Harvesting Lithium:
water, brine and the industrial dynamics of production in the Salar de Atacama

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Abstract

Geographical research on lithium and other renewable energy materials explores the geopolitical dimensions of resource supply and the 'new geographies' associated with an expanding resource frontier. The material characteristics and environmental conditions of lithium production, however, are largely overlooked in this perspective. In the context of a global speculative boom for lithium linked to its growing role in energy storage, this paper adopts a grounded, exploratory approach to investigate the dynamics of production and resource management at one of the world's most significant sources of lithium: the brine deposits of the Atacama Salt Flat/Salar de Atacama in northern Chile. We show how lithium production from brine has a distinctive 'eco-regulatory' character as it involves managing a series of hydrogeological conditions and physical processes that are largely external to capital. The paper highlights the infrastructures (pumps, pipes, ponds) associated with the harvesting of lithium from brine and examines how production on the *salar* generates a series of ecological contradictions (notably around water depletion) with potential to disrupt accumulation. We also examine the multiple flexibilities afforded by the eco-regulatory character of production, and show how these enable lithium producers to adapt fixed infrastructures to dynamic political economic conditions. By focusing on both contradictions and flexibilities of lithium production, the paper draws attention to trajectories of capitalisation in the lithium value chain and their environmental consequences; and considers the political-economic incentives shaping further capitalisation. The paper concludes by considering the implications of this exploratory case study for critical resource geography.

Keywords: lithium, eco-regulation, capitalization, ecological contradiction, flexibility, Atacama

1. Introduction

Decarbonisation of the global energy system, characterised by a large-scale shift to renewables and electrification of end uses such as power and transportation, will require the extraction and processing of a wide range of raw materials. The material demands of decarbonisation are now widely acknowledged, and the past few years have seen increased attention - from investors, technologists and critical geographers alike - in a broad suite of ‘e-tech’ materials closely associated with the provision of low-carbon energy including a range of so-called ‘battery minerals’ (IRENA 2019, Mulvaney 2019, Klinger 2018). Among them is lithium, a light metal element with multiple applications in stationary and portable energy storage. Global production capacity for lithium-ion batteries is growing rapidly, exemplified by Tesla’s Gigafactory in Nevada and BYD’s recently constructed facility in Chongqing. These and other lithium-ion battery facilities are designed to serve rising demand for electric traction (e.g. electrically powered cars, scooters and buses), and for energy storage at domestic, utility and grid-scale linked to the expanding role of renewables in electricity supply (Jaffe 2017, Roskill 2017, Olivetti et al. 2017).

Our interest in this paper is not the battery revolution per se, but in understanding the political ecological consequences of surging lithium demand for locations that host lithium extraction and processing facilities (or have the potential to do so). Rising lithium prices between 2015 and 2018 drove the formation of multiple new companies to acquire and develop lithium reserves; existing lithium producers sought to ramp up production; and downstream users in the battery value chain experienced increasing competition to secure reliable sources of high quality supply. Prices have halved since 2018, however, as supply grew ahead of demand and China (the largest market) recalibrated its support for electric vehicles. The recent history of lithium, then, exhibits some of the classic features of a speculative resource boom in which expectations of demand in advance of supply churn together capital, property, materials and labour in a ‘cyclonic' frenzy (Innis 1946, Barnes 2002, Keeling 2010). To date, there has been relatively little research into the consequences of the lithium boom (or bust) for sites of extraction, or in understanding how ‘demand’ articulates with the political-ecological conditions of places that host lithium reserves.

In response, this paper adopts a grounded approach to explore the dynamics of production and resource management at one of the world's most significant sources of lithium: the brine deposits of the Salar de Atacama in northern Chile (Fig. 1). Our exploratory study seeks to understand how the dynamics of industrial production (the process through which lithium is separated from its background conditions, purified and concentrated as a raw material for input into battery manufacture) are accommodated to the physical environment of the lithium reserve. Research like this is particularly relevant considering the proliferation of 'green imaginaries' related to lithium, as an abundant source of clean energy that can substitute for fossil fuels in transportation and preserve norms of automobility.

Our analysis of the reciprocal relations between industrial dynamics and hydrogeological conditions of lithium production on the Salar de Atacama contributes to the growing field of critical resource geography. Specifically, our account articulates three of this field's principle concerns: it (i) understands lithium reserves as a form of 'produced nature' constituted through capacities that are neither fully social nor fully non-human (Bakker and Bridge 2006, Irarrázaval and Bustos-Gallardo 2019); (ii) investigates empirically the reciprocal and dynamic character of relations between practices of production and 'ecological' (i.e. physical environmental) conditions on the *salar*, attentive to how these create both obstacles and opportunities for capital circulation (Boyd et al. 2001, Henderson 1998, Castree 1997; Delgado 2017); and (iii) acknowledges the technological, institutional and discursive mechanisms through which lithium is dissociated from other physical and social contexts and made an object of economic and political power (Merchant 1980, Richardson and Weszkalnys 2014; also Sanchez-Lopez 2019 in relation to lithium in Bolivia).

In bringing these conceptual tools to the problem of e-tech mineral sourcing, the paper makes two contributions. First, it shows in a conceptually-informed and empirically-grounded way how lithium production from the Salar de Atacama requires managing a series of physical conditions and processes that are largely external to capital. These 'ecological conditions of production' (Benton 1989; O'Connor 1992) include the hydrogeology of brine formation, variations in lithium content within the three-dimensional space of the *salar*, and the rate of solar insolation. We show how lithium production on the *salar* involves optimising these naturally-given environmental conditions so that value-adding transformations occur; and how, consequently, lithium is 'harvested[1]' in a process that is more akin to agriculture than either a classic extractive process (in which lithium is taken from the environment in a ready-made form) or an industrial process of transforming raw material into finished product. We explore the implications of this ecologically-embedded and "eco-regulatory" (Benton 1989) character of lithium production for resource management, in the context of a speculative boom in lithium demand. Specifically, we highlight how brine is a flexible resource whose processing can be adapted (temporally, spatially, volumetrically, and chemically) to market conditions; we show how producing lithium from brine creates a series of contradictions (notably around water depletion) that must be managed if they are not to disrupt accumulation; and we highlight emerging efforts in the Atacama to overcome these contradictions by capitalising some of the ecological conditions of production.

Second, the paper's critical resource geography approach to lithium production significantly extends the range of geographical tools for understanding emerging geographies of lithium (and, by extension, other e-tech minerals). Recent research on lithium in both the technical and social science literature already reflects a broad geographical sensibility. Work by Narins (2017: 322), for example, argues that the growing "social value of lithium has contributed to (an) increased consumption-production imbalance which lays at the heart of contemporary competition for lithium resources." Other work similarly describes the geographical concentration of supply and demand, and the global-scale geographies of trade and investment associated with the battery supply chain (Barandarian 2019, Sun 2017, Olivetti et al. 2017, Moreno-Brieva and Marín 2019). Several authors have also stressed the place-based social and environmental impacts of lithium exploitation and the conflict with surrounding indigenous communities (Gutiérrez et al. 2018; Agusdinata, 2018; Liu et. al 2019, 2020; Babidge 2013, 2015; Babidge et al. 2019; Jerez 2018). In our view, however, these accounts offer a rather restricted geographical reading of the rapidly growing lithium economy as they are limited to establishing the location of demand and supply, quantifying forms of spatial connection (e.g. trade flows, dependence on imports), or assessing ecological impacts and conflicts with local actors (mainly indigenous communities). Our aim is to

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[1] The harvest concept is also used by lithium companies, technical reports, social movements, state agencies, etc. to describe the production processes performed by the firms in the salt flat (see Cochilco 2014, SQM 2015, Jerez 2018).

complement current work by developing a richer account of lithium production as an economy centred on natural processes, harnessing geographical arguments for the production of nature and conceptual insights from critical resource geography (Himley et al. 2020). The remainder of the paper is organised into four sections. Section 2 provides a brief orientation to the production and consumption of lithium, and describes the field research on which the paper's analysis is based. Section 3 introduces relevant literature in critical resource geography and sets up the exploratory case that follows in Section 4. Section 5 concludes.

