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Natural laboratories in emerging countries and comparative advantages in science: Evidence from Chile

José Miguel Aguilera[1,2] | **Felipe Larraín**[2,3]

[1]School of Engineering, Pontificia Universidad Católica de Chile, Santiago, Chile

[2]CLAPES UC, Pontificia Universidad Católica de Chile, Santiago, Chile

[3]Instituto de Economía, Pontificia Universidad Católica de Chile, Santiago, Chile

Correspondence
José Miguel Aguilera, Centro Latinoamericano de Políticas Económicas y Sociales de la Pontificia Universidad Católica de Chile, Pontificia Universidad Católica de Chile, Vicuña Mackenna 4860, Macul, Santiago 6904411, Chile.
Email: jmaguile@ing.puc.cl

Abstract

Entering the knowledge society and mobilizing science and technology are critical for emerging countries (ECs) to address important challenges of society and promote long-term economic growth. Natural laboratories (NLs) are geographical or geophysical singularities that provide comparative advantages and leverage to ECs for scientific research and international collaboration. Based on empirical evidence and learning experiences from five NLs in Chile, we propose the foundations of a conceptual framework for public scientific policies based on NLs and their possible implementation in ECs. Scientific research in NLs may address local, national, and global societal challenges while decentralizing scientific activities, encouraging transdisciplinary research in territories, anticipating the effects of climate change, and protecting biodiversity while promoting international partnerships and alignment with 2030 Sustainable Development Goals.

KEYWORDS

emerging countries, regions, science policy, scientific knowledge, Sustainable Development Goals, transdisciplinary research

INTRODUCTION

Entering the knowledge society and mobilizing science and technology (S&T) are critical for emerging countries (ECs) to address important challenges of society and promote long-term economic growth (Annan, 2004; Fedoroff, 2012; Sachs, 2005). However, investment in S&T in

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ECs has been historically low as it competes with other pressing national priorities that have shorter impacts in terms of social and political outcomes. For example, while the 12 largest Latin American countries barely contributed 2.4% of the world's research and development (R&D) expenditures in 2017, the United States, China, Japan, South Korea, and 24 countries from Europe accounted for almost 80% (Anonymous, 2018a). In addition, while two-thirds of the R&D effort in the developed world comes from the private sector, public institutions perform most R&D in ECs (Dehmer et al., 2019). Given this situation, nations from the developing world find it extremely hard to compete in scientific research with developed countries as demonstrated by any metric, for example, number of published research articles and related citations, degree of scientific diversification, number of patents, scientific awards, etc. (Cimini et al., 2014; de Rassenfosse & Seliger, 2020; King, 2004).

Another problem facing ECs is that their S&T agendas have been largely patterned after the so-called linear model of scientific research implemented in developed countries after World War II (Aguirre-Bastos & Gupta, 2009; Barletta et al., 2017; Rapini et al., 2015). It has been questioned whether the wide adoption of this model has added social or economic value to people in ECs (Barletta et al., 2017; Gonzalez-Brambila et al., 2016). Evidence for its limited impact abounds failure to embrace the complexity of societal problems, low impact on capacity building, insufficient incentives to promote learning and knowledge transfer, and poor performance of coordinating research agencies, among others (Barletta et al., 2017; Crane, 1977; Feinson, 2003; Goldemberg, 1998; Padilla-Pérez & Gaudin, 2014).

Bringing science closer to people's problems and national challenges have been a constant preoccupation of policy makers in developed and less-developed countries alike (Padilla-Pérez & Gaudin, 2014; Shneiderman, 2018). There are a few examples in Latin America, where long-term public policies in S&T have advanced scientific knowledge while improving living conditions. This has been the case of the eradication of infant malnutrition in Chile (Monckeberg, 2011), the development of alternative renewable energy sources (ethanol) in Brazil (Goldemberg, 2007), and the advances in biomedical sciences in Cuba leading to low-cost vaccines and cancer treatments (Holmgren & Schnitzer, 2004; Reardon, 2016).

Most ECs have exploited their comparative advantages based on natural resources for economic growth and development (Chenery, 1961; Faccarello, 2015; Khurana & Nauriyal, 2017). However, comparative advantages provided by locations or territories that are unique for the generation of scientific knowledge have been largely overlooked. Paleontology and archeology seem to be exceptions since they rely on unique sites with fossils or valuable cultural heritage, respectively (Mapunda, 1991; Osman, 2018). Europe, on the other hand, regards the exceptional natural and geographical conditions of the Outermost Regions (i.e., Canary Islands, Azores, French Guiana, etc.) as unique laboratories for research in biodiversity, terrestrial and marine ecosystems, pharmacology, and space sciences (European Commission, 2011; Lorincz, 2011).

In 1933, ornithologist H.S. Swarth called the Galápagos Islands a natural laboratory of evolution and a place to watch nature's experiments unfold (Hennessy, 2018). Lately, the term "natural laboratory" (NL) appears in scientific studies ranging from the impact of climate change on the biodiversity in the Mediterranean (Sarà et al., 2011) to the effects of health policy in Europe (Mackenbach et al., 2013). Journalists started to call natural laboratories the Galapagos Islands and the Amazonian rainforest to highlight the effects of human intervention on these ecosystems (Anonymous, 2009; Begley et al., 1989). Several scientists are also explicitly referring to these two locations as NLs for global climate change, loss of biodiversity, and the effects of urban pollution (Harpp et al., 2014; Martin et al., 2016; Shrivastava et al., 2019). However, NLs continue to be only a convenient expression linking scientific studies in specific fields to some regions or territories, overlooking that they are sites of confluence for many disciplines and may play a broader role in the science-policy landscape.

