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ESSAYS ON ECONOMICS OF COPPER AND WATER IN A CLIMATE CHANGE CONTEXT

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ESSAYS ON ECONOMICS OF COPPER AND WATER IN A CLIMATE CHANGE CONTEXT

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DEDICATION

IN MEMORY OF MY DEAR NONNO … RICARDO STURLA ROCCA

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> *"THE PURPOSE OF STUDYING ECONOMICS IS NOT TO ACQUIRE A SET OF READY-MADE ANSWERS TO ECONOMIC QUESTIONS, BUT TO LEARN HOW TO AVOID BEING DECEIVED BY ECONOMISTS."*
>
> JOAN VIOLET MAURICE (JOAN ROBINSON)

CONTENTS[1]

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[1] The numbering of tables, figures and equations is internal in each of the 3 essays.

1 **ESSAY I**. THE WEALTH GIFTED TO THE LARGE-SCALE COPPER MINING INDUSTRY IN CHILE: NEW ESTIMATES, 2005-2014[2]

Abstract

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[2] Sturla Zerene, G.; López, R. E.; Figueroa B., E. and Accorsi, S. The wealth gifted to the large-scale copper mining industry in Chile: new estimates, 2005-2014. *CEPAL Review*. N°124, pp. 9-119. April 2018. RUL: https://repositorio.cepal.org/bitstream/handle/11362/43953/1/RVI124_Sturla.pdf

This article estimates the economic rents received by the 10 mines that comprise Chile’s large-scale private-sector copper-mining industry. The methodology used produces a conservative calculation and includes two corrections that have hitherto been ignored in the literature: the reimbursement of exploration expenses and the compensation needed for volatility in the copper price. Estimates show that the wealth transferred to these firms between 2005 and 2014 was at least US$ 114 billion. These rents are neutral in terms of investment and production decisions; in other words, if the private mining companies had paid the Chilean Treasury the calculated amount, their total investment and output would have been unchanged, but the country at large could have benefited from the huge voluminous resources in question. Moreover, in the absence of any other distortion, the firms would still have earned returns equivalent to what they would have obtained under perfect competition.

Keywords
Copper, mining, private sector, rent, measurement, natural resources, prices, tax revenues, Chile

JEL classification
Q30, Q32, Q33

1.1 INTRODUCTION

"…all Chileans need to consider how an additional peso can be put to best use - an extra peso for a bridge, a school, a public-sector worker, a pensioner …"

Rodrigo Valdés, Minister of Finance of Chile, 2015-2017,

La Tercera newspaper, 25 August 2016, Santiago.

"…we must not let this vast and wealthy region become nothing more than a foreign factory …"

José Manuel Balmaceda, President of Chile, 1886-1891,

Message to Congress, 1 June 1889, Santiago.

Chile's large-scale private-sector copper-mining industry consists basically of 10 large transnational corporations which account for around 60% of all copper produced in the country. Most of the copper produced by these firms is exported as concentrate, which implies a minimum level of product processing. In addition to the large private-sector mines, there is a public-sector firm, Corporación Nacional del Cobre de Chile (CODELCO), which generates about one third of Chile's total copper production.

Copper is responsible for a huge share of Chile's tax revenues; yet the bulk of copper's contribution to the Chilean State comes from CODELCO (around 60% of the total), while the 10 large private-sector mining firms contribute less than half of that amount. In other words, CODELCO's effective tax rate per ton of copper produced is nearly four times higher than the rate faced by the large private-sector mining companies.

This provides a major justification for this study: why do large private firms pay much lower taxes than the State enterprise —especially when CODELCO's mines are much older and have a far lower average mineral grade?

Nonetheless, CODELCO's heavy tax burden has not prevented it from maintaining a healthy financial situation in most years. This implies that the private mining firms could contribute much more to the Chilean State than they currently pay, without jeopardizing their economic viability; and they would still earn normal rates of return on their capital.

In other words, it would appear that private mining companies are appropriating large economic rents. This paper attempts to put a value on those rents, using very conservative assumptions in its estimation, in order to provide a lower-bound value.

The article is organized as follows. Section 1.2 sets out the conceptual framework to be used, emphasizing the concept of economic rent and its relationship to natural resources and the mining rent. It also makes a brief review of the literature on this subject in the case of Chile. Section 1.3 describes the process by which mining rents are estimated by the World Bank, which also provides the data set used in this study. Section 1.4 describes the methodology used to calculate the rents, and section 1.5 presents the results. The article concludes with some final thoughts.

1.2 CONCEPTUAL FRAMEWORK

1.2.1 Economic rent

The classic definition of economic rent refers to the excess economic return that a specific factor of production receives —that is, an amount above the minimum return needed for it to continue in the same use. When all factors of production are considered together, the economic rent associated with a productive enterprise can be understood as a payment above the minimum necessary for the enterprise to remain in a given economic activity. The origin and subsequent theoretical development of this concept are discussed in the Letters of David Ricardo, 1810-1815, compiled by Piero Sraffa (Ricardo, 2005), in the literature review by Tollison (1982), and in the studies of Shepherd (1970) and Hammes (1985), among other sources.

In the concept of economic rent, the opportunity cost of all productive resources used is already discounted. Since opportunity costs include the profit that would have been made if the resources employed in a certain activity had been invested in the next best alternative use, economic rent represents a surplus over the profit needed to allocate the resources to the activity in question. More simply, the rent is the surplus value of production after deducting all costs, including a normal return on capital and relevant risk premiums. Wessel (1967) distinguishes between the concepts of Ricardian and Paretian rent, emphasizing that the latter is calculated by deducting opportunity costs. The present study uses the concept of economic rent in its Paretian sense.

1.2.2 Economic rent and natural resources

A key feature of natural-resource-based economies is that they tend to generate large economic rents, which can inflate the return earned on the capital that exploits them to levels well above normal rates of return. The economic rent generated by the activities in which the natural resources, whether renewable or non-renewable, are extracted, directly constitutes the *in-situ* scarcity value of the resources in question. Hence, the rent is what the owner of the natural resource can legitimately charge entities that use the resource in a productive process. The present study focuses on the calculation of this rent in Chile, specifically, the rent received by the 10 firms that form the large-scale private-sector copper-mining industry (*gran minería privada del cobre*), hereinafter referred to as GMP-10.

1.2.3 Origin of economic rent in the mining industry

Minerals differ from other natural resources, since they require an "exploration" phase prior to extraction or exploitation. Finding minerals has been a historically difficult and expensive task, with slim chances of success. There are two different mineral exploration regimes:

(i) Free-entry exploration: in this mode of operation, there is perfect competition in the exploration market, so the rents accruing to the economic agents that undertake exploration work tend to dissipate in the long run.

(ii) Exploration subject to entry barriers: this situation can involve lobbying mechanisms that impede free access to exclusive exploration concessions, or simply the maintenance and exploitation of the rights derived from concessions previously granted by the State. In both cases, the final de facto effect is the existence of entry barriers to exploration, which also then become de facto entry barriers to the extraction or exploitation of the mineral in question. This situation generates an institutionally-based artificial shortage; and it constitutes a source of rent appropriation by the mineral exploration and extraction firms. Moreover, the rent generated under this regime does not dissipate as it does under free entry: firms that enjoy exclusive access to mineral deposits tend to appropriate these rents; and, given the heterogeneity of the deposits and the natural scarcity of the mineral resource, the existence of these rents does not elicit additional investment. This is because the return on capital obtained from mines currently being operated can seldom be replicated, since the costs of exploring and exploiting new potential deposits are usually greater than those of deposits already discovered and in operation.

This study considers the second of the two regimes, since Chile has legislation that grants exclusive exploration concessions and mining rights, on a cost-free basis and in perpetuity. In 2013, 42% of the country's total area was under concession, encompassing all zones with mining potential (SERNAGEOMIN, 2013). In Chile, therefore, copper is a resource for which the scarcity value is determined by entry barriers to exploration activities, which grant free and exclusive access to a handful of firms. In the case of GMP-10, the firms in question own the exploration and exploitation concession, which enables them to retain the corresponding rents.

1.2.4 The nomenclature used in the study

- *WB total mining rent:* the rent calculated by the World Bank in relation to all the mining activity undertaken in Chile. The estimated amounts can be found in World Bank (2016).

- *WB GMP-10 mining rent:* that portion of the WB total mining rent associated with the companies that operate the 10 mines that comprise the large-scale private-sector copper-mining industry in Chile.

- *GMP-10 compensated rent:* the remaining rent, obtained by taking the WB GMP-10 mining rent (in which all production costs have already been deducted from the value of mineral sales) and subtracting two additional compensatory returns that have not previously been considered in any study on Chile. These are:
    - (i) the return needed to compensate for the high risk associated with mineral exploration activity; and
    - (ii) the return needed to compensate for the high risk associated with the volatility of the price of the raw materials (copper) on the international market.

- *GMP-10 appropriated gratuitous rent:* this is obtained by subtracting the GMP-10 compensated rent from the tax revenue that the State of Chile obtained from the large-scale private-sector copper-mining industry. This corresponds to economic rent as strictly defined; so, if it were taxed away, it would not generate distortions in the economy. This rent is referred to as "gratuitous" because it should pertain to the owner of the mineral ore (the State of Chile), but instead is gifted to the firms that exploit it.

1.2.5 Studies of mining rent in Chile

Despite the fundamental importance of mining rents for Chile's economy, few studies exist on the subject. The most important is undoubtedly that done by the World Bank (2011), which is described in greater detail in section 1.3.

Although mining rents have been estimated in recent years, the studies in question contain major methodological errors. For example, when calculating the economic rent, Poblete (2015) considers the sales that the mining firms report rather than the total production of copper and other minerals at market price. This is not consistent with economic theory and generates a serious distortion, since a large proportion of sales is reported at transfer prices, which are generally below the market price (COCHILCO, 2015; Correa, 2016).