2. Placing Lithium: a brief history of lithium's growing embeddedness in energy storage

Although industrial uses of lithium in ceramics and lubricants have a long history, applications to energy storage were first pioneered in the 1970s in the context of the US space programme. The current 'speculative moment' surrounding lithium is fuelled by growing demand for energy storage systems at a wide range of scales, associated with the replacement of internal combustion engines by electric mobility, and the growing role of electricity generation from renewable (i.e. flow) resources like wind and solar (which, in turn, is fed by the rapidly falling costs of renewable generation) (Moreno-Brieva and Marín 2019). The energy storage capabilities of lithium, engineered in the form of lithium-ion batteries, offer a tantalising opportunity to address the long-running challenge for electricity networks of aligning supply and demand in real time. Historically, the prohibitive cost of storing electrical energy have meant electricity producers install generating capacity sufficient to meet peaks in demand (with capacity under-utilised for much of the time), and have made it difficult to incorporate intermittent flow sources like wind and solar. The larger storage capacity of lithium ion batteries, their speed of re-charge, and their lower cost on a per unit of energy basis have enabled the development of 'mega-batteries' (i.e. 100 or more megawatts, equivalent to a small power station) such as Tesla's giant battery in South Australia, lowering energy costs and reducing the risk of blackouts.

Initial development of the lithium ion battery value chain was largely consumer driven, with the pace and scale of uptake shaped by end uses such as portable electronics (Zicari, 2016; Fletcher 2011). Recent applications of lithium ion batteries to transport and electrical grid power storage, however, are largely policy driven and derivative of support for electrical vehicles and the growing penetration of (intermittent) renewables in electricity supply. For example, China's recent decision to scale back subsidies for buyers of EVs (in an effort to drive innovation) saw global EV sales fall for the first time, weakening lithium demand and precipitating the bankruptcy of at least one new lithium producer (FT 2019, Bloomberg 2019). More broadly, expectations of future demand are fed by green growth scenarios, and discourses of clean development and the green economy advocated by international organisations like the United Nations, OECD, UNEP, European Union, and other trade agencies which stress a "technological transformation by scaling up clean technologies" (UN DESA 2011, cited in Brand 2012:29). The current speculative moment surrounding lithium, then, is under-cut by uncertainties about the future focus of energy and environmental policy and the direction of technological innovation. While lithium is currently dominant in the electricity storage sector, rapid innovation means there is no consensus it will be the battery mineral of choice tomorrow. There are additional uncertainties about the potential for lithium recovery post-use that weigh on lithium producers: rates of lithium recycling are currently low (less than 5% in the EU) and lithium's low value as a proportion of the total battery (compared to cobalt, for example) offers little financial incentive for lithium recovery. To date, technology development in the sector has focused primarily on extending battery life and reducing charging time, rather than recycling of battery materials. However, a marked shift in the scale of lithium recovery could significantly reduce demand for new lithium supply.[2]

2.1. Sourcing and mobilising lithium

Concerns about lithium scarcity prompted by rising demand have been widely discounted: reserves are large relative to demand, their global distribution is less concentrated than for other minerals, and lithium is substitutable in many applications (Olivetti et al. 2017; USGS 2019; Mineria Chilena 2018; Lebedeva et al. 2016).[3] Lithium occurs in sufficiently high level of

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[2] New recycling technologies are anticipated to reduce costs and expand the market for recycled materials by 2030 (according to a report by the London-based Circular Energy Storage (CES), see Willuhn 2019).

[3] For this reason, lithium is not among the 'critical raw materials' listed by the EU (2017), although it is likely to become part of an updated 2020 list because of the growing significance of EV battery manufacturing to EU industrial strategy (Euractiv 2020).

concentration and quality for commercial exploitation in two forms: liquid brines and hard rock deposits. In the former, lithium is sourced by pumping saline groundwater and extracting its dissolved lithium content; in the latter, sources of the mineral spodumene are mined and processed from granitic rocks.[4] These two processes are qualitatively different, influencing the spatial and socio-ecological forms that lithium extraction takes, the speed at which facilities can be constructed, processing times and overall production costs. Over half of the world's lithium reserves are concentrated in South America, primarily in the form of brines within the "Lithium Triangle" (a region of the Andes including parts of Argentina, Bolivia, and Chile - see Figure 1). Most of the world's hard rock reserves of lithium are in Australia and China, with smaller amounts in Zimbabwe, Portugal, Brazil and the US. Brine sources have significantly lower overall production costs, with Chilean sources having some of the lowest costs worldwide. However, recent brine developments (e.g. Orocobre's Olaroz operation in Argentina) indicate they can be significantly slower to bring into full production than hard rock mines, in large part because production is reliant on ambient evaporation rather than rock milling (TSX 2018). Consequently, hard rock sources of lithium based on mining the mineral spodumene have been growing in significance.

[Insert Figure 1 here – Map showing location of the Salar de Atacama and key sites]

Australia is the world's largest lithium producer, producing 60% of global supply from three active mines. Chile, the second largest producer, accounts for around 19% of global supply, all of which is extracted from brine at the country's two major operations in the Atacama (SQM-Tianqi and Albemarle). Elsewhere in the Lithium Triangle, Argentina currently produces around a third of the volume of Chile from two brine operations (Olaroz and Mina Felix). Bolivia has substantial lithium reserves and production is focused on the Salar de Uyuni, the world's largest salt flat. State ownership and control of minerals are established in Bolivia's 2003 Constitution and, over the last decade, the state has implemented policies with the aim of developing a lithium-related industrial sector, including a plant for battery production with support from Chinese investors in

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[4] Spodumene is a lithium aluminium inosilicate, $LiAl(SiO_3)_2$

2014. However, recent political turmoil has increased uncertainty and plans to build plants with German and Chinese capital cancelled in 2019 after social pressure. China, the largest market for battery-grade lithium, is also a substantial lithium producer and currently has about half the output of Chile. Some of China’s output is sourced from brines in the Qinghai-Tibet Plateau and some from spodumene hard rock deposits in Sichuan.

Having identified the context in which lithium demand is rapidly growing, and outlined the broad material conditions in which lithium is produced, the remainder of the paper adopts an exploratory case study approach to one of the key sources of lithium: the Salar de Atacama in Chile which hosts two large operations (SQM-Tianqi and Albemarle). We focus on the sourcing of lithium from brine to capture the materiality of a process dominating lithium production in South America; and to examine how production is adapted to the material and ecological conditions of the Atacama. We gathered data during two field visits to SQM’s operations on the Salar de Atacama (in 2018 and 2019, where we held discussions with the operators and toured the facilities). We reviewed documents available at the documentation centers and digital repositories of several state agencies (e.g., National Water Agency, Corfo, National Geology, and Mining Service, Environmental Assessment Service, Chilean Nuclear Energy Commission) to obtain technical, historical, economic and institutional data on the lithium industry in Chile. Our analysis is also informed by data collected by one of the authors [redacted for review] who lived in the Salar de Atacama between 2014–2020. He gathered qualitative data based on his personal experience and interviews with local actors (indigenous leaders, scientists working in the area, everyday water users), and site visits. Finally, we categorized, systematized, integrated, and analyzed data through conceptual mapping techniques and iterative theoretical discussions regarding the materiality of brine/lithium production, beginning in the field and evolving in the face of new evidence.