During the last 6 years, we have analyzed the origin, evolution, and relevance of five areas of scientific research in Chile that exhibited unique characteristics in the S&T portfolio. These are astronomy, Antarctic science, biodiversity studies, oceanography, and marine sciences, and mitigation of natural disasters. All these scientific fields shared to different extents, some common features that set them apart: they occur in unique locations at the planetary scale, have a regional or territorial scope, are socially relevant at the local, national, and global levels, and impress by the excellence of international collaborations and scientific output (Aguilera & Larrain, 2018).

Based on the recollection of this empirical evidence, the aim of this article is to present a concept of NLs. Moreover, we propose the concept as a framework to exploit the comparative advantages of unique locations or territories in ECs, generating scientific knowledge with impact on pressing societal problems and aspirations. This article is organized as follows: (a) first, we elaborate on the concept of NLs and describe its evolution in Chile since their inception; (b) next, we analyze and discuss the major characteristics and research activities in five NLs; and (c) finally, we propose a conceptual framework based on NLs that may be applied in the development of science policies in ECs.

A CONCEPT OF NLs

NLs are unique locations (e.g., a territory or a geophysical singularity) at the planetary level that provide comparative advantages for the advancement of scientific knowledge with regional, national, and global impacts and have attracted the attention of the international scientific community (Aguilera, 2013; Aguilera & Larraín, 2018).

Three basic pillars sustain our concept of NLs (Figure 1):

- The uniqueness of a territory or a geophysical singularity for scientific research at the planetary scale is validated by the international scientific community. This is a necessary but not sufficient condition that needs to be complemented with local settings, interests, and actions

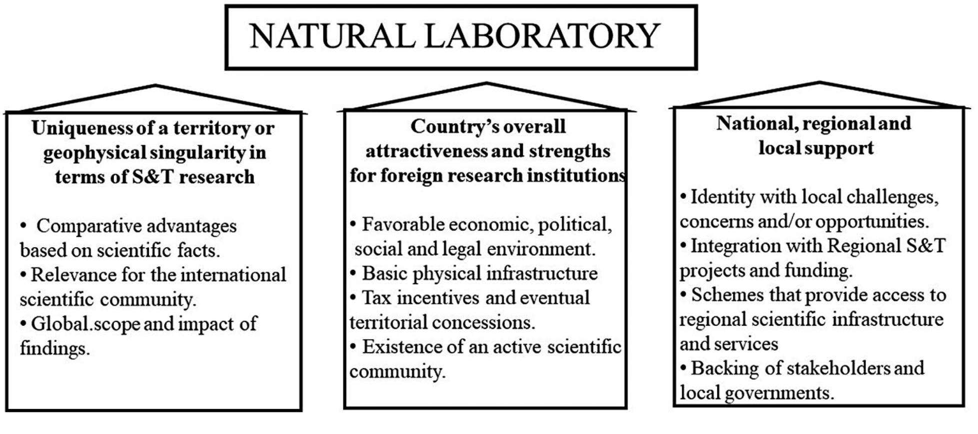

FIGURE 1 The three basic pillars that sustain the foundations of a conceptual framework based on natural laboratories. *Source*: Conceptualized and designed by the authors

that enable the collaborative advance of scientific knowledge.

- The country's attractiveness and strengths in terms of political, economic, legal, cultural, and social environments encourage and facilitate the investments and activities of foreign world-class research institutions (Tucar, 2018). This includes access to basic physical infrastructure (e.g., transportation, communications, health services, public utilities, etc.) and to an active local academic community supported by a national S&T research system.
- National and regional[1] support may be in the form of incentives, land concessions, logistic advantages, availability of qualified technical personnel, and access through collaboration schemes to research teams, laboratories, and experimental fields.

We propose that these three pillars are the foundations of a conceptual framework that aims at exploiting comparative advantages for scientific research in ECs, linking local, national, and global challenges with science while encouraging transdisciplinary research in territories and regions, and promoting win–win international collaborations. This concept of NLs is different from test beds and living labs defined as controlled experimental spaces for innovation and technology (Engels et al., 2019), and innovation clusters, which are local technological ecosystems that benefit from spatial proximity (Ferras-Hernandez & Nylund, 2019). In short, the main output of NLs is scientific knowledge and not necessarily innovation.

The scope of this article is to advance on the concept of NLs and no attempt was made to derive a formal analytical model. However, the three suggested basic pillars of NLs, that is, territorial uniqueness, country's attractiveness, and ancillary support, together with the associated issues listed in the preceding paragraphs are some possible input variables of any model. Potential quantitative and qualitative output variables would take into account the many expressions of knowledge generation, social impacts, scientific infrastructure, institutional building, etc., most of which are described later in the individual cases of the NLs presented.

In the following sections, we elaborate on how the concept of NLs has permeated society, academia, and policy makers in Chile, leading to a refreshed view of research activities in astronomy, Antarctic science, oceanography, biodiversity studies, and mitigation of natural disasters.

Brief background on Chile's science, technology, and innovation system

During the last 10 years, Chile invested annually in R&D between 0.33% and 0.39% of GDP, equivalent to approximately USD 1.2 billion in 2018 (OECD, 2019a). The private sector's contribution to the STI effort is approximately 33%, significantly lower than the OECD average of ca. 68% (OECD/UN, 2018, p. 52). The National Commission for Scientific and Technological Research (CONICYT), created in 1967, was de facto the cornerstone of S&T policies until October 2019 when the Ministry of Science, Technology, Knowledge, and Innovation (MSTKI) became operational. In 2006, the National Council for Innovation and Development (CNID) was created to directly advise the Presidency of the Republic on science and innovation opportunities and develop a long-term STI strategy (CNID, 2013; OECD/UN, 2018). In 2017, the national STI space involved five Ministries and over 30 major programs and initiatives supported by governmental funds, most of them assigned on a disciplinary basis (Balbontín et al., 2018).