None of the recent studies considers exploration expenses, which must be increased ex-ante, since exploration activity entails a high probability of failure which must be economically compensated. A second issue that is ignored is compensation for the volatility of copper prices, which requires the rents to value at trend prices rather than at the prices observed on the market. Failure to do so may result in rents being overestimated when measured in a mineral price upswing or super cycle period.

1.2.6 A modern methodology

The methodology used in this study ensures that the rents estimated correspond to a "lower bound" or minimum value. For that purpose, two important corrections are made which are generally ignored in the literature —even in the estimates by the World Bank and the Organization for Economic Cooperation and Development (OECD)— which significantly reduce the estimated amount of the rent:

(i) *Exploration expenses:* to maintain their long-term production potential, copper mining firms must undertake a lot of exploration work to replace deposits that are becoming depleted. The fact that mineral exploration activities are often unsuccessful means they are subject to a high risk that needs to be rewarded with a higher ex ante rate of return. Thus, when calculating the economic rent, apart from deducting observed exploration costs, the calculation must also include a premium for the ex ante risks of these expenses.

(ii) *Commodity-price volatility:* the prices of raw materials, particularly copper, fluctuate widely, with periods of very low prices and other high-price or boom periods. As a result, rents that may seem excessive during peak periods may, in part, be merely compensating for losses occurring during low-price phases. Measuring rents in periods of very high prices, as at the time of this study, can lead to overestimation; so taxing them away completely would be distorting. This problem is tackled by removing the effect of short-term fluctuations from the copper price and using trend prices instead of those observed in the market. The values thus estimated correspond to long-term rents.

This methodology involves estimating a minimum value of the rent compared to more conventional measures. This can be a disadvantage, since the true value of economic rent tends to be underestimated. Nonetheless, the study aims precisely to estimate the rent as conservatively as possible, to obtain a lower-bound value. From the public-policy standpoint, the risk involved in not taxing all of the rent is likely to have less negative consequences than to tax it in excess as a result of overestimates. In the first case, an underestimation of the rent only causes a distributive effect because less revenue is collected than could otherwise be obtained. In the second case, if the rent is overestimated, taxing it can cause economic-efficiency losses.

The methodological procedure used in this study is as follows. The World Bank measurement of Chile's total mining rent is used to obtain the GMP-10 portion, which is implicit in the WB calculation and amounts to US$ 204 billion in 2005-2014.[3] This is then reduced by deducting the amounts needed to offset the

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[3] This article uses United States dollars at October 2016 prices throughout.

uncertainty of exploration expenditure (just over US$ 18 billion) and to compensate for the volatility of the copper price (nearly US$ 30 billion). The GMP-10 compensated rent is thus calculated as US$ 156 billion. From this amount, the taxes paid by GPM-10 (nearly US$ 42 billion) are deducted to obtain a GMP-10 gratuitous rent of US$ 114 billion. This amount is equivalent to almost six times the total value of Chile's current sovereign wealth funds (Ministry of Finance, 2015).

1.3 MINING RENTS ACCORDING TO THE WORLD BANK

1.3.1 General considerations

In the study *The Changing Wealth of Nations: Measuring Sustainable Development in the New Millennium* (World Bank, 2011), the World Bank calculated the mining rents of various countries, including Chile; and these have now been updated to 2014. This official database spans a 45-year period and is kept permanently up to date.

- The calculation methodology (World Bank, 2011, Brandt, Schreyer and Zipperer, 2013) considers the following:
- The production of minerals, measured in terms of refined units equivalent, associated with the deposits or mines located in the country.
- The price observed on the international minerals market, for the purpose of estimating sales value, which generally differs from the amount reported by the companies themselves.
- The total costs of mining production in deposits or mines, including the opportunity cost of capital (Brandt, Schreyer and Zipperer, 2013).

In the case of Chile, this study considers the following mining products in addition to copper: tin, gold, lead, zinc, iron, nickel, silver, bauxite and phosphate. Copper rents are predominant — accounting for over 95%— compared to the rents associated with other minerals, especially in 2005-2014 (Brandt, Schreyer and Zipperer, 2013). Moreover, most of the minerals considered are themselves by-products of the large-scale copper mining industry and are therefore present, although to a lesser extent, in these firms' revenues. It should be noted that the contribution made by these minerals to the calculated rents is underestimated, since the by-products of the large private copper mining sector have been systematically under-reported owing to the lack of measurements by laboratories that are genuinely independent of the mining companies (Castillo, 2015).

It should be noted that the rents measured by the World Bank do not correspond to economic rents strictly defined —as used in this study— since they do not deduct the returns needed to compensate for exploration expenditure risks and the volatility of international mineral prices. These two issues are addressed in this study and the corresponding calculations are made.

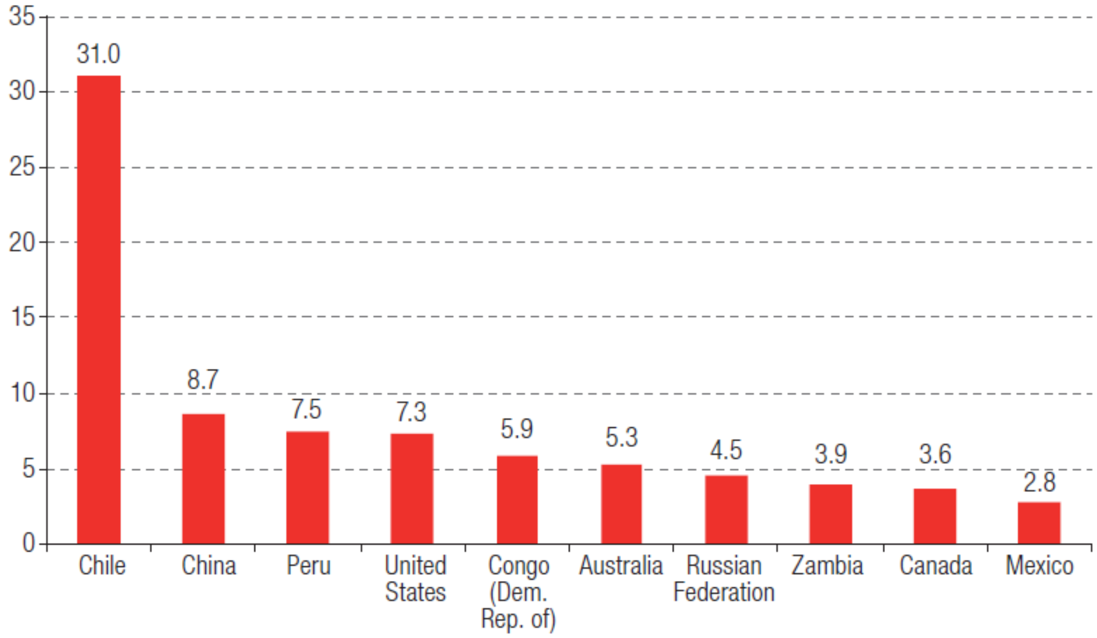
1.3.2 Mining rents in Chile compared to those of other copper-producing countries

In 2014, 31% of all copper produced in the world was mined in Chile, as shown in figure 1 which reports the global production shares of the 10 countries that extracted the largest amount of copper in that year.

Figure 1

Share of the largest copper-producing countries in global copper production, 2014

(Percentages)



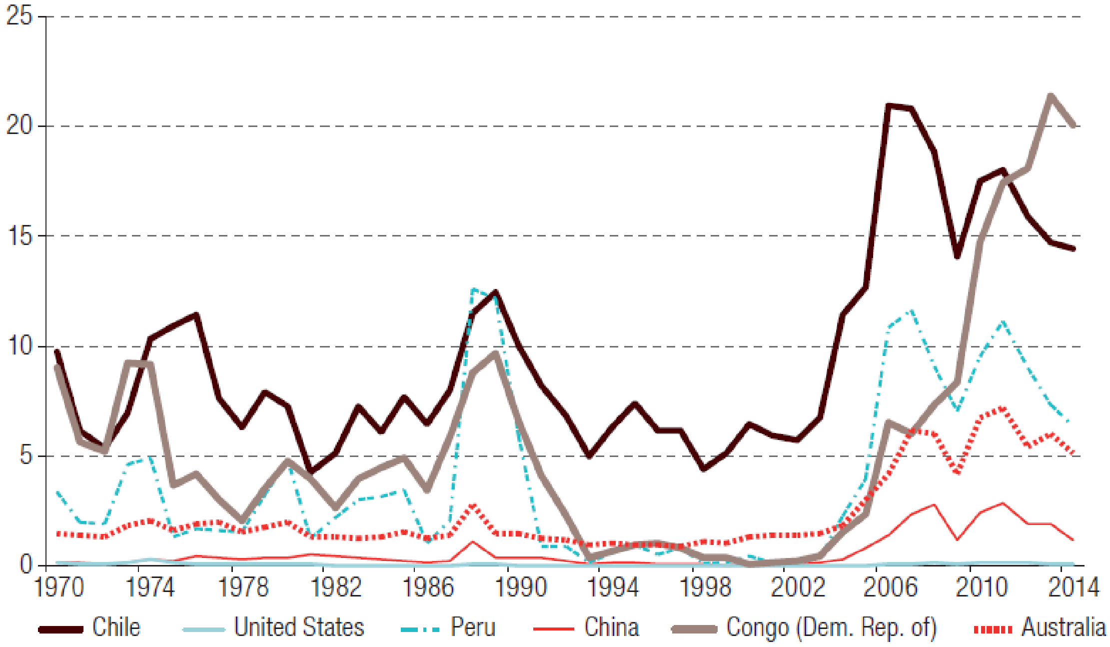
Source: Prepared based on World Bank, World Development Indicators, 2016.

