar de Atacama: The Damping Capacity of Salt Flats. *Science of the Total Environment*, 654:1118–1131.

Marbler, A. (2024). Water Scarcity and Local Economic Activity: Spatial Spillovers and the Role of Irrigation. *Journal of Environmental Economics and Management*, page 102931.

Moran, J. B., Boutt, F. D., McKnight, V. S., Jenckes, J., Munk, L. A., Corkran, D., and Kirshen, A. (2022). Relic Groundwater and Prolonged Drought Confound Interpretations of Water Sustainability and Lithium Extraction in Arid Lands. *Earth's Future*, 10(7).

Munk, L. A.and Boutt, F. D., Moran, B. J., McKnight, S. V., and Jenckes, J. (2021). Hydrogeologic and Geochemical Distinctions in Freshwater-Brine Systems of an Andean Salar. *Geochemistry, Geophysics, Geosystems*, 22(3).

Pokorny, B., von Lübke, C., Dayamba, S. D., and Dickow, H. (2019). All the Gold for Nothing? Impacts of Mining on Rural Livelihoods in Northern Burkina Faso. *World Development*, 119:23–39.

Reuters (2020). The Atacama Indigenous Council (CPA) Accuses SQM of Over-Extracting Brine from the Salt Flat. https://www.reuters.com/article/idUSKCN25A2PA. Accessed: yyyy-mm-dd.

Russ, J. (2020). Water Runoff and Economic Activity: The Impact of Water Supply Shocks on Growth. *Journal of Environmental Economics and Management*, 101:102322.

Schenker, V., Oberschelp, C., and Pfister, S. (2022). Regionalized Life Cycle Assessment of Present and Future Lithium Production for Li-ion Batteries. *Resources, Conservation and Recycling*, 187:106611.

Sociedad Quimica y Minera de Chile (2021). Sustainable Lithium. https://www.sqmlithium.com/wp-content/uploads/2021/05/SQM-Sustainable-Lithium-English-20210504.pdf. Accessed: January 25th, 2024.

Sociedad Quimica y Minera de Chile (2022). Sqm Shares its Views on Salar Futuro. https://ir.sqm.com/English/news/news-details/2022/SQM-Shares-Its-Views-on-Futuro-Salar/default.aspx. Accessed: yyyy-mm-dd.

Sociedad Quimica y Minera de Chile (2024). Agua industrial. Accessed: 2024-02-18.

Tanaka, S., Teshima, K., and Verhoogen, E. (2022). North-South Displacement Effects of Environmental Regulation: The Case of Battery Recycling. *American Economic Review: Insights*, 4(3):271–288.

Tran, T. and Luong, T. V. (2015). *Lithium Process Chemistry*, chapter 3, pages 81–124. Elsevier.

United States Geological Survey (2024). Lithium. Technical report, United States Geological Survey. Accessed: January 25th, 2024.

U.S. Securities and Exchange Commission (2018). Report of Foreign Private Issuer. https://www.sec.gov/Archives/edgar/data/909037/000114420418002507/tv483508_6k.htm. Accessed: January 25th, 2024.

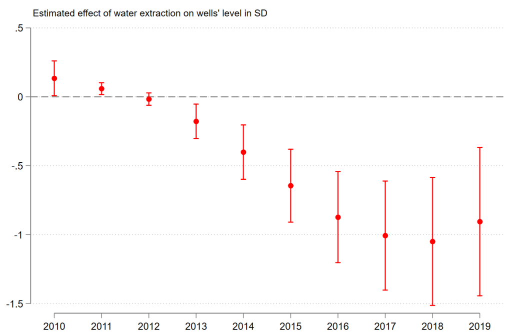
van der Ploeg, F. (2011). Natural Resources: Curse or Blessing? *Journal of Economic Literature*, 49(2):366–420.

Vera, M. L., Torres, W. R., Galli, C. I., Chagnes, A., and Flexer, V. (2023). Environmental Impact of Direct Lithium Extraction from Brines. *Nature Reviews Earth & Environment*, 4(3):149–165.