Idea, evolution, and highlights of the concept of NLs in Chile

The concept of NLs was conceived during 2011–2012 at CONICYT when the agency was responsible for the promotion of science and the national scientific policy. Some of the important chronological events and major highlights of dissemination activities after the concept of NLs was officially presented in 2013 are presented in Table 1. They included displays in Santiago's subway wagons, a TV series, and presentations in academic, business, and cultural meetings. An important milestone was the incorporation of the concept of NLs as an alternative to respond to

TABLE 1 Chronology and highlights in the development, dissemination, and endorsements of the concept of natural laboratories in Chile

Year	Highlights	Reference
2011–2012	Elaboration of the NLs concept at CONICYT	https://www.conicyt.cl/blog/2013/08/05/laboratorios-naturales-para-una-ciencia-mundial/
2013	NLs are the national scientific theme-of-the-year by the science communication program EXPLORA-CONICYT	https://www.conicyt.cl/explora/explora-presenta-chile-laboratorio-natural/
	Santiago's Metro subway wagons displays graphics of NLs	https://www.conicyt.cl/explora/explora-conicyt-te-invita-a-viajar-en-el-tren-de-chile-laboratorio-natural-en-metro-de-santiago/
2014	Eight chapters of TV series *Chile*: *Natural Laboratory* broadcasted on open national TVN channel	https://www.tvn.cl/cultura/laboratorionatural/capitulos/
2017	CNID endorses the concept of NLS	http://www.cnid.cl/wp-content/uploads/2019/01/Propuesta-ENI-GOREs-ERI_VF.pdf
	Astronomy and Antarctica proposed as NLs (Presidential Program)	http://www.sebastianpinera.cl/images/programa-SP.pdf
2018	Presentation of the book *Laboratorios Naturales para Chile*	http://buscador.emol.com/noticias/Jos%C3%A9+Miguel+Aguilera
	Announcement in first Presidential address: Chile world's capital for Astronomy and Antarctica research	https://cdn.digital.gob.cl/filer_public/76/db/76db640b-c5c2-44bc-bae4-0b98da6c7139/discurso_presidencial_2019.pdf
	Presentation of NLs at the Annual ENADE Conference (National Business Meeting)	http://www.icaretv.cl/ciencia-y-nuevos-negocios
2019	Presentation of NLs at the Congress for the Future	https://www.youtube.com/watch?v=QupU9NF3608
	COP25. Chile natural laboratory for climatic change	https://www.emol.com/noticias/Tecnologia/2019/12/04/969320/Recomendaciones-Comite-cientifico-COP25.html
2021	National Agency for Research and Development (ANID) launches a call for proposals to develop NLS	https://www.anid.cl/concursos/concurso/?id=741

national challenges and opportunities in the strategies for STI elaborated by CNID in 2013 and 2017 (CNID, 2013, 2017; Rivas, 2018).

NLs had a positive reception and acceptance at the national (e.g., Presidential Program for 2018–2022) and international levels. Sachs (2018) commented that the concept of NLs was "bold, insightful and on the mark... [The] concept of NLs will not only spur Chile's innovative efforts but also serve as a beacon and inspiration for countries around the world." Bajak (2017) also mentioned it in relation to Chilean science in the journal *Nature*. The concept of NLs is now commonly used in government documents, national scientific publications, videos promoting Chile's image, and by the media. Table 2 summarizes some supporting facts, learning experiences, and major accomplishments of the NLs discussed in this article.

MAIN NLs IN CHILE

Chile offers many opportunities for global scientific research and international collaborations due to its unique geographical and geophysical conditions as well as a favorable political, social, and economic environment (Mullin et al., 2010; OECD/UN, 2018). In this respect, Chile stands out among ECs for having scientific collaborations with over 100 countries and attracting around 1330 international coauthors in publications between 2002 and 2016 (Chinchilla-Rodríguez et al., 2019; OECD, 2017).

Among the uniqueness that makes Chile attractive for scientific research and international collaborations are the clear skies and sun-struck lands in the north, the proximity to Antarctica, the pristine ecosystem and biodiversity of the sub-Antarctic region, the coastal projection to the South Pacific Ocean, and the position along with the Pacific Rim of Fire (Aguilera & Larraín, 2018). The following sections describe the relevance of scientific research carried out in these territories in astronomy, polar science, biodiversity and climate change, oceanography, and mitigation of natural disasters. As will be demonstrated later, these geographical and geophysical singularities are accompanied by the other prerequisites of NLs, namely, a collaborative scientific activity of international excellence, and a documented record of governmental and regional support. Figure 2 presents a map of Chile with the approximate locations of the NLs.

The Atacama Desert: Clear skies for astronomy and astrophysics

Astronomy extends peoples' horizons to the Universe awakening their interest in science. From a practical perspective, scientific discoveries associated with astronomy and astrophysics (A&A) have contributed to technological developments such as charge-coupled devices (CCDs), medical imaging systems, clean working rooms, and the wireless local area network (WLAN), among others (Rosenberg et al., 2014).