While we acknowledge the limits of a single case study for generalisation, we embrace its capacity to develop a conceptual understanding of complex phenomena (Yin 2018). In adopting a method widely used in critical resource geography, our goal is to theorise the practices that sustain lithium production from brine in one of the most water-scarce environments on earth. We do not presume to make global claims regarding lithium extraction: on the contrary, we believe our conceptualization of the eco-regulatory and partially capitalised character of lithium production opens interesting paths for critical resource geography.

3. Critical Resource Geography and Industrial Dynamics

Drawing on early work in critical resource geography, we approach the Salar de Atacama as a key ‘pressure point’ in a rapidly accelerating social metabolism of lithium closely tied to the global value chain for batteries (Benton 1989, Bridge 2000). Our focus is on understanding the 'ecological conditions'[5] that sustain lithium production in the Salar de Atacama, and the extent to which the production of this resource is tied to processes that remain uncapitalised (or only partially capitalised). Our focus on the ecological conditions of production also extends to the consequences for water resource management of efforts to wring value from the *salar* via lithium production.

Conceptually our analysis is informed by three bodies of work that have had a formative influence on critical resource geography. First, we take seriously the ‘nature-facing’ character of lithium production by focussing on the material and ecological processes through which tradeable lithium compounds are produced from naturally-occurring brine. An early foundation for critical resource geography was work in the historical materialist tradition highlighting important structural differences between the appropriation of nature in extraction and the transformation of raw materials in manufacturing (Bunker 1988). This research established a heuristically useful (although not analytically definitive) distinction between the nature of labour in agriculture and mining (Boyd et al. 2001). Foundational work by Benton (1989: 67), for example, distinguished ‘eco-regulatory’ forms of labour, deployed “to sustain or regulate the

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[5] A term drawn from left-green thought (e.g. O’Connor 1988, Grundmann 1991, Leff 1994, Toledo 1992) encompassing a wide range of uncosted (or partially costed) environmental services that support the process of commodity production. The term expands Marxian analysis of the driving tension internal to commodity production (between the forces and relations of production) to also include tensions between forces/relations and the contextual conditions under which the physical environment is incorporated into production (Bridge 2000).

environmental conditions under which seed or stock animals grow," from the work of primary appropriation (e.g. mining). While there are transformative moments to both these labour processes, eco-regulatory labour has a different 'intentional structure' because "the transformations are brought about by naturally given organic mechanisms, not by the application of human labour" (Benton 1989: 67). Benton's characterisation of eco-regulation as a distinctive form of productive practice continues to have analytical value, although his wider critique of Marx's concept of the labour process has been subsequently challenged (Burkett 1998). In particular, it draws attention to how labour is "devoted to optimising and maintaining the conditions under which some organic transformations take place" (Benton 1992: 60); and that, accordingly, the spatial and temporal distribution of labour is "to a high degree shaped by the contextual conditions of the labour process and by the rhythms of organic developmental processes" (1989: 67-8). In short, his analysis draws attention to eco-regulatory practices' unusual degree of dependence on "the characteristics of their contextual conditions... (and how) these elements in the process are relatively impervious to intentional manipulation and in some respects are absolutely non-manipulable" (Benton 1989: 68).

Contemporary resource geography has inherited a rich analytical repertoire in this area. It includes work paying close attention to the temporal disjuncture between production time and labour time in eco-regulatory activities like agriculture and forestry (Mann and Dickinson 1978: Mann 1990; Henderson 1998) where for long periods of time capital is "abandoned to the sway of natural processes" (Marx 1885) such as plant and animal growth; and the influences on the labour process of the spatial form of eco-regulation and primary appropriation (Prudham 2005; Page 1996). Research on 'industrial dynamics' in resource geography, for example, has focused on the ways in which the embeddedness of production in physical, chemical and biological conditions is variously an 'obstacle, opportunity and surprise' to capital (Boyd et al. 2001; cf. Benton 1992 and Henderson 1998, Delgado 2017). Several authors have theorised this relationship, and its mediation through technology, as a process of 'subsumption', drawing attention to qualitative differences in the way capital brings external conditions under its control. In an early and influential statement on industrial dynamics, Boyd et al. (2001) distinguish between the formal and real subsumption of nature: the former involves expanding throughput without a qualitative change in how biophysical processes are harnessed (a strategy characteristic of inorganic sectors like mining), whereas the latter involves intervening in biological processes to take hold of them directly as a productive force, so that they can be sped up, steered or otherwise optimised for commodity production. Recent work has problematized this inorganic/organic distinction to explore how real subsumption may extend to the extractive sector (Delgado 2017, Boyd and Prudham 2017). Labban (2014), for example, has shown how some classically extractive activities can also involve the subsumption of biochemical processes, such as the 'biomining' of gold ores by bacterial oxidation. Indeed, this paper takes up Labban's recommendation (2014: 573) that studies of resources extend their focus using such conceptual tools "to comprehend better the emerging materiality and spatio temporality of capitalist extraction."

Second, in seeking to understand the ecological and material conditions of lithium production we mobilise the concept of ecological contradiction. Pioneered by O'Connor (1991), the concept of ecological contradiction draws attention to capital's tendency to under-produce (i.e. over-exploit) the ecological conditions on which production and accumulation depend. It therefore both describes a structural tension between economic strategy and ecological appropriation and, at the same time, positions this tension as a potential source of accumulation crisis - a 'second contradiction of capitalism' on a par with the wage relation (O'Connor 1991). Research in critical resource geography on capital circulation in ecologically-embedded sectors like aquaculture (Bustos-Gallardo and Irarrazaval 2016), mining (Bridge 2000) and fossil fuels (Clark and Foster 2009) has harnessed the analytical power of ecological contradiction to show how capital and nature confront each other in these sectors, and how capital's reliance on natural processes (and their systematic underproduction by capital over time) can manifest as a wider ecological crisis. Here the notion of contradiction highlights the "self-destructive appropriation of labour power, urban infrastructure and external nature" (O'Connor 1998: 177), and the efforts of both capital and the state to forestall the expression of contradiction in a crisis of accumulation. We find critical resource geography's work with the concept of ecological contradiction instructive for thinking about the tensions inherent to industrial dynamics in a nature-based sector and, specifically, for understanding the ecologically-embedded character of lithium production in the

Salar de Atacama. Accordingly, we harness the concept to develop a geographical account of how the optimisation of ecological conditions upon which commercial lithium harvesting depends creates a series of tensions and risks with the potential to disrupt accumulation (Bustos-Gallardo & Irarrázaval 2017, Araghi 2009, Bridge 2000)