Figure 2 displays mining rents from 1970 to 2014, as calculated by the World Bank (World Bank, 2016) in the six countries that produced the most copper in the latter year. Rents are expressed as a proportion of gross domestic product (GDP). This figure shows that, in Chile, mining revenues exceeded 5% of GDP nearly every year, even in periods when the price of copper was very low. This suggests that the generation of economic rents is not merely a cyclical phenomenon, typical of periods of prosperity in the copper market, but clearly a long-term issue.

Figure 2

Annual mining rent as a percentage of GDP in the six countries that produced the most copper in 2014, 1970-2014[a]

(Percentages)



Source: Prepared based on World Bank, World Development Indicators, 2016.

[a] GDP = gross domestic product.

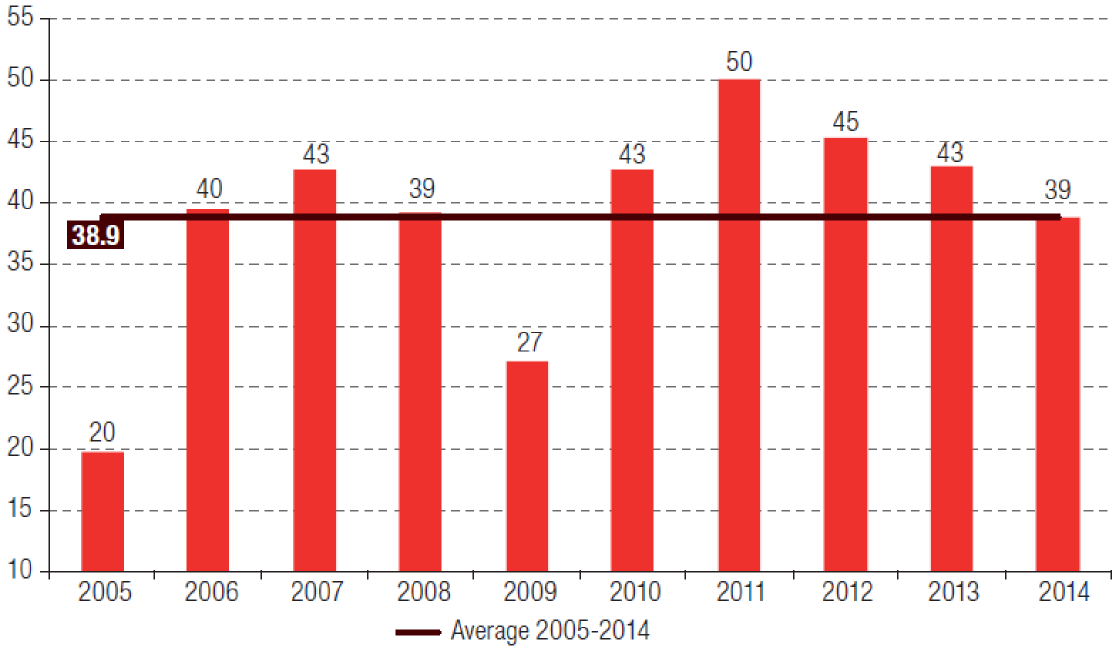
1.3.3 Mining rents in Chile as estimated by the World Bank

Figure 3 shows the value of mining rents in 2005-2014, as estimated by the World Bank for Chile (World Bank, 2016), totaling US$ 389 billion, with an annual average of US$ 38.9 billion, representing 17% of Chile’s GDP.

Figure 3

Chile: annual economic rent from mining, as estimated by the World Bank, 2005-2014

(Billions of dollars)[a]



Source: Prepared based on World Bank, World Development Indicators, 2016.

[a] At October 2016 prices.

1.4 METHODOLOGY FOR CALCULATING THE GMP-10 APPROPRIATED GRATUITOUS RENT

1.4.1 General considerations

Between 2005 and 2014, GMP-10 has accounted for an average of 57% of Chile's copper production; and when CODELCO is included, the figure rises to 88%. The remaining 12% is produced by smaller mines. Although there are deposits, such as Spence, El Tesoro and Esperanza, which have outputs similar to those of the GMP-10 firms, these are not yet officially listed in this group (COCHILCO, 2015). That is the first reason why these deposits have not been included in this study; the second reason is that two of them only started operating after 2005.

The aim is to estimate the appropriated GMP-10 gratuitous rent in an economically consistent way. This is done in four stages, based on the amounts of total mining rent reported by the World Bank:

(i) determination of WB mining rent (CODELCO + GMP-10)
(ii) calculation of WB GMP-10 mining rent
(iii) estimation of GMP-10 compensated rent
(iv) calculation of GMP-10 appropriated gratuitous rent

This section develops the methodology for the first three of these stages. The last stage merely involves deducting the taxes paid by GMP-10 to the State of Chile from the GMP-10 compensated rent obtained in stage 3.

1.4.2 Calculation methodology

The mining rent measured by the World Bank in relation to Chile (World Bank, 2016) corresponds to the total rent generated by the mining sector of the Chilean economy, for which a methodology has been established to obtain the WB GMP-10 mining rent and subsequently the GMP-10 compensated rent. The calculation methodology used is described in this section. A basic element of the methodology is that the value of mineral sales is measured based on the international prices of the metal rather than the sales reported by the firms, as has been done in other studies. This approach follows the method implemented by the World Bank (2011) and by Brandt, Schreyer and Zipperer (2013); and it has the advantage of being independent of company reports, which often understate sales in order to reduce taxes.

1.4.2.1 CODELCO plus GMP-10

The rent estimated by the World Bank in relation to CODELCO and GMP-10 is assumed equivalent to their share in Chile's total copper production each year. This method of obtaining the rent associated with the large-scale copper mining industry (public and private) is consistent and conservative. Brandt, Schreyer and Zipperer (2013) show that the mining rents associated with the large-scale copper mining industry account for 90% of the rent generated by all-natural capital recorded in Chile. Data from the World Bank (2016) show that in 2005-2014, 89% of the country's natural-resource rents came from mining. To obtain the rent from large-scale mining, the rent obtained from medium- and small-scale copper mining should be excluded from this total amount. Accordingly, based on the two studies mentioned above, the following methodological criterion has been defined: each year, the proportion of the mining rent reported by the World Bank, corresponding to the large-scale copper mining industry (both public and private) will be equivalent to the latter's share in total copper production in Chile. This is a conservative assumption, since rents obtained from large-scale mining tend to be higher than those of small and medium-sized mines, as a proportion of their production.

The mining rent calculated by the World Bank for GMP-10 ($R_{bm,Gmp10}$) and the State-owned CODELCO ($R_{bm,Cod}$) can be expressed as:

$$R_{bm,Gmp10} + R_{bm,Cod} = (1-B) \cdot R_{bm,Total} \qquad [1]$$

where,

B= the share of total World Bank mining rent that does not correspond to GMP-10 or to CODELCO,

$R_{bm,Total}$ = total World Bank mining rent.

1.4.2.2 WB GMP-10 mining rent

The same World Bank procedure (Brandt, Schreyer and Zipperer, 2013) can be used to express the WB GMP-10 mining rent in terms of the WB CODELCO rent, from equation [1], as follows:

$$R_{bm,Cod} = p \cdot q_{Cod} + S_{Cod} - c_{Cod} \cdot q_{Cod} - (r+\delta) \cdot K_{Cod} \qquad [2]$$

where,

p = market price of copper,

q_{Cod} = CODELCO production,

S_{Cod} = additional revenue from CODELCO by products,

c_{Cod} = total unit cost of CODELCO operations,[4]

r = normal rate of return to capital,

δ = capital depreciation rate,

K_{Cod} = CODELCO capital stock

Thus, it is possible to obtain the following expression for the World Bank GMP-10 mining rent.

$$R_{bm,Gmp10} = (1-B) \cdot R_{bm,Total} - R_{bm,Cod} \qquad [3]$$

1.4.2.3 GMP-10 compensated rent

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[4] This total operating cost does not correspond to the direct unit operating cost, c_1, referred to below, because corrections have been made to take account of copper sold in concentrate form. Annex A1 describes the methodology used to take account of the fact that CODELCO sold an average of 14% of its copper in unrefined state during the period.

The GMP-10 compensated rent ($R_{C,Gmp10}$) is the World Bank rent corresponding to GMP-10, with two additional corrections: exploration risk premium (η) and compensation for the volatility of the copper price (ϕ).

$$R_{C,Gmp10} = R_{bm,Gmp10} - \eta - \phi \qquad [4]$$

The exploration risk premium for GMP-10 (η) is defined since López and Figueroa (2014). This premium corresponds to the increase in exploration expenditure, according to the probability of success in the exploration tasks, and the rate of return to capital, less the declared exploration expenditure:

$$\eta = E_{Gmp10}\left(\frac{r}{1-\theta} - 1\right) \qquad [5]$$

where,

E_{Gmp10} = GMP-10 exploration expenditure

$(1-\theta)$ = probability of success in GMP-10 exploration tasks

The compensation for volatility in the copper price (ϕ) is defined from the difference between the market price and the copper trend price.

$$\phi = (p - p_T) \cdot q_{Gmp10} \qquad [6]$$

where,

p_T = trend price of copper

q_{Gmp10} = GMP-10 copper production

Thus, [4], [5] and [6] give equation [7], in which the GMP-10 compensated rent is expressed in terms of the WB GMP-10 mining rent and additional corrections.

$$R_{C,Gmp10} = R_{bm,Gmp10} - E_{Gmp10}\left(\frac{r}{1-\theta} - 1\right) - (p - p_T) \cdot q_{Gmp10} \qquad [7]$$

1.4.3 Data for the calculation

1.4.3.1 <u>General information</u>

To make the required estimates, annual data are needed on the international price of copper and on the total costs and production of GMP-10 and CODELCO. Costs and production levels (copper and by-products) have been obtained from the Chilean Copper Commission (COCHILCO, 2015). The average cost per unit among GMP-10 is US$ 1.60 per pound and that of CODELCO is US$ 1.29 per pound (FCH/Alta Ley/CORFO, 2015). This indicates that the State firm is more efficient, so it will generate higher rents. To calculate the annual economic rent of GMP-10, these production costs may be biased towards understatement, since studies by international consultants indicate that CODELCO's production cost is higher than that GMP-10 (Mining Press, 2013). On the other hand, the average annual production of GMP-10 was 3,070,000 tons of refined copper per year, while that of CODELCO was 1,756,000. The capital stock, of both CODELCO and GMP-10, has been calculated on the basis of the perpetual inventory system formula.