It was not until the 1960s that the international A&A community started to acknowledge that the dark and dry skies in the Atacama Desert of northern Chile offered exceptional conditions for astronomical observations, that is, an average of 330 clear nights a year (Leighton, 2014; Pease, 1999). The country's institutional advantages (i.e., a positive legal, social, and political environment) attracted foreign institutions as well as agreements that assured long-term land concessions and exemptions of many taxes and duties (Rodriguez, 2017). As a result, by 2025, around 75% of the world's terrestrial capacity in astronomical observation in the optical and IR spectra will be located in Chile, representing an investment of over 6 billion dollars in infrastructure

TABLE 2 Natural laboratories in Chile: supporting facts, learning experiences, major accomplishments, and future challenges

Natural laboratory	Learning experiences and accomplishments	Future challenges and possible impacts
Atacama desert: (Astronomy and Astrophysics)	• Boom of local astronomy research based on access to 10% of the observation time in international telescopes • Negotiations and relationships with institutions supporting international observatories for 60 years • Impact on citizens: increased interest in astronomy and development of astronomy-based tourism in regions • Promotion of Chile's scientific image in the world	• Increase the national participation in international research projects • Assemble all actions in A&A in the MSTKI • Development of a local instrumentation industry • Preservation of the favorable conditions of territories • Larger impact on STEM education • Expand activities with local communities and other regions
Chilean Antarctic Territory	• Initiatives that promote national and international Antarctic research activities and collaborations • Investments in regional S&T infrastructure and logistics • Regional identification and support by a local community	• Elaboration of a national policy on Antarctic and climate change research • Position Punta Arenas as an international hub for Antarctic research • Increase the support to research infrastructure in the Antarctic peninsula • Transfer of INACH to the MSTKI
Sub-Antarctic region	• 15-year research initiative supported by a foreign university • Establishment of the southernmost research center for transdisciplinary science on biodiversity. • Integration of socioethical and stakeholders aspects in research planning	• Replication of model of transdisciplinary research on biodiversity in other territories • Enhance coordination with other centers in Patagonia • Set bases for sustainable science-based tourism in the region
Eastern South Pacific Ocean	• Pioneering role among ECs in actions promoting the conservation of oceanic ecosystems • Early development of the salmon cluster through international collaboration and government support	• Increase the participation in international oceanic research initiatives, programs, and projects • Coordination of scientific actions to improve the sustainability of marine resources and particularly, the fishing and aquaculture industries • Develop technologies for value-added marine products

(Continues)

TABLE 2 (Continued)

Natural laboratory	Learning experiences and accomplishments	Future challenges and possible impacts
Continental shelf: (Natural disasters)	• Early development of antiseismic engineering capacities • National network for seismic data generation • Establishment of a multidisciplinary center for disaster resilience	• Increase the preparedness and resilience of the society to natural hazards • Consolidation of the multidisciplinary center for disaster resilience • Foster international collaboration with other seismic countries, specially developed countries from the Pacific Ring of Fire

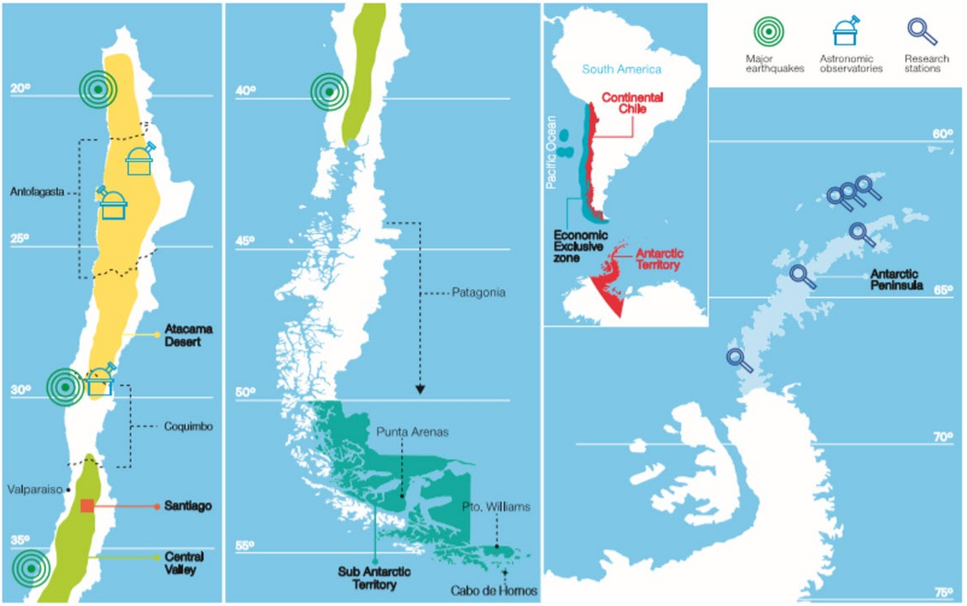

FIGURE 2 Territories and natural laboratories in Chile. *Source*: Conceptualized and designed by the authors, drawn by Catalina Fuentes (Comunicaciones UC)

(Rubio, 2019). This amount is equivalent to almost 10 times the annual operational budget of CONICYT in 2017 (Balbontin et al., 2018). In retribution, the observatories set aside 10% of the observation time for Chilean astronomers, but scientists say that this is not enough, given the tax exemptions and diplomatic status of facilities and foreign personnel (Leighton, 2014; Vanzi, 2019).

A&A has had impacts on scientific research in Chile that are unparalleled in the emerging world. Since 1998, the number of full-time professors at universities has more than quadrupled (Clocchiatti, 2019). Undergraduate demand in some of the 13 astronomy departments is as high as for medicine and engineering. Local funding for astrophysics has steadily grown from USD 2 million in 2006 to USD 6.8 million in 2010 (Catanzaro et al., 2014). Bibliometric analysis for the period 2005–2015 shows that the number of articles by Chilean astronomers almost doubled, with a steady rise in the normalized citation impact and international coauthorship (Cortes et al., 2018). However, these observatories are peculiar in at least two aspects. First, they are property of foreign organizations and operate independently in land concessions under diplomatic status. Second, they fall into the category of "research infrastructure," that is, an organizational structure dedicated to provide scientific equipment, data, or services for use in scientific research of their members (OECD, 2019b).