Third, our understanding of how the ecological conditions of the Salar de Atacama shape strategies of lithium production is informed by a small but growing interest in critical resource geography in the 'flexibility' of production strategies in agriculture and mining. 'Flexibility' here references the adaptability of key productive assets to external events, and acknowledges how production strategies in nature-facing sectors are often adapted to accommodate the ecologically-embedded character of production. Knapp (2016), for example, shows how the hard rock mining sector has evolved to accommodate a series of ecologically-based constraints on extraction. She identifies three "registers of flexibility: spatial, temporal and interpretational" through which mining firms have sought to address the geo-spatial fixity of mineral deposits, the challenge of resource scarcity and localised depletion, and the environmental consequences of extraction (Knapp 2016: 1890). For Knapp, flexibility is a broad and exploratory concept that folds together a range of different strategic and institutional actions, blurring "the boundaries between extraction, production, manufacturing, consumption and disposal" and materialising in the form of the 'flexible mine' (2016: 1889). We share Knapp's interest in the adaptive re-tooling of mining assets in the service of accumulation, although we use flexibility in a more concrete way in relation to the extraction of lithium from brine. Specifically, we explore the analytical potential of flexibility for understanding the capacity of brine (and dedicated production infrastructure) to produce multiple commodities under different market conditions; and the discursive mutability of materials extracted from the *salar* within resource regulation and policy. In agrarian studies there has been an interesting debate about 'flex-crops' linked to a similarly speculative moment, in which farmers across the world turned to crops that could serve multiple markets (i.e. were interchangeable as either food or fuel) in the context of policy-driven demand for renewable energy (Gillon 2016, Borras et al, 2016).[6] Ensuing debate over flex-crops has

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[6] Flex crops have been defined as "crops and commodities that have multiple uses… that can be, or are thought to be, flexibly inter-changed" (Gillon 2016: 118). For Borras et al. (2016) the degree of flexibility can be measured in

focused on the distributional effects of flexibility (e.g. whether producers or consumers have been the primary beneficiaries) which has shifted attention away from examining how flexibility is shaped by the ecologically-embedded character of production. Our goal in taking up the concept of flexibility, therefore, is to train its insight into the adaptability of production on this under-examined question, exploring the interconnections between the flexibilities of brine and the ecological conditions of brine/lithium production.

Our argument unfolds in three steps in the following section. First, we focus on the industrial process of lithium production from brine, identifying the surprising extent to which this large-scale industrial process relies on physical environmental conditions that are external to capital and specific to the Atacama Desert. We emphasise the 'eco-regulatory' character of lithium production from brine and how it is more like agriculture than conventional mining. Second, we outline the way in which the ecologically embedded character of lithium production from brine generates a series of structural tensions between the technologies/infrastructures of extraction and ecological conditions in which they are deployed (and on which they depend). We interpret these tensions as ecological contradictions, illustrate them via reference to water depletion, and show their potential to undermine the profitability of extraction on the *salar*. Third, we describe how lithium producers harness the flexibilities of brine to reproduce political-ecological conditions conducive to accumulation. We also reflect on the limits to brine's flexibility, and consider how these relate to the ways in which brine/lithium production on the *salar* has been only partially capitalised.

4. Lithium production in the Salar de Atacama

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two ways: either at origin (one crop may be developed into multiple commodities) or at the end (multiple uses may be simultaneously realized).

Chile is widely considered a radical example of laissez-faire approaches to natural resource management, characterised by private property rights to resources, limited state regulation, and the use of market instruments for reallocation (Liverman & Vilas 2006, Tecklin et. al 2011, Bauer 1998). Lithium, however, is something of an exception: despite the pro-market approach to mining development, Chile is the only country to have reserved lithium to the state as a non-concessionable strategic mineral of national interest (Nem Singh 2010, CEPAL 2015). Until 1979 lithium in Chile was regulated like any other mineral by the Mining Code of 1932 and, consequently, it could be privately owned without exceptional limitations. However, consideration of lithium's potential for use in nuclear fusion in the context of the Cold War led the Chilean state to declare it a resource of national interest following US recommendations (Decree-Law N 2886). The U.S. mining company Anaconda had discovered lithium deposits in the Salar de Atacama in the early 1960s, and the then Chilean National Institute for Geological Research started to evaluate the technical feasibility and economic potential of brine exploitation (e.g., potassium, lithium, magnesium, boron, sulfates). When this potential was confirmed in 1977, the government granted mining rights over a large part of the *salar* to the state economic development agency CORFO (Corporación de Fomento de la Producción) to exploit brines and develop two independent projects: the Lithium Project (currently Albemarle) and the Potassium Salts and Boric Acid Project (currently SQM).[7]

In the early 1980s, the military dictatorship started to impose a radical neoliberal model for managing resources. Within this context, the state passed new mining laws (the Mining Code and Organic Constitutional Law on Mining Concessions) that actively supported private capital. Although the nuclear potential of lithium was discarded, lithium continued to be categorised as a non-concessionable and strategic resource with its exploitation and commercialization carefully regulated and controlled by the Chilean Nuclear Energy Commission. Under this model, only the state or state-owned companies could explore, exploit, produce, and trade lithium, including its derivatives and compounds. Within this context, CODELCO (the state-owned copper company)

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[7] Initially this was 59,820 mining rights, although CORFO quickly renounced 27,052 leaving only 32,768 which are the ones it maintains to this day.

was granted several unexploited lithium concessions and CORFO retained the concessions it had received prior to the new mining code.

Notwithstanding the state's active role in lithium and its reserved character, lithium production was not completely nationalized. The dictatorship opened a space for manoeuvre that balanced its neoliberal political-economic model and the national character of lithium. The Chilean Constitution, established by the dictatorship in 1980, does not explicitly prohibit private investments on lithium, opening the door for private participation in the whole commodity chain. Indeed, despite being a strategic resource, lithium is currently exploited, explored, and traded by two private companies - Albemarle and SQM – which operate facilities initially granted by the state as a lithium concession (i.e. prior to 1979) or that were granted a Special Lithium Operation Contract (*Contrato Especial de Operación de Litio*). Thus, although lithium companies in Chile originally had a mixed private-public character, between 1988 and 1995 they were fully privatized. After several mergers and acquisitions, Albemarle and SQM have become the only companies currently exploiting brines for lithium production. As a result of their distinctive histories, these two companies are subject to different exploitation regimes that regulate their relationship with the state: in the case of SQM, mineral rights to lithium are still owned by CORFO and are leased to the company; in the case of Albemarle, CORFO sold its rights to the company which is now the sole owner of the lithium deposits.[8]

The areas around the *salar* are occupied by the Atacameños indigenous people, or Likan-antai, who are settled in villages at different altitudinal levels (Figure 1), where they still develop agro-pastoralist practices, combined with wage labor (mainly in the different mining companies in the area, including the lithium industry) and jobs in the tourism sector.[9] Mine operations in the *salar* have affected these communities (e.g., limited access to old pastoral territory, pollution, impact in their water sources, rapid change to cultural practices, proletarization) (Babidge 2013). Besides, concessions are located in the land they claim as ancestral territory, creating disputes

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[8] For details about this process, see Lagos (2012) and Ebensperger et al. (2005).

[9] For a general synopsis of Atacameño livelihoods and cultural practices, see Castro and Martínez (1996). For a general outline of the archaeological, ethnohistorical, and historical context, see Nuñez (2007).

over the land and control of natural resources (Babidge 2013, Jerez 2018, Babidge et. al. 2019). This situation has been a driver of several ongoing and tense conflicts.[10]

4.1 The eco-regulatory character of lithium production from brine

The industrial process of producing lithium from brine involves pumping salty water from beneath the *salar* and concentrating it via evaporation under ambient climatic conditions, a process that can be understood as a form of water mining (Garcés 2020). The process requires managing a series of hydro-geological conditions and physical processes (such as evaporation) that are, to a great degree, external to capital: inputs of technology and labour are directed towards monitoring, sustaining or mediating physical environmental conditions that foster the isolation and progressive concentration of lithium into commercially valuable quantities. Following Benton (1989), lithium extraction from brine can be understood as an eco-regulatory process: its 'intentional structure' (to use Benton's phrase) sees labour focused on monitoring and optimising the site-specific physical conditions of brine concentration and evaporation, with the key transformations central to commodity production brought about by naturally given organic mechanisms rather than human labour.