It is also assumed that the normal rate of return on capital required by investors in Chile is 10%. This could also understate the annual GMP-10 rent, however, since it is higher than the normal rate that Brandt, Schreyer and Zipperer (2013) estimate and use in relation to Chile. In fact, some major mining projects use 8% rates of return to gauge the feasibility of investment projects in Chile. An example is the Alto Maipo Hydroelectric Project, whose shareholders expected an 8% return on their investment of over US$ 2 billion.[5] The shareholders were AES Gener and Antofagasta Minerals, the latter being the owner of the Los Pelambres mining company, which is one of the GMP-10 firms.

To calculate untaxed rent, the tax base permitted by the mining legislation is used, including deductions for all variable costs plus financial costs. In addition, capital assets can be depreciated at an accelerated rate, which can be as little as three years in the case of machinery and equipment.

1.4.3.2 Return on exploration expenditure

To correct for the return on capital that is required in exploration activities, the WB GMP-10 mining rent must be reduced by the exploration expenses that private mining companies are forced to incur to sustain their activity over time. This expense is considered ex-ante, in other words the expected returns must include the probability of succeeding or failing in the exploration activities, in the planning stage. As noted by López and Figueroa (2014), companies should be allowed to legitimately appropriate part of the profits or mining rent, in order to undertake mining exploration activities. The portion in question must be calculated on the basis of the expected profitability of the exploration performed, including the probability of success of the activity.

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[5] This information was obtained recently from the Chilean newspaper *El Mercurio* (2017), in the context of the near-final decision not to build the hydroelectric power station and the "legitimate return" claimed by its shareholders.

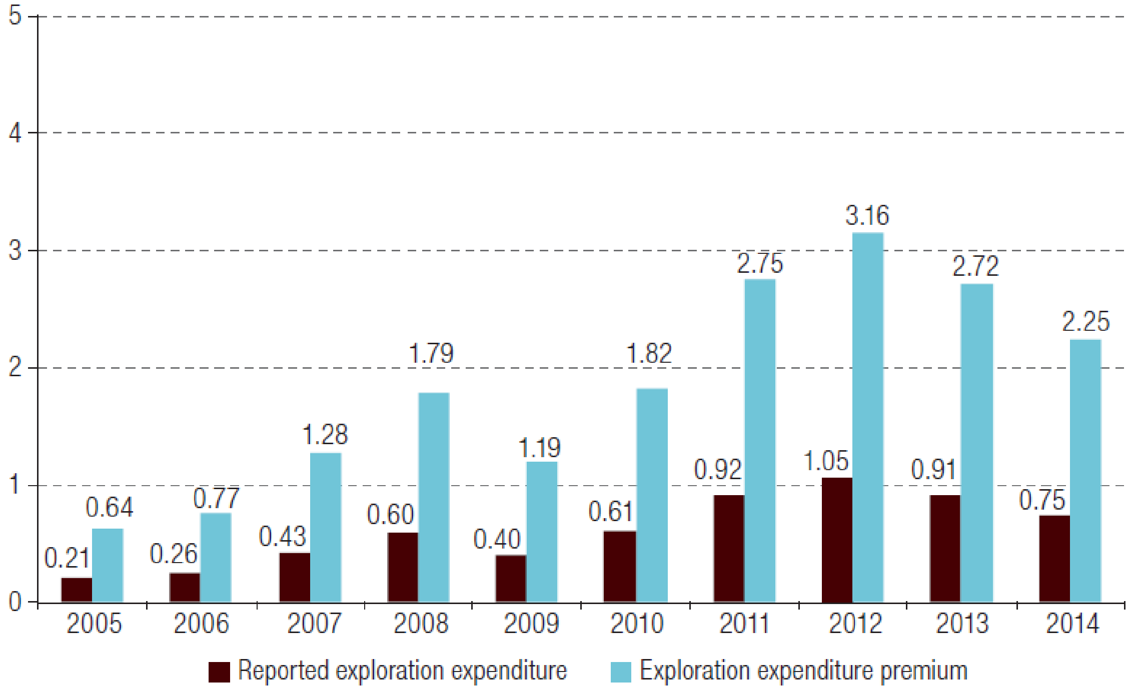
Bartrop and Guj (2009) define a typology of mining exploration activities. To avoid the economic rent being overestimated; and, following these two authors, Chile's GMP-10 has been typified as an industry that has carried out and permanently undertakes exploration work in search of large deposits in unexplored areas. It is also considered that exploration faces a high level of risk because there is little previous work, the geology is poorly known, the explorable areas are remote, and large-scale exploration programs are required. The lowest value of the probability of success is 2.5%, which could be considered excessively low for Chile, given current knowledge of the geology of certain areas and the amount of copper thought to exist in the subsoil of certain areas of the country, for example. Nonetheless, this assumption makes it possible to maintain conceptual consistency and avoid the risk of overestimation when calculating the net GMP-10 rent. In view of the above, the premium, ex ante, turns exploration expenditure into an investment needed to sustain the mining activity.

Figure 4 reports the annual exploration expenditure of all private mining firms in Chile, which here are assumed to be equivalent to GMP-10, according to the data provided by COCHILCO (2015). It also displays the premium for exploration expenditure, which in the case of this study corresponds to three times the declared expenditure, given a 10% normal rate of return and a 2.5% probability of success.

Figure 4

Chile: annual GMP-10 exploration expenditure and the compensatory return required by this activity, 2005-2014

(Billions of dollars)[a]



Source: Prepared based on COCHILCO (Chilean Copper Commission), Anuario de estadísticas del cobre y otros minerales, 1996-2015, Santiago, 2015.

[a] At October 2016 prices.

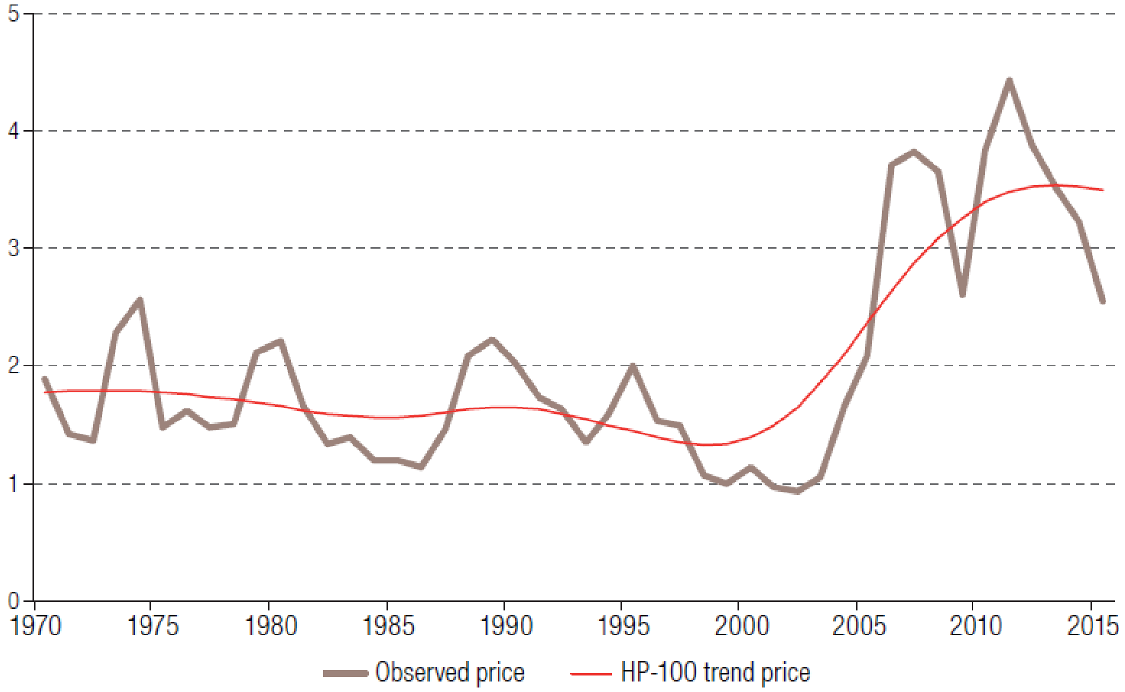
This way of measuring exploration expenses has the potential for overestimation, especially since the data used to calculate them comes from what the firms themselves declare; and the firms have incentives to inflate them artificially. Unfortunately, this is the only available source of data on exploration expenses.

1.4.3.3 Return for copper price volatility

The price of copper has fluctuated widely over the last 45 years, including a strong upswing at the start of the twenty-first century. This section uses a 45-year series of copper prices spanning 1970-2014, together with time series tools, to determine a long-term or trend price for copper in 2005-2014. The aim is to recalculate the GMP-10 mining rent, using a long-term copper price series, from which the cyclical component has been removed. In other words, the copper prices observed each year are turned into a smoothed long-term trend series, from which short-term fluctuations have been eliminated.