Four aspects of the presence of international observatories in northern Chile are worth separate comments:

- *Citizens' involvement in science*. Interest in astronomy among the public has created social value. Visitors to the ALMA observatory exceed 7000 per year and books on astronomy by Prof. José Maza have sold over 70,000 copies (Brown, 2019). This is quite remarkable in a country, where <10% of the population declares having visited a research laboratory and 77% are little or not informed about science.[2] People's interest in undertaking sky-related activities is on the rise. There are over 20 astrotourism observatories deployed in several regions and estimated returns from the stargazing activity will exceed USD 20 million per year by 2025 (Brown, 2019).
- *Safeguarding the conditions of NLs*. Astronomical observation depends on intrinsic environmental factors and exogenous anthropogenic sources of nuisances, such as light pollution from nearby urban centers, and dust and smoke from mining and other industrial operations (Murdin, 2001). The government, giving protection to the Regions where the main observatories are located (OPCC, 2019), has duly addressed the problem of light pollution. Starting July 2019, a law compels that all industrial projects in areas intended for scientific research in astronomy (and in glaciers) be subject to a study of environmental impact.
- *Relation with ancestral communities*. Astronomical activities have involved large territories with special significance for ancestral communities. The huge land areas required by some observatories (e.g., 72,500 ha for ESO's Paranal and 13,500 ha in the case of ALMA) implied negotiations with local indigenous communities in terms of their access to these territories, preservation of archeological sites, and participation in educational and outreach activities.
- *Country image*. Astronomy has projected the image of a trustworthy nation to collaborate in international initiatives requiring an S&T base (Vanzi, 2019). Fifty percentage of the news in the international press related to S&T highlights the leading position of Chile in astronomy research.[3] Portraying Chile as a hub of scientific research may contribute to a positive country image for food exports and the promotion of tourism (Rodriguez, 2017).

While this NL has contributed to the exceptional development of A&A sciences in Chile, it has had a marginal impact on technology transfer, enabling innovation and the development of a local astronomical instrumentation industry (Vanzi, 2019). Guridi et al. (2020) have discussed the legacies of the astronomical activity in Chile.

Chilean Antarctic Territory

The Protocol on Environmental Protection to the Antarctic Treaty (Madrid, 1991) designated Antarctica as "a natural reserve, devoted to peace and science." Antarctic research is critical to understand the past and future of our planet in terms of climate change, the dynamics of ocean circulation, projections of the sea level, loss of biodiversity, and the impact of these matters on society (Kennicutt et al., 2019). Worldwide research in Antarctica has been coordinated since 1958 by the Scientific Committee on Antarctic Research (SCAR) and scientific knowledge as well as policy-relevant results are communicated to the associated country members. There are 40 year-round stations and 36 seasonal stations operating in Antarctica that sustain the scientific research of 30 countries (Hughes et al., 2018). The Antarctic Peninsula, protruding from Antarctica toward the southern tip of continental Chile, houses 43 scientific bases from 23 countries (see Figure 2).

According to international law, Antarctica is a global common, but Chile claims the Chilean Antarctic Territory (or Chilean Antarctica) extending from 60°S to the South Pole and between 53°W and 90°W (see map, Figure 2). The Chilean Antarctic Institute (INACH), founded in 1963 and depending on the Ministry of Foreign Affairs, moved to the southern port of Punta Arenas in 2003, stimulating scientific activity and international collaborations (Retamales, 2018). A demonstration of the national commitment to Antarctic science is the three research stations in the Antarctic Peninsula overseen by INACH and the operation of a research vessel. INACH administers most of Chile's scientific endeavors in Antarctica including ecosystem resilience and adaptation, climate change, and biotechnology. In 2018, over 200 scientists participated in around 100 projects, 37% of them in international collaborations with 22 countries (INACH, 2019). The number of articles by Chilean authors in the Web of Science almost doubled in the period 2006–2016 and citations rose to over 2200 by 2018 (INACH, 2019; Retamales, 2018).

Punta Arenas, with a population of around 125,000, is a Regional capital that houses a major State University (Universidad de Magallanes) and two research centers devoted to Antarctic science, biodiversity, and natural studies. It is the city in the world closest to the Antarctic Continent and a port of entry for many scientists as well as international polar research vessels and aircraft that transport personnel and materials for exploration and research programs in Antarctica. Twenty-two of the 34 countries that have programs in Antarctica operate their missions from this city. The regional government and private entities aim to position Punta Arenas as a gateway to the Antarctic Continent and a hub for logistics and services (A-PAL, 2018).

There is a strong commitment of Chile to Antarctic research. In 2017, the Chilean National Antarctic Policy recognized the need to protect the continent for "both, its ecosystem fragility and its status as a natural laboratory that meets exceptional conditions for the development of science" (Gladkova et al., 2018). The promise of the present government to promote Antarctica as a natural laboratory seems to be coming to fruition with the announcement of the construction of an International Antarctic Center in Punta Arenas and the installation of a high-speed digital highway to reach Puerto Williams (see map) and eventually the Antarctic Peninsula.

Sub-Antarctic region

The sub-Antarctic area of the American Continent includes the territory between ca. 50 and 60°S, being the only continental land on the planet between those latitudes. The Southern Hemisphere at these latitudes has temperate and subpolar ecosystems modulated by an oceanic climate (mild winters and cool summers). These climatic conditions have led to a larger diversity of species in the south than in the north (Chambers et al., 2016; Rozzi et al., 2012). The variety of moorland, swamps, forests, glaciers, and alpine ecosystems in the Chilean sub-Antarctic territory is home to a rich biodiversity of nonvascular and vascular land–plant species (Rozzi et al., 2008).