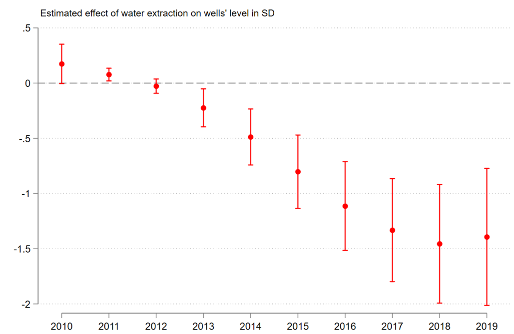
A Effect on wells excluding different regions

Figure 13: Robustness of the effect of extraction of lithium on wells levels for different control groups

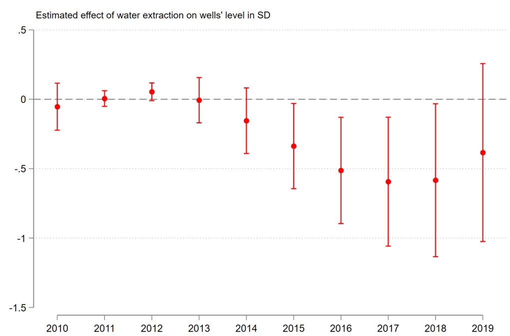
(a) Excluding Arica and Parinacota



(b) Excluding Antofagasta

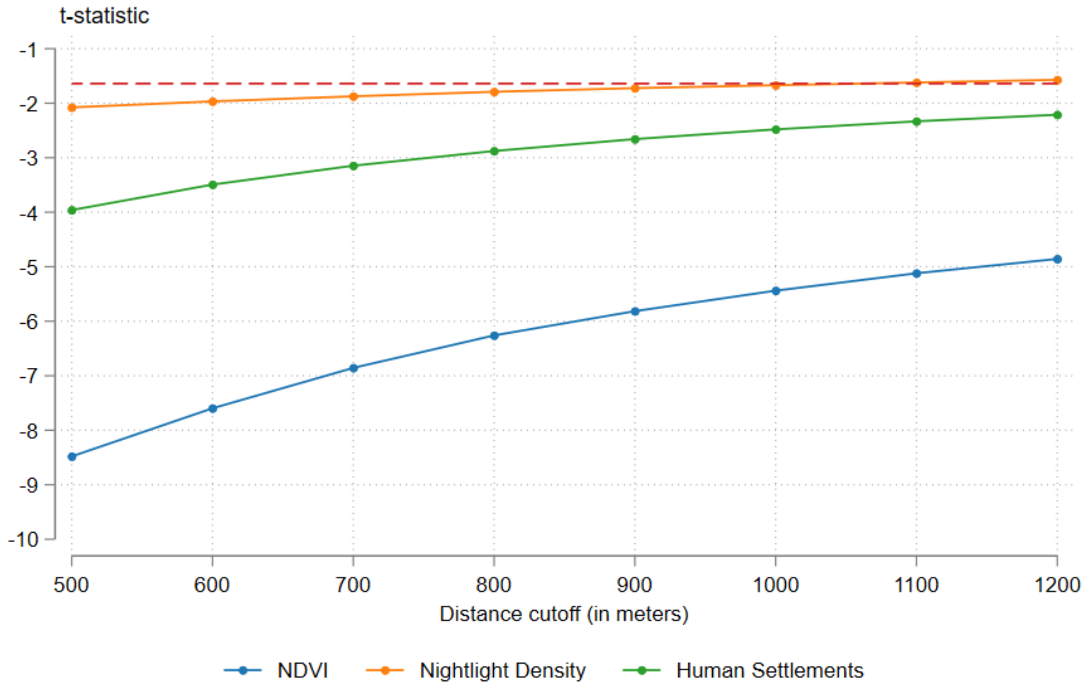


(c) Excluding Tarapacá



Notes: Notes: This figure reports coefficients of an event study regression based on Equation 1, where the dependent variable is the water levels in standard deviations. Each panel introduces a different definition of the control group, by excluding a region.The regression controls for well and year fixed effects. Standard errors are clustered on a well level. Source: SQM measurement well reporting and DGA.

Figure 14: Robustness of the effect of extraction of lithium on NDVI, nighttime light density, and human settlements



Notes....

B Effect on each village separately

C Identification and construction of IVAs