There are several tools available to decompose trend cycles, of which the most basic is linear regression. The time-series literature provides sophisticated statistical methodologies that have computer packages that can be applied to observed time series. The most widely used and validated methodology is probably the HP filter (Hodrick and Prescott, 1997). The present study uses the HP-100 filter, which is recommended for the annual series, to extract a trend price from the observed series. The HP-100 filter makes it possible to decompose the observed price series into a cyclical component and a trend component. Thus, the trend series of the price can be interpreted as the time sequence of the long-term price. Figure 5 shows the evolution of the observed copper price with a solid black line and the long-term trend price with a dashed grey line.

Figure 5
International observed copper price and long-term price obtained using the Hodrick and Prescott filter, 1970-2015
(Dollars per pound)[a]



Source: Own elaboration.

[a] At October 2016 prices.

The WB GMP-10 mining rent is recalculated on the basis of the trend copper price in 2005-2014. The costs —including opportunity costs— are exactly the same as before; the only variable that changes is the copper price.[6]

1.5 RESULTS

1.5.1 GMP-10 compensated rent

This section presents the GMP-10 compensated rent, which is estimated by subtracting, from the WB GMP-10 mining rent, both the premium for the risk

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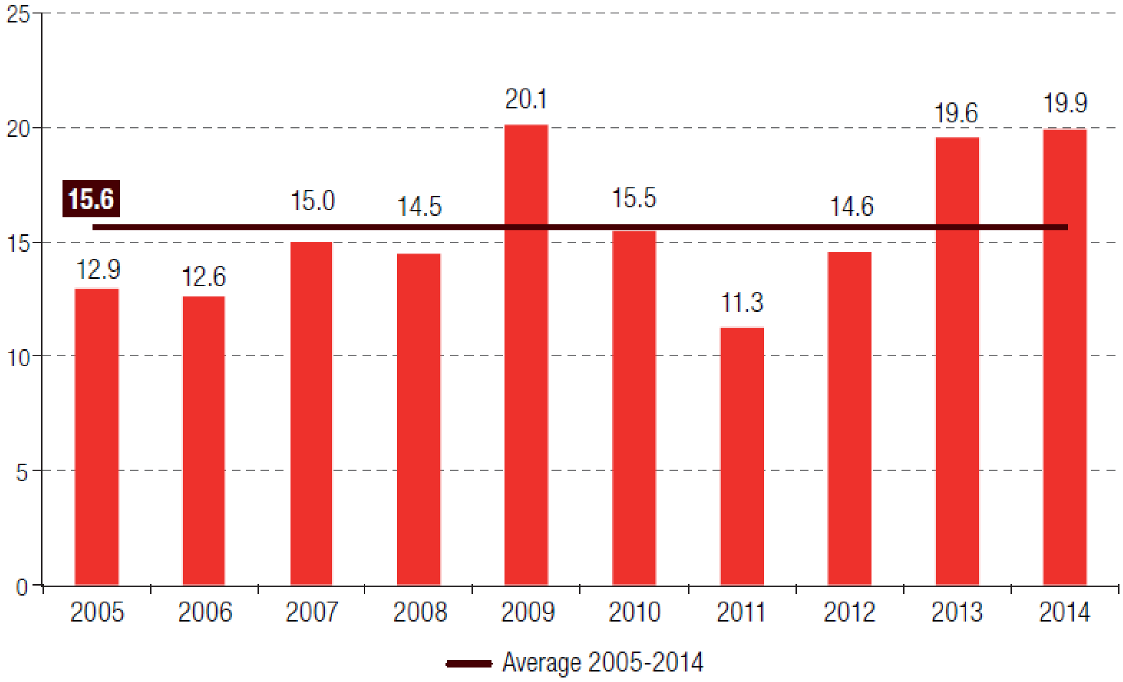
[6] The mining companies' net profitability for 2017 was calculated using the methodology described in this study based on trend copper prices. The trend price for 2017 turns out to be US$ 2.82 per pound of copper, slightly higher than the price reported by the Mining Council (US$ 2.70 per pound) but very similar to that predicted by Goldman Sachs (US$ 2.85 per pound). This projection yields an average net pre-tax rate return on capital of nearly 40% in this year for the 10 large private mining companies —equivalent to about US$ 9 billion.

involved in mining exploration activities and the compensation required for the volatility of the copper price. Figure 6 displays the GMP-10 compensated rent estimated in this way. The adjustment reduces the GPM-10 rent by US$ 29.7 billion in 2005-2014, simply because the prices observed during this period are above trend. In addition, the correction for the deduction of the exploration risk premium reduces the estimated GMP-10 rent by another US$ 18.6 billion in the period considered. Thus, when incorporating both corrections, the estimate of GMP-10 compensated rent is US$ 48.3 billion lower than that of the World Bank in the period as a whole. In other words, the WB GPM-10 mining rent in the period is reduced from US$ 204 billion to about US$ 156 billion. This means that the average annual rent for 2005-2014, corrected after deducting both components, amounts to US$ 15.6 billion, which corresponds to 6.9% of Chile's GDP. This amount is US$ 4.8 billion less than the WB GMP-10 mining rent.

Figure 6
Chile: annual GMP-10 compensated rent, 2005-2014
(Billions of dollars)[a]



Source: Own elaboration.

[a] At October 2016 prices.

1.5.2 GMP-10 appropriated gratuitous rent

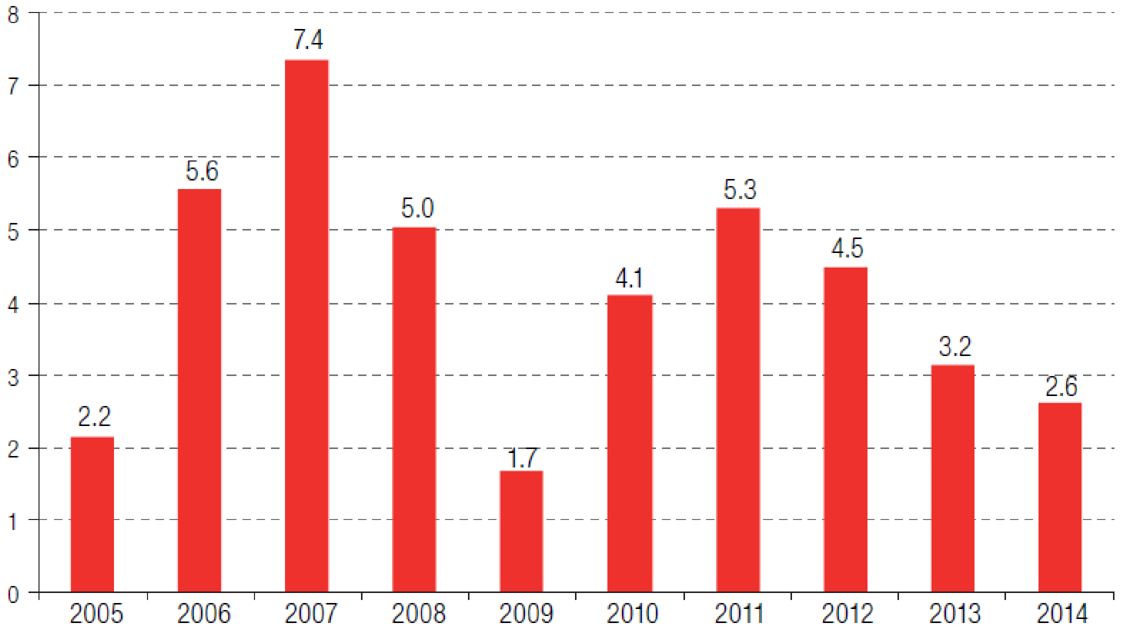
Section 1.2.4 defined the GMP-10 appropriated gratuitous rent as GMP-10 compensated rent minus the taxes paid by the large-scale private mining sector in each year of the period studied. These taxes, as defined in the Chilean tax code, are of three types: (i) first category tax, which is levied on the firms' taxable profits; (ii) additional tax, which taxes Chilean-source earnings by natural or legal persons without domicile or residence in Chile; and (iii) the specific mining duty

(IEM), which taxes mining activity profits obtained by a mine operator. Figure 7 shows the tax revenue received from GMP-10 by the Chilean Treasury (DIPRES, 2015), which totaled US$ 41.6 billion in 2005-2014.

Figure 7

Chile: tax revenue obtained from GMP-10 by the Chilean Treasury, 2005-2014

(Billions of dollars)[a]



Source: Prepared by the authors, based on Budgetary Affairs Bureau, "Evolución, administración e impacto fiscal de los ingresos del cobre en Chile", Santiago, Ministry of Finance, 2015 [online] http://www.dipres.gob.cl/572/articles-133158_doc_pdf.pdf.