Moreover, the coast of the most southerly locations in the American Continent around Cape Horn (Cabo de Hornos) is one of the least explored places on earth, hosting a diversity of marine habitats with abundant seaweed and fish species (Friedlander et al., 2018). This planetary distinctiveness, an asset for the country, led to the designation of the Cape Horn zone as a Biosphere Reserve by UNESCO in 2005. Nevertheless, it was not until the year 2000 with the creation of the Omora Ethnobotanical Park on an 800 ha land concession near Puerto Williams (300 km south of Punta Arenas) that the world's attention was captured by the incomparable biological and cultural diversity of the territory (see map in Figure 2). Puerto Williams will soon house the Cape Horn Sub-Antarctic Research Center, a joint venture between Universidad de Magallanes and the University of North Texas with the financial support of the Regional Government (Rozzi & Schuttler, 2015). The region has designated itself as a “natural laboratory” to implement a transdisciplinary approach that articulates programs at social, ecological, and political scales, emphasizing biocultural education, environmental ethics, and ecological tourism and conservation activities (Rozzi, 2018).

Eastern South Pacific Ocean

Oceans absorb, store, and redistribute most of the energy received from the sun, take up almost one-fourth of CO_2 from the atmosphere, and provide through photosynthesis over half of the oxygen that we breathe. Hence, oceans play key roles in important global challenges such as climate change, ocean acidification, overexploitation of marine resources, loss of biodiversity, pollution, and food security (OECD, 2016).

The 4200 km long coast of mainland Chile is a privileged observatory for the vast southern area of the eastern South Pacific Ocean (ESPO; Figure 2). It also defines an Economic Exclusive Zone five times larger than the terrestrial territory. The geographical situation of the ESPO makes it a natural laboratory for the study of atmospheric–oceanic interactions, coastal–ocean exchanges, hypoxic conditions in deep oceanic trenches, and the prediction of the effect of climate change on local ecosystems.

Oceanographic research takes place in several university centers and field stations along with the country and includes topics such as marine life and ecosystems, physical oceanography, coastal habitats, marine conservation, and sustainable aquaculture (Aguilera et al., 2019; Lange & Ulloa, 2003). Since 2013, a modern USD 68 million research vessel operated by the Chilean Navy supports oceanographic studies. Major contributions to marine conservation efforts and awareness about ecological risks in Chile stem from several coastal research stations assigned as marine concessions to universities (Anonymous, 2018b; Fernández & Castilla, 2005). Today, Chile is a good example of scientific knowledge being translated into policies for the long-term conservation of oceanic ecosystems (Carr et al., 2019). Over 40% of the Chilean jurisdictional waters have some status of Marine Protected Areas (MPA), compared with 7% of the global ocean, and a world target of 10% of marine coastal areas for 2020 (The David and Lucile Packard Foundation, 2019). These MPAs are strategic areas for monitoring global climate change and fostering the sustainability of production systems and the conservation of marine biodiversity.

A recent review has identified crucial knowledge gaps in environmental and sustainability issues and presented the scientific actions to solve these problems (Quiñones et al., 2019). In this respect, the aquaculture and fisheries sectors need a research agenda and the necessary policy frameworks to develop the adaptive capacity to respond to social, ecological, and sustainability issues.

Continental shelf (south-eastern stretch of the Pacific Ring of Fire)

Natural disasters cause human, physical, and economical losses as well as long-term psychological distress in the affected population. Almost 7000 natural disasters were recorded worldwide between 1994 and 2013, claiming 1.35 million lives (Wallemacq et al., 2015). In the period 1980–2011, Chile led among the OECD countries in disaster losses due to earthquakes, tsunamis, volcano eruptions, droughts, landslides, and fires, with an economic value equivalent to 1.15% of GDP (G20/ECD, 2012). Not surprisingly, the German Laboratory for Natural Hazards (ANDES) has chosen Chile as "a natural laboratory for natural hazards and the ideal place to develop scientific methods to better understand possible escalation chains and to prevent future natural disasters" (DLR, 2019).

Chile's continental shelf is on the southeastern part of the so-called "Pacific Ring of Fire," an extremely turbulent region with frequent earthquakes, volcano eruptions, cyclones, floods, droughts, and tsunamis (Guha-Sapir et al., 2004). Chile adopted seismic regulations for earthquake-resistant construction in 1930, 3 years before then in the United States (Reitherman, 2008). Effects of seismic events and reconstruction experiences after large earthquakes in the country are subjects of attention and study around the world (Booth, 2018; Cowan et al., 2011). Scientific and engineering capabilities were boosted in the last decade after the Mw 7.1 earthquake in southern Chile that caused over 500 fatalities in February 2010. The National Seismological Center monitors in real time more than 100 stations along with the country, gathering data with modern broadband seismometers, accelerometers, and GPS instruments (Barrientos, 2018), and the National Volcanology Observatory permanently surveys the activity of 43 volcanoes.

Disaster mitigation and recovery are country and region specific because they interrelate in complex ways many dimensions of public and private infrastructure, economic activity, social organizations and institutions, ecosystems, culture, etc. (Tierney & Oliver-Smith, 2012). Thus, to design and implement a public policy for disaster management a National Institute for Disaster Resilience was recently launched (de la Llera et al., 2018).

POSSIBLE IMPACT OF NLs IN RESEARCH POLICIES OF ECs

A constant preoccupation of policy makers in ECs has been bringing scientific research closer to people's problems. In a recent article, Kuhlmann and Rip (2018) argue that addressing the present society's challenges requires fresh ideas for the design of STI policies and that their implementation will involve an iterative and learning process. We suggest that the empirical evidence gathered so far for Chile's NLs, regardless of the shortcomings of their diverse experiences, provides a basis for a conceptual framework of a research policy in ECs. This policy aims at addressing, from a comprehensive and integrated perspective of S&T, challenges such as decentralizing scientific activities, encouraging transdisciplinary research, and promoting international partnerships and collaborations.