To a large degree, lithium production on the Salar de Atacama relies on the particular hydrogeological and hydro-ecological features of the Atacama Desert. The desert's exceptional topography and environmental features produce a combination of physical conditions conducive to the formation of brine and its low-cost exploitation (Munk et al. 2016). First, volcanic activities, hydrothermal water sources, active tectonic processes, large and closed basins and a hyper-arid climate with high radiation levels have facilitated the accumulation of massive, thick evaporite deposits characterized by a high concentration of excellent quality lithium (see details in Alonso et al. 1991, Salas et al. 2010). Second, brine extraction is an evaporitic process that heavily relies on natural evaporation rates (Flexer et al. 2018). The high levels of solar radiation, low humidity, high winds and high elevation of the Atacama Desert combine to create some of the highest

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[10] See details in Environmental Justice Atlas (2020).

evaporation rates in the world which, together with low rates of precipitation, substantially reduces production costs (Sarricolea and Romero 2015).

[Insert Figure 2 here – the lithium-from-brine process on the *salar* de Atacama]

The process for extracting lithium harnesses these core hydrogeological and hydro-ecological processes to achieve commercially valuable concentrations of lithium. Production involves a series of hydrological interventions that seek to foster and steward lithium availability within subsurface brines and, once pumped to the surface, to optimise lithium yield from brine at low-cost. These interventions are summarized in Figure 2 and elaborated below. Both sites of lithium extraction (SQM and Albemarle) are located in the southern part of the *salar* (see Figure 1). At these sites, brine solutions containing approximately 0.15% lithium concentration and 2.5% potassium concentration (Talens et al. 2013) are pumped to the surface via an extensive network of wells from depths of 1.5 to 60 meters under the crust of the *salar*. Once at the surface, brines from individual wells are blended via a very large network of surface pipes and poured into a sequence of large and shallow open-air evaporating ponds (see Figures 3 and 4). In the first set of ponds, potassium chloride is precipitated after approximately 6 to 9 months of evaporation. A further period of evaporation (approximately 4-5 months) in a second set of pools produces lithium concentrations of approximately 6%. After lithium chloride reaches an optimum concentration and purity, it is harvested and transported 262 km by road to chemical plants offsite in Antofagasta for turning it into lithium hydroxide and lithium carbonate and related end products.[11]

During the evaporation process across the two sets of ponds, numerous products are precipitated and obtained from brine (e.g. halite, sylvanite, sodium chloride, and carnallite). These products are treated as commodities, byproducts or impurities according to market conditions. After each set of evaporation pools, solutions are reinjected in the *salar* in a process described by technicians as akin to making a "deposit in a lithium bank." Indeed, by stewarding

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[11] These include lithium carbonate (technical grade), lithium carbonate (battery grade), lithium hydroxide (technical grade), lithium hydroxide (battery grade), and concentrated and purified lithium chloride solution.

lithium availability via reinjection, SQM has reportedly increased lithium content in the vicinity of extraction over time from 0.13% lithium in 1998 to 1.12% lithium in 2016 (SQM 2016).

[Insert Figure 3 [Landsat 8 image] and Figure 4 [lithium evaporation ponds]]

As this brief description shows, the productivity of lithium extraction from brine depends heavily on contextual physical conditions that regulate the concentration of lithium in subsurface and surface brines. The model of lithium production on the *salar* is incompletely capitalised as it relies very significantly on the hydrogeological processes of brine formation below the surface and the efficiency of ambient evaporation rates. While technological interventions can modify some of these processes (e.g. via the design of evaporation ponds, or via reinjection of solutions), key parts of the process - including brine concentration, variability in the chemical composition of brine, and evaporation rates – are reliant on ambient hydrogeological and atmospheric hydro-ecological processes.

4.2 Form, time and space: three ecological contradictions of producing lithium-from-brine

Here we introduce the concept of ecological contradiction to the analysis, building on our prior discussion of lithium-from-brine as an eco-regulatory process. 'Contradiction' highlights the dual character of productive relations with the *salar*: how the work of lithium producers to harness "naturally given organic mechanisms" (Benton 1989: 67) on the *salar* at the same time undermines the physical and socio-political conditions that sustain profitability. Short-term actions by individual firms towards the physical environment of the *salar* in the pursuit of profit have the potential, over time, to erode the political-ecological conditions that initially facilitated capital accumulation via the extraction and processing of brine, both for individual producers and across the basin as a whole (cf. Bridge 2000). The concept of ecological contradiction, therefore, allows us to examine how lithium production from brine is prone to crisis, notwithstanding its eco-regulatory character; and it sets the stage to illustrate - in the next section - how lithium producers seek to harness some of the flexibilities of the eco-regulatory process to forestall expression of these ecological contradictions as a crisis of profitability. We identify below three ecological contradictions associated with the material form, temporal dynamics and spatiality of lithium production from brine. We then (Section 4.3) illustrate some of the ways in which lithium producers are harnessing the flexibility of brine to forestall the expression of these contradictions as a crisis of profitability.

Ecological Contradiction #1 (Form): The material form in which lithium is extracted (i.e. as brine) requires water; but pumping and evaporation are degrading the water balance in the salar, undermining future brine production

Lithium production is predicated on the extraction (via pumping) of lithium-containing brines from beneath the *salar* and their subsequent evaporation/concentration on the surface. The isolation and recovery of commercially valuable quantities of lithium requires bringing large quantities of liquid (the volumetric bulk of which is water) to the surface and dispersing most of the water component to the atmosphere. In effect, lithium production from brine massively accelerates the natural process of evaporation that contributed to the formation of the *salar* over time. Like all extractive activity, the process of brine appropriation at the heart of the lithium production process contains the threat of depletion. However, depletion emerges as an ecological contradiction in this case not primarily because lithium production is ‘auto-consumptive’ and depletes the capital base of the extractive enterprise (i.e. the available supply of lithium from the *salar*), which is a common feature of mining. Rather, the contradiction emerges because of the dependence of production on appropriating lithium in a material form (brine) that requires mobilizing and evaporating large quantities of water in one of the most arid regions on earth. The contradiction of depletion is expressed, therefore, in relation to the management and availability of water rather than lithium. There are several specific expressions of this contradiction in relation to water, both at individual facilities and for the basin as a whole. Most significantly, there is growing concern about the consequences of brine extraction on the regional water balance. Lithium production from brine across the southern part of the *salar* has created conditions of water deficit. An international consultancy report (Amphos 21, 2018) on the hydrogeology of the Salar de Atacama (commissioned by what was then Corfo's Non-Metallic Mining Committee) concluded that outflows from the *salar* exceed inflows. While the regional water balance in the 1980s was stable, this equilibrium changed radically in the 2000s when both brine pumping and freshwater extraction (by lithium and copper companies) increased significantly. The report found that "in a natural regime, the inputs are similar to the outputs: 6,810 liters per second compared to an interval between 6,575 and 6,975 l/s, respectively. However, in a system influenced by anthropogenic extractions, and for the period between 2000 and 2015, the outputs are greater than the inputs in the Salar de Atacama basin. Thus, the outflow reaches an average annual flow of between 8,442 l/s and 8,842 l/s" (Amphos 21 2018: 82).