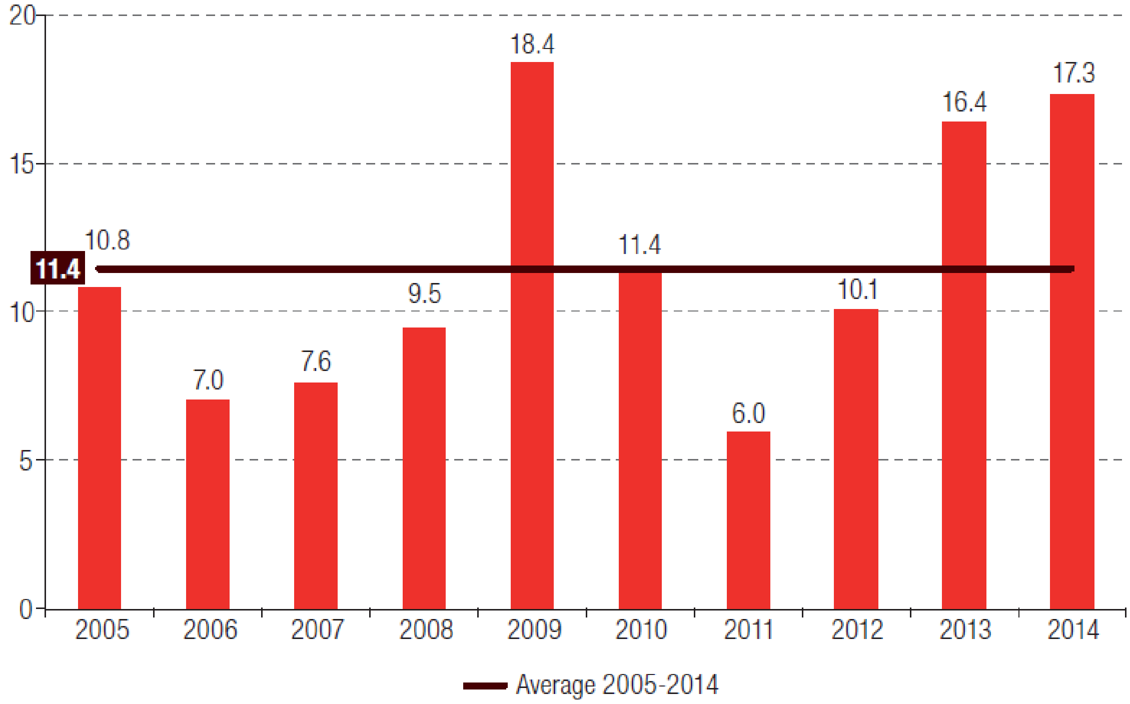
[a] At October 2016 prices.

Subtracting taxes paid from the GMP-10 compensated rent gives the GMP-10 appropriated gratuitous rent, amounting to US$ 114 billion in the study period. This amount represents an average of US$ 11.400 billion per year, equivalent to 5.1% of GDP and 23.3% of public spending during the period. Figure 8 shows the GMP-10 appropriated gratuitous rent, in dollars at October 2016 prices (annex A2 contains figures displaying this rent relative to GDP and as a percentage of public expenditure).

Figure 8

Chile: GMP-10 appropriated gratuitous rent per year, 2005-2014

(Billions of dollars)[a]



Source: Own elaboration.

[a] At October 2016 prices.

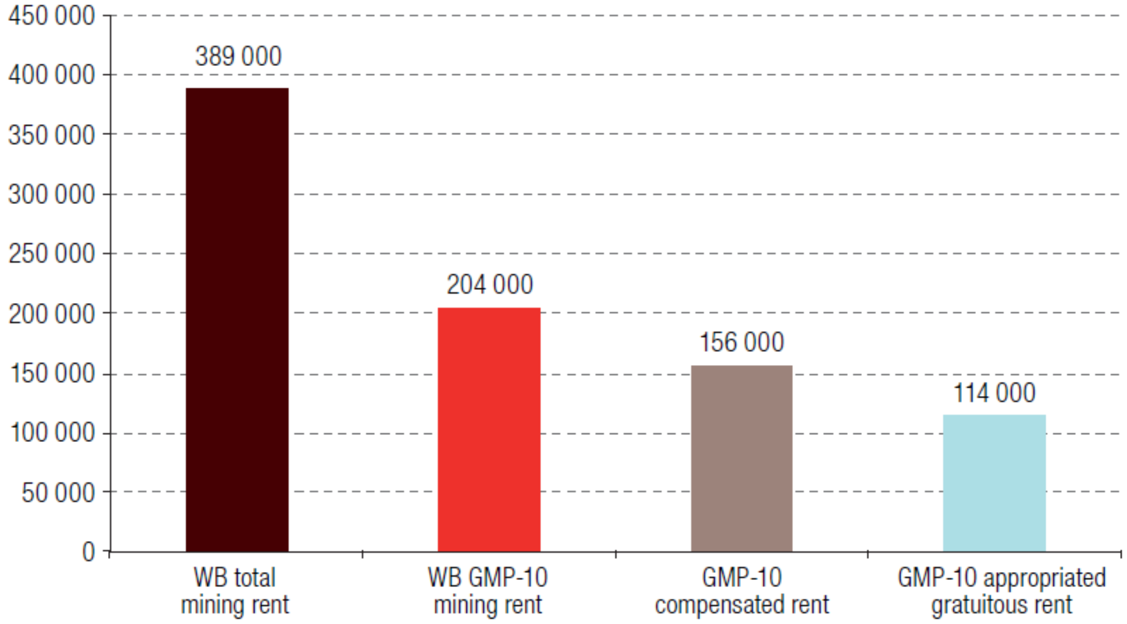
1.5.3 Summary of results

Figure 9 displays the total amounts of each of the four economic rents defined in this paper, in the period spanning 2005 to 2014. The amounts are expressed in millions of dollars at October 2016 prices (the time trend is shown in annex A3).

Figure 9

Chile: mining rents by type, 2005-2014

(Millions of dollars)[a]



Source: Own elaboration.

[a] At October 2016 prices.

1.5.4 Sensitivity analysis

As noted above, this study assumes a 2.5% probability of success in exploration, the lowest rate reported in the literature. It is also assumed that knowledge of the geology of the territory is non-existent. Chile is considered a mining location, which means that there is already a considerable knowledge of the geological characteristics of the country (SERNAGEOMIN, 2013). For this reason, recent studies have recommended a probability of 10% to 20%, instead of 2.5% (Bartrop and Guj, 2009).

Moreover, based on a study by the Chilean Production Development Corporation (CORFO) (FCH/Alta Ley/CORFO, 2015), the direct unit costs of GMP-10 are assumed to be higher than those of CODELCO, averaging about US$ 1.60 per pound in the period considered. However, the study by the Mining Benchmark international consultancy (Mining Press, 2013) indicates a unit cost of just US$ 1.21 per pound in the period. This latter estimate is perhaps more credible than that of CORFO, considering the consensus of analysts and the fact that CODELCO's deposits are generally older and of lower grade than private-sector ones.

Although this study has focused on calculating a conservative and lower-bound estimate of economic rent, a sensitivity analysis was performed with more reasonable assumptions for the probability of exploration success and unit costs, based on the studies mentioned above. Table 1 reports GMP-10 appropriated gratuitous rents under different assumptions. The appropriated rent assuming a

10% probability of success and the unit cost indicated by Mining Benchmark amounts to US$ 163 billion, more than 30% above the base estimate of the present study. These simulations provide a quantitative idea of how conservative that estimation is.

Table 1
Chile: GMP-10 appropriated gratuitous rent in six scenarios, 2005-2014
(*Billions of dollars*)

Probability of exploration success *(percentages)*	Cost (CORFO) *(US$ 1.60 per pound)*	Cost (Benchmark Mining) *(US$ 1.21 per pound)*
2.5	114	145
5.0	126	157
10.0	132	163

Source: Own elaboration.

[a] At October 2016 prices.

1.5.5 Selected comparisons

This study has estimated that GMP-10 appropriated gratuitous rent totaling US$ 114 billion in 2005-2014, representing an annual average flow equivalent to 5.1% of the country's GDP. The following examples put this in context.

The resources thus gifted averaged US$ 11.4 billion per year between 2005 and 2014. It has been estimated that free education in the country, understood as full State funding at all levels of education, requires additional financing equivalent to almost US$ 5 billion per year. It is also estimated that the recently enacted tax reform will raise US$ 6 billion per year at most.

In other words, the wealth transferred annually to these large transnational companies in 2005- 2014, could have financed free complete education, and the remaining US$ 6.4 billion could have been used to definitively upgrade the health-care and pensions systems. All of this could have been done without the need to design and implement a complex tax reform with uncertain effects on investment and economic efficiency.

Lastly, if Chile had saved these US$ 114 billion and invested them as sovereign wealth funds, they would have generated a permanent annual income flow of over US$ 7 billion, assuming a conservative investment pattern. In other words, the country would have a stable annual flow of income each year, irrespective of the fluctuations in the price of copper, equivalent to nearly all public health expenditure, which means that the country's public health services could be doubled permanently.

Lastly, Chile holds an annual telethon —a national solidarity activity to finance the care and rehabilitation of people with chronic or temporary disabilities, which raised roughly US$ 47 million in its 2016 edition. The amount ceded gratuitously to the large-scale mining industry in 2005-2014, could finance about 2,420 telethons of that year.

1.6 FINAL THOUGHTS

Perhaps the most relevant question that emerges from the estimates made here is: who gratuitously cedes these voluminous resources to these firms? The answer must clearly be sought among those in Chile's executive and legislative branches who allow the laws that make this absurd gift possible to persist. The political authorities of today's developed countries, such as Canada, the United States and Norway, changed their laws long ago to make a very large proportion of mining rents and natural resources taxable, which enabled them to stop squandering resources that belonged to all of their citizens and lay the foundations for strengthening their economies and social rights in their countries (Taylor and others, 2004; Guj, 2012; Figueroa, López and Gutiérrez, 2013; Bowie, 2016).

As far as the authors are aware, the fact that Chile is unable to recover these huge rents for all Chileans is also largely due to citizens' relative ignorance of the magnitude of the losses caused by unwillingness of the political and economic authorities to develop the necessary mechanisms to capture these rents. This study is intended to help correct this disinformation.

This article closes by recalling the comment by Minister of Finance, Rodrigo Valdés, quoted at the outset; but the question to be asked of "all Chileans" needs to be broader than what the Minister proposes. Instead of "how to use an additional peso" the question is why Chile does not keep the billions of dollars in rents gifted to private mining companies each year, which would finance many bridges, many schools, the wages of many thousands of public sector workers and pensions for many thousands of pensioners across the country. This should also be asked of the Presidents of the Republic and the parliamentarians of recent decades. Unless the people demand an answer, this huge amount of national wealth will continue to be squandered; and Chileans will continue to ignore President Balmaceda's clear warning, also quoted at the start of this article, of the risk of letting "... this vast and wealthy region become nothing more than a foreign factory ..." (Balmaceda, 1889).