The right column in Table 2 summarizes some of the future challenges and potential impacts that we envision for the NLs in Chile. The main challenge is to get institutional support from MKSTI in terms of research policies that potentiates their particular schemes, expands the capability to seize new research opportunities (e.g., participation in major international programs and projects), and provides funding for the long-term operation (e.g., improve or update the research infrastructure). Some expected positive spillovers include the valorization of territories, appreciation of science and STEM education, promotion of the country's image, and economic activities (scientific tourism, specialized small industries, and logistics services). In this section, we elaborate on viewpoints that could guide strategies in ECs for decentralizing scientific activities, encouraging transdisciplinary research in territories, anticipating the effects of climate change, promoting international partnerships, and contributing to the U.N. Sustainable Development Goals.

Addressing societal challenges and opportunities

ECs share several conditions that negatively affect the lives of a significant number of people, leading to poverty and inequalities in access to basic services, health, education, housing, and a clean environment, among others. Long-term solutions to these issues most likely depend on interconnections among economic development, social policies, and politics (UNICEF, 2010). However, local S&T capacities are necessary to inform policy makers, implement sound social policies, and needed welfare-enhancing actions.

Ten years ago, the World Bank suggested that successful development of science in Chile should be based on a few key areas of excellence and the collaboration between regions, a concept to be extrapolated to other ECs (World Bank, 2008, p. 12). This recommendation was reiterated in a report by OCDE on policy assessment for economic transformations, stressing that defining "functional territories" would avoid duplication of efforts, enhance the sharing of resources, and promote synergies in STI (OCDE/UN, 2018). In addition, recent suggestions propose that grand global challenges should be addressed through interdisciplinary research actions that promote economic development and welfare in developing countries (Gibson et al., 2018; UK Research and Innovation, 2019). A recent report of Chile's National Council for Innovation and Development incorporates these advises and acknowledges that the concept of NLs contributes to define a role for S&T in addressing the main multidimensional societal challenges of the country (CNID, 2019). As a result, the National Agency for Research and Development (ANID) launched a call for proposals "…to promote the development of NLs focused on strengthening scientific activity, and the economic and social development of territories."

Decentralizing scientific research

Chile is the most territorially centralized country of the OECD (OECD/UN, 2018). In the period 2008–2018, over 60% of the research projects financed by CONICYT were carried out in Santiago and Valparaíso, the two largest cities in the country and distant 150 km from each other (CONICYT, 2019). Centralized (top-down) research policies and the discretionary use of funding by local Regional governments has resulted in the dispersion and often duplication of scientific efforts. For instance, at least six centers or institutes perform research in marine ecosystems and coastal resources in the five southernmost Regions of Chile (Quiñones et al., 2019). Interestingly, NLs bridge over administrative Regions and cover vast territories removed from academic centers in large cities. It is remarkable that this decentralization occurs naturally and it is not the result of a decision by a central authority.

For its regional deployment, a policy based on NLs may take elements from the roadmap of the Europe Research Areas initiative aimed at integrating regional research efforts in related fields, improving flows of knowledge and sharing of infrastructure (Reillon, 2016). From the viewpoint of human resources, NLs are likely to attract national and foreign scientists by the novelty and transcendence of the research challenges, the possibility of participating in major international collaborations, and eventually by accessing infrastructure and research funding (Biancani et al., 2018). Importantly, NLs may generate the knowledge stock that precedes and promotes innovation and the technological development of the territories involved (Bell & Albu, 1999; Njøs & Jakobsen, 2017).

Fostering transdisciplinary research in territories

Challenges and opportunities to be encountered in territories demand an integrated view from different scientific disciplines and not the mere cooperation among them (König et al., 2013; Siedlok & Hibbert, 2013). Transdisciplinary research (TR) tackles societally relevant problems creating knowledge that is solution-oriented, goes beyond disciplinary boundaries and at the same time is understandable and shared by the participating stakeholders (O'Brien et al., 2013; Pohl et al., 2017). In addition, TR enables mutual learning among researchers from the concerned disciplines and institutions (Lang et al., 2012). NLs are an opportunity to implement this transdisciplinary vision by integrating community-based and participatory research to assure that the requirements posed by real-world problems and sustainability are duly met (Klein, 2004). Most research in NLs has to give attention due to external factors as control over them may be limited (e.g., light and dust pollution in astronomy) or restrictive (e.g., impacts on biodiversity and local communities). Unlike disciplinary research which has a narrow focus and a rigorous methodological approach, the practice of TR generates along the way outputs unrelated to the original objectives such as a participatory attitude, cross-learning between participants, and the building of networks.

Promoting international collaboration and access to funding

International collaboration is crucial to improve national competitiveness and productivity in scientific output (Adams, 2013). Collaborations in science aid ECs in solving complex societal problems as many of them (e.g., energy and water supplies, threats of climate change, conservation of biodiversity, natural disasters, etc.) overlap with issues pertinent to developed countries (European Union, 2009). Moreover, strong and well-supported scientific partnerships may partly deter the "brain drain" (Fedoroff, 2009). Developed countries, in turn, are interested in research collaborations with small nations that focus on global societal problems while delivering front-line science (Witze, 2016). For example, in 2016, the UK Government launched a £1.5 billion fund to support cutting-edge research that addresses the challenges faced by developing countries (UK Research and Innovation, 2019). In this regard, Chile and other ECs should actively promote the favorable institutional conditions, achievements, and uniqueness of present and potential NLs to further attract into their territories world-class science and needed funding. Although most ECs benefit from cross-geographical collaborations in terms of scientific impact, attention should be given to the possible effect of unequal scientific relations on S&T dependence and sociocultural identities (Guerrero Bote et al., 2012; Hwang, 2008).