Ecological Contradiction #2 (Time): Reliance on the 'free labour' of the sun facilitates low cost lithium production from brine (and high rates of profitability vs. hard rock mining); but dependence on the weather introduces risk and uncertainty to the rate of production

Firms producing lithium in the Salar de Atacama have invested in an evaporative infrastructure that takes advantage of the region's particularly stable atmospheric conditions: with over 4,000 hours per year of sunshine (2,500 kwh per square meter average radiation), the intensity of solar insolation contributes to much lower costs of lithium-from-brine than hard rock mining. Production costs for brine lithium in Chile are estimated around US$3,000/ton, compared to hard rock mining costs of nearly 9,000US$ per ton (Roskill 2017). Reliance on ambient atmospheric conditions dictates the spatial form of lithium extraction (an infrastructure of extensive, inter-connected open-air ponds). Turning control of evaporation over to the sun also governs the temporality of lithium production from brine; gives lithium production a seasonal character (lithium yields fall during the winter); and exposes the process to weather-related risks, some of which may be exacerbated by growing climate variability (see Babidge et al. 2019). There is some scope for controlling evaporation rates via regulating the depth of brine and lithium ponds, rate of pumping and chemistry of surface solutions. However, full control of evaporation would require further capitalisation in the form of innovation in new lithium recovery technologies (Flexer et al. 2018) or, alternatively, its elimination altogether via the use of non-evaporative extractive technologies. However, the low costs of production available to firms on the *salar* by "abandoning (production) to the sway of natural processes" (Marx 1885) (i.e. the sun) work against any direct incentive for firms to embrace major technological change.

Ecological Contradiction #3 (Space): An expansion of pumping is necessary to maintain production; but expanding pumping changes the density of brine and puts lithium reserves at risk.

The lithium production process demands the redistribution of brines in the *salar*. When brine is pumped from below the surface, it is moved from a large underground area to shallow pools on the surface where evaporation increases the brine´s density. This redistribution has two effects: first, the increasing density of the brine in the evaporation pools means the pools' content becomes heavier; and, second, the process of pumping produces a depression cone around the well (depleting the water table and reducing pressure around the wells). The combination of these effects, in turn, causes the superficial brines to sink (see details in Flexer et al. 2018). In addition, extension of the depression cone through the *salar* can lead to it contacting the boundary with freshwater sources: when this happens, further pumping will cause an influx of fresh water to replace the volumes of water removed through pumping brines (Houston et al., 2011). This effect will have both environmental and productive impacts (Flexer et al. 2018).
If fresh water flows towards the brine aquifer, the freshwater aquifer will diminish, causing severe ecological effects related to water depletion. In turn, if freshwater infiltrates the brine aquifer, it will dilute brines, affecting the lithium content of the reserves. How much freshwater will flow towards brine sources will depend on both the interconnection between both aquifers and their permeability level (Flexer et al. 2018, Houston et al., 2011). At the same time, this will determine the level of both environmental and productive impacts.

4.3. The flexibilities of brine: harnessing material heterogeneity and ontological ambiguity

We have shown how there are significant structural tensions – expressed here using the language of 'contradiction' - between the technologies of extraction used on the *salar* and the ecological conditions of production. The same 'ecological conditions' of the *salar*, however, also offer lithium producers an important source of flexibility as they seek to adapt fixed assets and infrastructures to dynamic political-economic conditions. These flexibilities enable produces to sustain lithium production from brine, in the face of its underlying ecological contradictions, in two broad ways: (a) the materiality of the *salar* is harnessed by producers to adjust production to market conditions; and (b) ontological ambiguity surrounding the character of the 'natural processes' on which production relies is harnessed institutionally to secure an advantageous regulatory framework. We identify below four specific flexibilities of brine, based on observations in the field. These are of value to lithium producers on the *salar* as they seek to adapt to political-economic conditions and address potential crises of accumulation.

First, the natural processes of brine formation create a heterogeneous brine reserve, characterised by spatial and volumetric variation in the concentration of lithium, potassium, sodium, magnesium and other salts. Lithium producers harness this variation as a source of hydro-geochemical flexibility: producers are able to optimise lithium recovery by selecting and blending brines from different parts of the *salar*. Significant capital outlay is required to access this flexibility, however, in the form of multiple pumps (over 300 at the SQM facility), pipe networks (totalling hundreds of kilometres) to enable movement of brine across the surface from different locations on the *salar*, and a high resolution hydrogeochemical monitoring network that models salt distributions in three dimensions and over time. In short, the eco-regulatory character of lithium production from brine creates an 'intentional structure' in which investment is channelled towards harnessing natural variation in core processes *as a source of operational flexibility*.

Second, by varying the rate and longevity of evaporation, brine can be managed to yield not only lithium but also several intermediary products including potassium chloride, potassium sulfate, boric acid and magnesium chloride. Brine, then, has a material ambiguity under conditions of evaporation that offers producers a way of managing market risks associated with demand for specific products: for example, the evaporation process can be optimised for either potassium production (an intermediate product for the fertiliser market) or for lithium. Indeed, the ambiguous materiality of brine regarding intermediate product markets has shaped the organisational evolution of SQM from an industrial chemicals company in the 1990s (whose products targeted the agricultural market for fertilisers) into one of the world's major exporters of lithium carbonate for the battery sector. At the extreme, the material ambiguity of brine also potentially provides brine producers with a way to manage risks associated with the availability of water. Because the quality of the lithium solution at the end of the process is positively related to the amount of time brines are exposed to evaporation, the lower level of evaporation required to produce intermediary products offers producers a way to extend commercial exploitation of the salt flat under conditions of water scarcity.

Third, the eco-regulatory character of lithium production also offers other sources of flexibility that are partly 'interpretational' in nature (Knapp 2016). These are no less significant in sustaining production on the *salar* than the ability to manage the chemistry of brine: they are arguably more fundamental, as they go to the heart of managing water in one of the world's most arid environments. At issue here is the regulatory status of the liquids that lithium producers extract from a hydrogeologically integrated basin and, specifically, whether these liquids are classified and regulated as water (abstracted in large volumes from a water-scarce environment) or as brine. In the context of growing concern over the effects of brine removal on the regional water balance, the regulatory classification of 'brine' (versus 'water') is integral to the ability of lithium producers to continue pumping (and forestalling the effects of regional water depletion on lithium production). Lithium producers pump liquids from beneath the *salar* to feed the evaporation ponds: these liquids are technically and politically classed as 'brine' rather than water and, consequently, firms extracting brine are not required to obtain water rights for this part of the process (the legal mechanism through which other water users in the area, including mining companies and indigenous communities, must obtain access to water). At the SQM facility in the south of the *salar*, for example, 85% of the liquid extracted for use in lithium production is not classed as water (Table 1). This distinction enables firms to frame brine pumping as an action independent from freshwater extraction, and claim it has no effect on the hydrogeological or ecological balance of the basin. Indeed, in a recent interview Albemarle´s Country Manager, affirmed that

> The lithium production process uses virtually no freshwater. Albemarle uses less than 0.5% of the water used in the Basin, which is mainly used for washing equipment. Our processes use brine that has no alternative use either for human consumption or for agriculture. This water is ten times saltier than seawater. To affirm that the water that is evaporated from the lithium production ponds is responsible for the water shortage is equivalent to affirming that the thousands of square meters of water that are evaporated daily in the ocean in front of Antofagasta are responsible for the water shortage in the city or the coast in general (El Mercurio de Antofagasta, 2020)

Finally, the liquids that lithium producers reinject into the *salar* are classified as water, a designation that avoids regulatory requirements for underground chemical injection.