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28.

1.8 ANNEX A1

Discounts in respect of copper concentrate sales

Between 2005 and 2014, CODELCO sold an average of 14% of its copper in concentrate form. When calculating sales revenue at market prices, the effect of this should be corrected for, as described below (COCHILCO, 2015):

(i) The amount of copper contained in the concentrate must be reduced to take account of two effects: humidity (10% of the mass), and the cost of smelting and refining (15% of the mass).

(ii) In addition, three costs must be deducted per ton of copper: US$ 140 for *maquila*, US$ 10 for the scale effect, and up to US$ 400 for the losses associated with other minerals contained in the concentrate.

Given the above, the following are defined:

q_b = gross amount of copper in the concentrate;

q_e = effective amount copper in the concentrate, that is, after applying the two corrections described in point (i) above;

q_p = loss or difference between the gross amount and the effective amount of copper, namely

$q_p = q_b - q_e$; and

z = sum of the additional costs specified in point (ii) above, per effective ton of copper in the concentrate.

Thus, the rent associated with CODELCO can be expressed as a function of c_1, the direct unit cost. This form is equivalent to that presented in equation [2] of this article. Details of the rent associated with CODELCO are presented, having corrected for copper in the form of concentrate (the other variables are those defined in section 1.4.2).

$$R_{bm,Cod} = p \cdot (q_{Cod} - q_p) + S_{Cod} - c_1 \cdot q_{Cod} - z \cdot q_e (r + \delta) \cdot K_{Cod}$$

1.9 ANNEX A2

1.9.1 GMP-10 appropriated gratuitous rent

Figure A2.1

Chile: GMP-10 appropriated gratuitous rent per year, as a proportion of GDP, 2005-2014

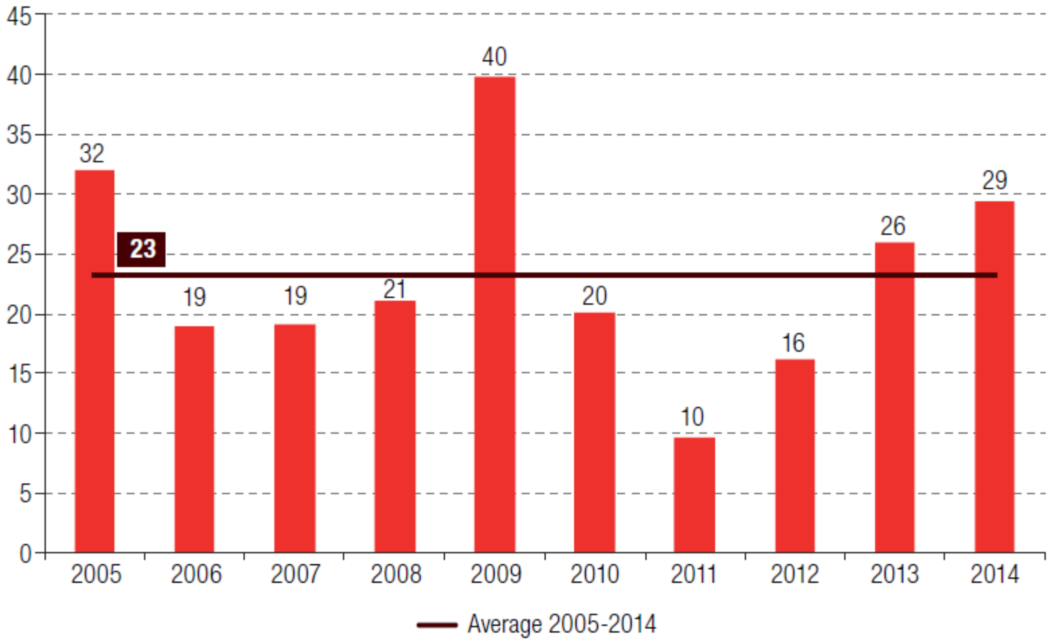
(Percentages)

Source: Own elaboration.

Figure A2.2

Chile: GMP-10 appropriated gratuitous rent per year, as a percentage of public expenditure, 2005-2014

(Percentages)



Source: Own elaboration.

1.1 ANNEX A3

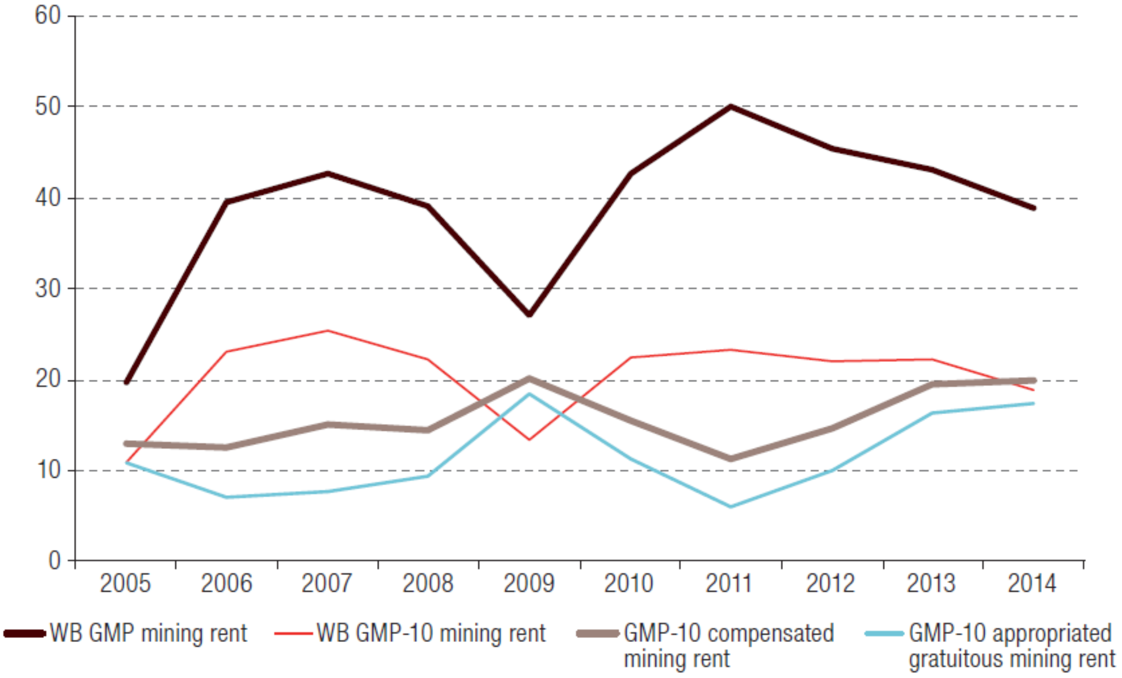
1.9.2 Time path of four types of rent

Figure 12 shows the annual estimates obtained for the four types of economic rent in the period spanning 2005 to 2014, measured in billions of dollars at October 2016 prices. The continuous grey line closest to the horizontal axis represents the GMP-10 appropriated gratuitous rent. This graph demonstrates that the estimation of this rent constitutes a "lower bound" estimate.

Figure A3.1

Chile: comparison of the four types of mining rent estimated in this study, 2005-2014

(Billions of dollars)[a]



Source: Own elaboration.

[a] At October 2016 prices.

2 **ESSAY II**. REDUCING GHG GLOBAL EMISSIONS FROM COPPER REFINING AND SEA SHIPPING OF CHILE'S MINING EXPORTS: A WORLD WIN-WIN POLICY[7]

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[7] Sturla Zerene, G.; Figueroa B., E. and Sturla, M. Reducing GHG global emissions from copper refining and sea shipping of Chile's mining exports: A world win-win Policy. *Jornal of Resources Policy*. Vol. 65,. March 2020. RUL: https://www.sciencedirect.com/science/article/pii/S030142071830151X

Abstract

Chile is the largest copper producing country of the world; and almost 50% of the copper it exports to the rest of the world is exported as copper concentrates to be smelted and refined abroad. However, 70% of the weight of these exported copper concentrates is gangue (valueless and undesirable material associated to the copper content in these exported concentrates). In this paper analyze and quantify the contribution Chile could make to the ongoing world efforts to reduce climate change and global warming, if it adopts a trading policy eliminating its exports of copper concentrates and replacing them with the greater value added exports of the refined copper obtained from smelting and refining those concentrates in Chile. This policy would allow a significant reduction of greenhouse gases (GHG) emitted every year to the global atmosphere. This reduction would occur through two channels: 1. avoiding the combustion of more than 600,000 tons of diesel oil currently used to transport by sea almost 6,600,000 tons of the gangue incorporated in Chile´s copper concentrate exports; and, 2. using Chile´s cleaner technology for smelting and refining copper concentrates instead of the dirtier technologies of the countries currently importing, smelting and refining the Chilean copper concentrates. For the first time, using data for 2014, we estimate the total net reduction in GHG emissions to the global atmosphere that the proposed trade policy would imply. We calculate the distance of the nautical routes used for the 919 shipments of concentrates exported by Chile that year; and we perform sensitivity analysis for 4 scenarios, employing two alternative values for two key parameters. Additionally, we compare the GHG emission performances of the copper smelting and refining metallurgic technologies employed in Chile and in every one of the 22 countries that import and smelt and refine Chilean concentrates. Our estimates for the 2 most extreme scenarios indicate that, if instead of exporting copper concentrates in 2014, Chile would had exported only refined copper, it would had contributed with a total net reduction of GHG emissions emitted to the global atmosphere of 2,227,047 and 2,799,279 ton CO2-eq tons that year, which are equivalent to approximately 5.6% of the total amount of GHG emissions that would had made Chile fully carbon neutral that year. This is a significant contribution regarding Chile´s commitment to the Paris Agreement as well as in terms of the required world efforts to reducing GHG emissions from sea shipping.