Preparedness for climate change

Climate change is of vital importance for society as a whole and highlights the interdependency of some global problems. Climate change will affect peoples' habitats and livelihoods to productive activities, imposing a challenge for policy makers in highly vulnerable ECs (Fankhauser & Stern, 2016). Scientists have already called attention to several effects of climate change in Chile. Among them are reduced water supplies in urban spaces (Aldunce et al., 2017), severe droughts leading to land reallocation in agriculture (Martin & Saavedra, 2018), retreating of glaciers (Barcaza et al., 2017), and loss of biodiversity (Bambach et al., 2013). In addition, reports highlight the geographical advantages of Chile as a natural laboratory to study climate change (Sarricolea et al., 2016). A multidisciplinary scientific committee is elaborating a public policy to face climate change in Chile based on seven "axes of action," namely, Antarctica, oceans, water resources, biodiversity, cities, adaptation and mitigation of effects, and energy, which are quite coincidental with scientific activities in NLs (Rojas et al., 2019). Future research policies regarding the effects of climate change in ECs will demand a multidisciplinary perspective at different territorial scales, increased cooperation, and the participation of several stakeholders (Hallegatte et al., 2016).

Complying with the U.N. Sustainable Development Goals

The U.N. General Assembly adopted in 2015 the *2030 Agenda for Sustainable Development* that includes 17 Sustainable Development Goals or SDGs and 169 targets (United Nations, 2015). Developing countries are committed to create their own national plans and comply with at least some of the SDGs, giving suitable attention to local circumstances (Kelman, 2017). A few schemes have been proposed to help the implementation of SDGs in ECs by aligning them with national and regional strategies (Akenroye et al., 2017; Stafford-Smith et al., 2016). For example, the CNID foresees alignments of NLs with SDG 11 (Sustainable Cities and Communities), calling for resilience to disasters and the development and implementation of disaster risk management approaches; SDG 14 (Life below Water) in enhancing the conservation, marine biodiversity, and sustainable use of oceans and their resources; SDG 15 (Life on Land) by ensuring the conservation, restoration, and sustainable use of terrestrial (including mountain) ecosystems; and SDG 17 (Partnerships for Action), mostly aimed at multistakeholder partnerships that mobilize and share knowledge for sustainable development, that is, at the heart of the concept of NLs.

CONCLUSIONS

While the expression "natural laboratory" is used in science, no concept has been anticipated that frames the particular characteristics, scientific activities, the role of international collaborations, and possible societal impacts of these sites in the context of ECs. We propose that NLs in unique locations (i.e., a territory or a geophysical singularity) are scarce resources at the planetary level that provide comparative advantages for scientific research with local, national, and global impact. They are valuable assets to attract and share the collaboration of the international scientific community. We argue that ECs have not fully exploited their NLs to advance scientific knowledge that addresses pressing societal problems, nor have they considered them as natural capital for decision-making. NLs are scarce resources at the planetary level and valuable assets to negotiate in collaboration agreements with international scientific institutions (as did Chile with the locations for astronomy). When examined under the prism of the proposed NL concept, research activities in Chile in astronomy, polar science, biodiversity, oceanography, and mitigation of natural disasters, share the territorial scope, impact on society, backing from key stakeholders, and a high level of international collaboration.

We suggest that the empirical evidence gathered so far for NLs in Chile, regardless of the shortcomings of their diverse experiences, provides a basis for a conceptual framework of a research policy in ECs. This policy aims at addressing, from a comprehensive and integral perspective of S&T, challenges such as decentralizing scientific activities, encouraging transdisciplinary research, and promoting international partnerships and collaborations. Implementation of the NLs concept in other ECs will largely depend on the fulfillment of conditions established by the proposed three basic pillars: territorial uniqueness, country's attractiveness, and ancillary support.

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CONFLICT OF INTEREST

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

AUTHOR CONTRIBUTIONS

Jose M. Aguilera and Felipe Larrain: Original concepts, Idea conceptualization, literature review, primary analysis, writing the original draft, vision from public policies, conclusions, writing a revised draft, final review, and editing.

ORCID

José Miguel Aguilera https://orcid.org/0000-0001-5754-2722

ENDNOTES

1 Chile is divided into 16 administrative regions, each one with a governor and a regional council. They are referred to in the text as **Region(s)**. The term **region** (or regional) is used to denote an area of land or territory that exhibits common geographical features.

2 The First National Survey on Public Perception of Science and Technology in Chile, a country-wide survey that involved 7637 people 15 years or older, was carried out by CONICYT in 2016. https://www.conicyt.cl/wp-content/uploads/2017/05/EXECUTIVE-SUMMARY-SURVEY-PPSyT-2016.pdf

3 The survey was conducted in 2016 by Fundación Imagen de Chile, the agency responsible for promoting Chile's image abroad. Information is available in https://marcachile.cl/wp-content/uploads/2018/05/informe-ciencias-imagen-de-chile.pdf. The Ministry of Foreign Affairs has also promoted Chile's natural laboratories through its embassies. See https://issuu.com/decyti/docs/boletin_6_final.

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AUTHOR BIOGRAPHIES

José Miguel Aguilera is Honorary Emeritus Professor at the Pontificia Universidad Católica de Chile. His research is focused on engineering and novel aspects of foods. He was President of Chile's National Commission for Scientific and Technological Research during 2010-2013.

Felipe Larraín is Professor of Economics at the Pontificia Universidad Católica de Chile. His main research interests concern macroeconomic policy and economic development and growth. He was Minister of Finance of Chile, 2010-2014 and 2018-2019.

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