Company	Brine extraction (L/S)	Fresh Water rights (L/S)
SQM	1700	240
Albemarle	442	24

Table 1. Rates of water extraction (brine and freshwater) in the *salar*
(based on Jerez Henriquez (2018: 28) and Babbidge et. al. (2019)

We can see here, then, how the material duality of water vs. brine – which finds expression in the insistence by lithium companies that “it’s not water, it’s brine” when referring to extracted liquids[12] - sustains current production processes on the *salar:* classing all liquid extraction as water would bring lithium production to a halt. The interpretative flexibility that allows brine extraction to be classed as ‘not water’ masks an underlying contradiction associated with the

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[12] The quote comes from a presentation made during our field visits to operations on the *salar*.

production of water deficit in the *salar*, and forestalls its eruption as a crisis for lithium producers. The contradiction of water depletion is not solved by this flexibility in any final sense, however, but rather is displaced into conflicts with other land users and land uses.

Finally, the reliance of lithium-from-brine on contextual evaporation enables lithium producers to strategically position the process as one in which the "sun does the labour" – i.e. a natural process more akin to agriculture than conventional mining. Stressing the nature-based, eco-regulatory character of production has value for lithium producers, particularly in the regional context of the Atacama Desert which hosts several very large copper mines adopting conventional extractive techniques. In this context, lithium producers differentiate themselves by styling their activity not as extraction but as harvesting - a process geared towards enhancing lithium yield from a natural, solar-driven process.

4.4 Between flexibility and contradiction: trajectories of capitalisation in Chile's lithium value chain

The material and interpretational flexibilities of brine exemplify how the direct confrontation with biophysical processes in resource sectors can offer particular opportunities for the owners of capital (Boyd et al. 2001). In this case, the flexibilities of brine offer the owners of fixed infrastructure on the *salar* opportunities to protect its value in the context of market and regulatory risk. However, the process of producing lithium-from-brine is not infinitely flexible: there are constraints on how far the prevailing pattern/form of fixed infrastructure (pumps, pipes and evaporating ponds) on the *salar* can be 'flexed' to sustain accumulation. For example, most of the flexibilities outlined in Section 4.3 entrench (rather than restructure) the process of water mining on which lithium production from brine depends.

The relationship between flexibility and the underlying ecological contradictions of production is, in part, a question of capitalisation. The flexibilities of lithium-from-brine are a function of how this process has been historically capitalised: current patterns of capitalisation create flexibilities that enable producers to adjust output to political economic conditions, but they also constrain flexibility in significant ways. The conceptual distinction between formal and real subsumption of nature is useful for approaching this question of capitalisation in relation to the ecologically-embedded character of lithium production (Boyd et al. 2001). Lithium from brine can be interpreted as an example of the real subsumption of nature: the evaporative infrastructure of pumps, blending pipes and surface ponds intensify the hydro-geological and hydro-ecological processes that have concentrated lithium in the *salar* over more-than-human timescales. Industrial producers have taken hold directly of natural processes with the goal of massively accelerating the concentration of lithium. From this perspective, lithium-from-brine confirms a growing recognition among critical resource geographers that the real subsumption of nature need not be limited to biologically-based processes like cultivation (as originally argued by Boyd et al. 2001), and it is also a feature of the extractive sector (Smith 2007, Labban 2014, Delgado 2017, Boyd and Prudham 2017).

However, the analytical division between 'formal' and 'real' does not handle well the eco-regulatory logic of optimisation. Under closer examination, the flexibilities of brine express elements of both the 'formal' and 'real' subsumption of nature (thereby illustrating the limitations of this binary division for analysing industrial dynamics in resource sectors). To the extent that the flexibilities of brine enhance productivity by extending the physical and ideological appropriation of nature (rather than augmenting the production process by taking hold of it directly), they illustrate key features of formal subsumption. For example, SQM gains access to specific brine chemistry by extending the horizontal or vertical depth of pumping – i.e. improving productivity by increasing both the spatial scope and internal differentiation of the 'lithium reserve' in the *salar* – rather than developing new process chemistry. Similarly, the rate of lithium brine production is controlled not by taking hold of the evaporation process directly (e.g. via heating or volatilisation) but by decreasing the depth of evaporating ponds or increasing their spatial extent. In short, productivity is controlled largely by redistributing brines over time and space to take advantage of contextual conditions. Consequently, the fixed capital and infrastructure committed to the industrial process are geared towards enabling this redistribution, rather than deepening direct control over hydrogeological and hydroecological processes. As a result, resource management in lithium production has a spatially and temporally extensive (rather than intensive) character: it focuses on the composition, flow and residency of brine in time and space. Nonetheless, the eco-regulatory character of lithium production from brine means that significant capital resources are directed towards optimising the hydro-geological and hydro-ecological processes that concentrate lithium. The 'intentional structure' of optimising natural processes – implying a form of managerial control based on conditioning inputs in order to maximize a particular output – illustrates important elements of real subsumption. The blending of brines from the *salar*, for example, relies on a detailed knowledge of geochemistry at a fine degree of spatial resolution, and the capacity to actively select and control where and when different brines are mixed. It rests, therefore, on the capitalisation of some – but not all – of the ecological conditions of brine production: specifically, it rests on capitalising two key 'ecological' conditions (brine differentiation, and the availability at a single point of multiple brines) while leaving other aspects of the process 'to the sway of nature'.

The way in which ecological conditions of production are capitalised has important environmental consequences. Lithium producers on the *salar* currently rely heavily on uncapitalised inputs, resulting in a spatially extensive model of extracting brines that is leading to a regional water deficit. The technological trajectory among individual producers is not towards further real subsumption involving, for example, the capitalisation of evaporation processes and the recycling of water inputs. As we have outlined, there are limited incentives for individual producers to depart from the current process and, furthermore, some of the flexibilities afforded by current forms of investment create mixed incentives that actively work against further capitalisation.

There are, however, several initiatives involving the state, universities and private firms in Chile exploring ways of making brine extraction more efficient through greater capitalisation of inputs. For example, the University of Santiago created the Center of Lithium and Applied Mineral Research in 2019, acquiring a 5400-hectare concession in partnership with a private firm in the Salar de Llamara (Tarapaca region) with the goal of producing more efficient brine extraction technologies. Furthermore, CORFO has launched a bid to create the Energy Transition Center and Advanced Materials for the Development of Lithium (Corfo, 2019) which would fund up to

USD$300 million of innovation in solar energy, low emission mining, and lithium advanced applied materials. More broadly, the University of Chile has created the Transdisciplinary Network on Lithium, Salt Flats and Energy to propose governance mechanisms for the resources of the Atacama.

For the most part, however, the state's interest in capitalisation of the lithium value chain has tended in a different direction – away from the salt flats and towards 'downstream' forms of value-added in the battery sector. The Chilean state has chosen the current speculative moment to push for a greater role in the global lithium economy although, to date, it has been frustrated in its efforts to do so.[13] For example, state contracts with lithium producers include a preferential price clause to promote downstream technological innovation and product development in Chile. Universities have also sought to harness the speculative moment around lithium, partnering with private firms to fund research into downstream product development. For example, the University of Chile, the University of Santiago, The Catholic University and the University of Antofagasta are collaborating with Soquimich, Chemetall and Marubeni to create a Lithium Innovation Center focused on reducing the price of lithium-batteries, and increasing their storage capacity and life-span.

5. Conclusion

This paper has explored the ecologically-embedded character of lithium production and its implications for resource management. We have highlighted how brine is a flexible resource whose processing can be adapted (temporally, spatially, volumetrically, chemically) to market conditions. And we have shown how producing lithium from brine creates a series of contradictions (exemplified by the case of water depletion) that must be managed if they are not to disrupt accumulation. At the core of our account is the way in which lithium production from the Atacama is based on the pumping of subterranean brines and the subsequent evaporation of

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[13] For more on the failed bids see Minería Chilena (2019).

their water content. We have explained how extracting lithium from brine depends on pumping saline groundwater to the surface and concentrating its dissolved lithium content via evaporation, a process that can be understood as a form of water mining. . To the extent that it is provisioned with lithium from the Atacama, the lithium-ion battery value chain (and the ‘clean energy’ it enables) rests on the continued dewatering of salt flats in one of the world’s most arid regions. In highlighting some of the contradictions associated with producing lithium from brine in northern Chile, we have shown how the Chilean state facilitates production through a series of institutional and ontological manueveurs that separate water from brine.

Beyond the specifics of our case, our paper opens up several analytical opportunities in the context of critical resource geography’s core conceptual concerns. First, lithium production from brine sits somewhat awkwardly across the categories of ‘agriculture’ and ‘mining’ by which resource geography in general, and the literature on industrial dynamics specifically, has organised the analysis of primary sector activities. Lithium-as-brine is like mining, as it involves the primary appropriation of a subterranean raw material (brine) via technology (pumping) and the instruments of property. Lithium-from-brine, however, replicates the eco-regulatory practices of agriculture, as capital is directed at manipulating the contextual conditions of brine formation (i.e. the three-dimensional hydrogeology of the brine-field) and the surface processes of brine concentration and chemical separation. Brine provides, then, a way to think about the ecological specificities of both agriculture and mining while, at the same time, continuing to problematise these categories (see Labban 2014; Boyd and Prudham 2017; Delgado 2017).

Second, brine extraction illustrates aspects of flexibility that are largely occluded in (or absent from) cases of mining and agriculture. As a consequence, by engaging with lithium/brine in the Atacama we have been able to develop an account of flexibility that extends the work of others (e.g. Knapp 2016, Borras et al. 2016, Gillon 2016) in two important ways: to consider an expanded repertoire of flexibility that includes the material and interpretative; and to situate flexibility in relation to underlying contradictions and institutional/technological responses. Third, the global lithium-ion battery chain is transforming the *salar*. The ecological and social effects of this transformation replicate many of the effects of other mining operations in the region, in the form of groundwater depletion and the resulting dispossession of other land users on the Salar de Atacama from a supply of water. In this instance, however, these extractive effects are legitimized by the state and lead firms via a hybrid 'green' discourse, which combines arguments about the 'natural' quality of brine and the harnessing of sunlight in the production process, with an argument about lithium's end use in 'clean energy.' In this context we affirm the analytical value of the concept of eco-regulatory labour while, at the same time, acknowledging the importance of a parallel critical analysis of how similar discursive claims (the 'sun does the labour') are used by state and firms to position extraction as a form of agriculture and license/enable dispossession in the process.

Finally, our account has shown the potential for critical resource geography to extend the discipline's emerging interest in the geographies of e-tech materials. Bringing some of the field's repertoire of critical theory to bear on this question makes possible richer accounts of the 'new geographies' associated with the techno-economic infrastructures of energy transition. Such accounts highlight, for example, not only new spatial patterns of trade and investment but also the wholesale reconstitution of political ecologies and place in relation to material demands. Such a perspective can have political relevance. Consider, for example, the way conventional 'green-growth' imaginaries position electric mobility as a technical solution to climate change. A critical resource geography account, by contrast, highlights the 'pressure points' (Benton 1989) through which new material demands are met and the way strategies of raw material production reproduce (rather than alleviate) many of the socio-ecological contradictions at the heart of the current environmental crisis. As efforts to substitute fossil fuels with clean energy gather pace, examining the contradictions of producing lithium from brine (notably around water depletion) are a way to look beyond - and potentially destabilize - false green imaginaries. In this way, critical resource geography's attention to the ecological conditions of production has the potential to reframe debates over decarbonization and green growth, bringing speculative techno-resource futures together with their concrete ecological transformations.

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Figure 1

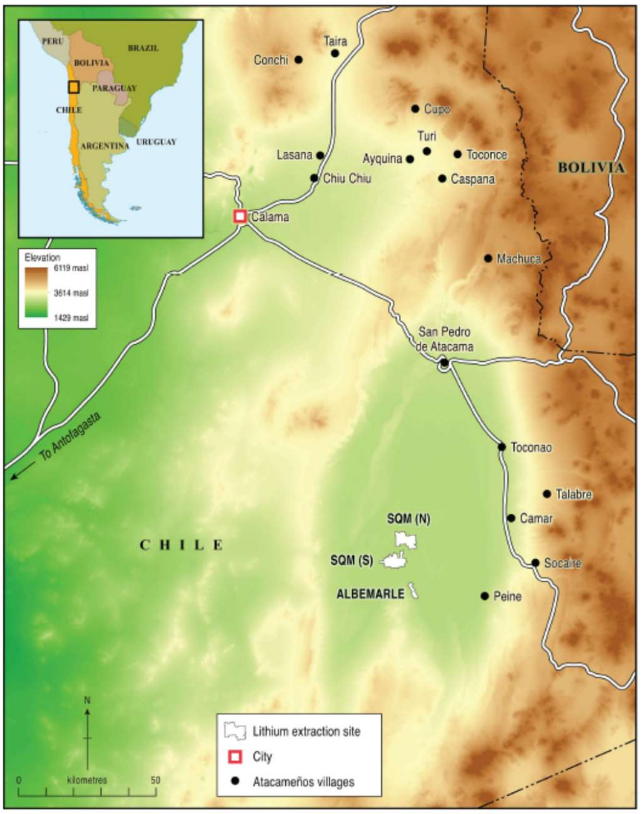

Figure 2

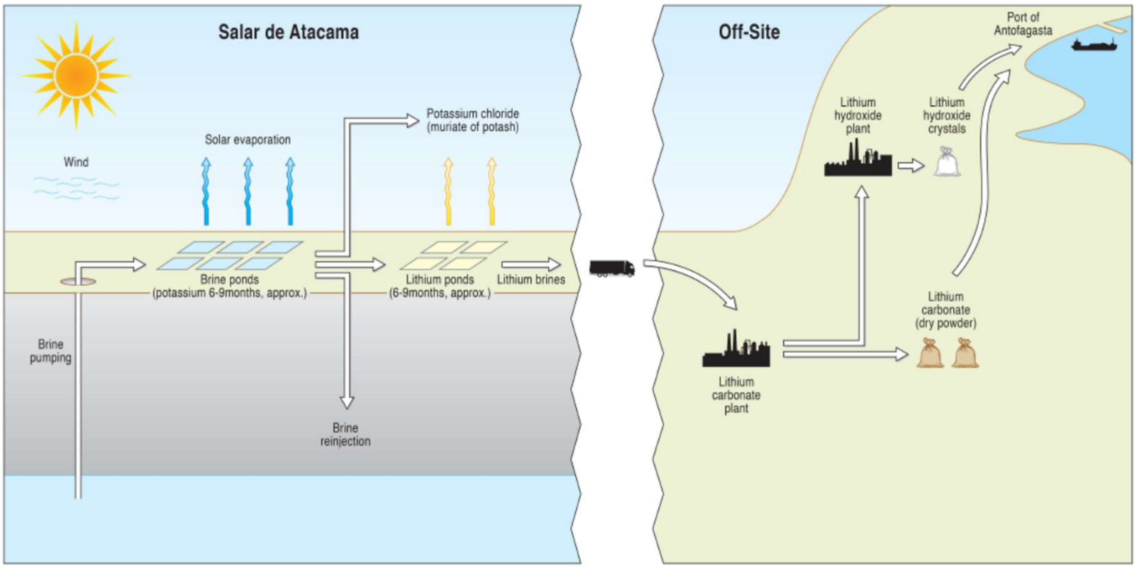

Figure 3

Figure 4

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