Keywords: Reduction of Fuel Burning, Global Carbon Emissions, Copper Mining, Maritime Transport, Climate Change

JEL Classification: Q32, Q42, Q56,

2.1 INTRODUCCIÓN

Chile is the largest copper producing country; in the last 10 years, it produced 30% of all the copper produced in the world (Cochilco, 2018). A significant portion of the copper exported from Chile is not refined copper. This portion is exported in the form of copper concentrate, an intermediate material resulting from an initial ore mine extraction, and processed afterwards through crushing, flotation, thickening and filtering, and which contains around 30% of copper, plus other minerals and, mostly, gangue (valueless and undesirable material). As an intermediate good, copper concentrate is destined to be processed later on through a set of metallurgic processes required to obtain a product with more than 99% of copper[8] (Codelco, 2015).

In 2014, Chile exported the equivalent to 5.8 million tons of refined copper, and almost 2.8 million of them, or 49%, were exported as copper concentrate and the other 3.0 million as refined copper[9]. Table 1 shows the shares of refined copper and copper concentrates in Chile´s total copper exports for the last decade, and for 2014 in particular (the most recent year for which the required data for our key estimations is available). In the early years of the last decade, the participation of copper concentrates in total copper exports was 41%, and it rose up to 47% by 2015.

Table 1
Chile: Shares of exported refined copper and copper concentrates in total exported copper; 2014 and 2006-2015 average.

TYPE OF COPPER PRODUCT	**SHARE OF TOTAL EXPORTED REFINED COPPER EQUIVALENT**	
	2014	**2006-2015 AVERAGE**
	(%)	
Refined copper	51	60
Copper concentrate	49	40

Source: Own estimations using information from Cochilco (2016)

As it is shown in Table 1, during the 2006-20015 period, 40% of Chile´s copper exports in terms of its refined copper equivalent were exported in the form of copper concentrates. However, in the last lustrum this share has increased and

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[8] These processes are basically transportation, smelting and thermal and electrochemical processes to get the desired final product: refined copper. In this work, every time copper refining is mentioned, this chain of processes is being referred.

[9] For the purposes of this work, refining involves collecting cathodes made of 99.9 % copper from electrochemical processes and the so-called blister copper (i.e. smelted copper that undergoes fire-refining in a furnace) which is made of 99.4% copper.

currently is more than 50%. Copper concentrate contains between 20% and 40% copper (Central Bank of Chile, 2015), with an average of 30% copper in 2014. The millions of tons of copper metal exported in the form of copper concentrate every year, 9,385,444 tons in 2014**,** are shipped from Chile to the importing countries accompanied by around 2.4 times its weight of gangue (mostly valueless materials and a small percentage of other ores which is not relevant to this study). This overload weight would not be transported if copper was exported in the form of refined copper instead of copper concentrates.

In 2014, 919 shipments of copper concentrate were sent from 13 Chilean ports to 22 foreign countries (Central Bank of Chile, 2015). The total direct nautical distance traveled by the freight-ships transporting these shipments was over 15.5 million kilometers (around 9.6 million miles), which is equivalent to 40.3 times the distance between the Earth and the Moon. Moreover, during the entire last decade, the ships that carried those millions of tons of gangue over such huge distances burned millions of barrels of diesel oil every year. As a result, millions of tons of greenhouse gases (GHG) were produced and released into the atmosphere and, according to IPCC (2014), they contributed to the ongoing climate change and global warming.

In fact, there is a scientific consensus on the impact that the GHG concentrations in the atmosphere cause on global physical processes and their implications on rising temperature and changing other climate variables (Levitus 2009; IPCC, 2014). The IPCC has reported that, with 95% confidence, the increase of carbon emissions resulting from human activities worldwide has had, and will continue to have, harmful consequences to the planet; including: sea level rise, more frequent and severe natural disasters (mega droughts, floods, wildfires) and reduced water availability for human consumption and relevant economic activities (IPCC, 2014).

Several scientific studies have warned that global warming of more than 1 °C, relative to 2000, will constitute "dangerous" climate change as judged from likely effects on sea level and extermination of species (Hansen et al., 2006). Regardless of these warnings, in 2009, the OECD had already projected that without new policy actions world GHG emissions would increase by about 70% by 2050 and continue to grow thereafter. This could lead to a rise in world temperatures of 4 °C above preindustrial levels, and possibly 6 °C, by 2100 (OECD, 2009). This would have large implications for the planet; it would cause a significant destruction of the habitats of plants and animals and yield reductions of important food crops, and large numbers of people will be exposed to severe droughts and floods (Hansen et al., 2012, 2010; Schmidt et al., 2014; IPCC, 2007).

Moreover, the most recent IPCC studies have warned that estimated anthropogenic global warming is currently increasing at 0.2 °C per decade due to past and ongoing emissions; that, warming greater than the global annual average is being experienced in many land regions and seasons, including two to three times higher in the Arctic; and that, warming is generally higher over land than over the ocean (IPCC, 2018). Just in September 2019, IPCC (2019) reported that it is virtually certain that the global ocean has warmed unabated since 1970 and that, with high confidence, it has taken up more than 90% of the excess heat in the climate system. This reports also warns that, since 1993, the rate of ocean warming has likely more than doubled, and marine heatwaves have very likely doubled in frequency since 1982 and, with very high confidence, they are increasing in intensity. Additionally, with almost certainty, the ocean has undergone increasing surface acidification, as result of absorbing more CO2. These studies had indicated also that, with high confidence, climate-related risks for natural and human systems are higher for global warming of 1.5°C than at present, but lower than at 2°C. Also that, these risks depend on the magnitude and rate of warming, geographic location, levels of development and vulnerability, and on the choices and implementation of adaptation and mitigation options (IPCC, 2018). The best scientific projections currently available indicate, with medium confidence, that by 2100, global mean sea level rise will be around 0.1 meter lower with global warming of 1.5°C compared to 2°C, and that, with high confidence, sea level will continue to rise well beyond 2100, and the magnitude and rate of this rise depend on future emission pathways. IPCC (2019) informs that a slower rate of sea level rise enables greater opportunities for adaptation in the human and ecological systems of small islands, low-lying coastal areas and deltas.

All this evidence is indicating that reducing GHG emissions and its concentrations in the planet's atmosphere is an urgent challenge that must be met, which implies that to achieve the Paris climate objectives of limiting the increase of global mean temperature to well below 2°C requires today, among other measures, drastic changes in energy systems (van Vuuren et al., 2017), global maritime shipping (Broder and Van Dike, 2017; Rahim et al. 2016) and aviation transport (Bows-Larkin, 2015). In fact, according to IPCC (2019), enabling climate resilience and sustainable development depends critically on urgent and ambitious emissions reductions, as well as on intensifying cooperation and coordination among governments. Emphasis is given to prevent and reduce emissions, in which Chile can and must take a specific responsibility (OECD, 2013). In this context, our estimates in this work are relevant, as they quantify a significant source of GHG emissions from Chile´s mining sector being emitted to the global atmosphere that may be eliminated. Refining copper in Chile is a contribution that the country is able and could do for the sake of the planet. In addition, as it is argued below, in the future, this may enable Chile to fulfill its international commitments to tackle global warming.

Here we do not analyze the reasons why not all copper concentrates are refined in Chile; but several authors agree in that there are no technical or economic reasons explaining this (Correa, 2016; Dulanto, 1999)). Moreover, prior to the last boom in copper prices (2004-2016), other authors were emphatic in pointing out that all copper exported from Chile must be domestically refined as a matter of a wise economic development policy (Dulanto, 1999; Meller, 2000). It seems that there are no arguments indicating that it would be technically unfeasible or economically inconvenient or inefficient to refine domestically the copper concentrates that Chile is currently exporting.

The first of the two main goals of this work is to estimate the avoidable quantities of fuel oil burned in transporting by sea the gangue contained in the copper concentrates exported from Chile every year. The other main goal of this study is to estimate how much more, or how much less, environmentally efficient is to smelt and refine the copper concentrates in Chile; in terms of how many more, or how many less, tons of GHG are emitted for smelting and refining 1 ton of copper concentrate in Chile, than in the more than 20 importing countries to which these concentrates are exported currently. The key factor to calculate this is the relative efficiency of the metallurgic smelting and refining technologies existing and used in the Chilean metallurgic industry compared with the average efficiency existing and used in the metallurgic industries of those other countries.

There is no additional foreseeable effects in the atmosphere if copper were to be refined in one country only or if this was done in a non-concentrated form (IPCC, 2014). In terms of potential local effects, Chile's long and diverse geography allows to locate one or more copper refining plants without effects on the population's health and eco-systemic services (ECLAC, 2009). The latter, plus the fact that a large part of copper mining and refining in Chile is located in extent desert areas with few population and without very vulnerable ecosystems nearby, indicated that most probably, the net effect of refining copper in Chile instead of in the countries that currently import Chilean copper concentrates will be a reduction in total CO2 ton-eq of GHG emissions. This is in fact corroborated by our estimations reported in the result sections below.

These results imply that a policy of refining copper concentrates domestically instead of exporting them could help Chile to achieve its international commitments to reducing GHG emissions. These commitments refer to reducing CO2 emissions per unit of gross domestic product (GDP) produced in the economy[10]. By 2013, emissions per value added in Chile were 0.92 tons of CO2-eq per million Chilean Pesos of GDP. This amount has been quite consistent through time. Emissions from copper refining for the same period were below the 0.8 tons of CO2-eq per million Chilean Pesos (López et al., 2016 and Cochilco, 2016). This means that domestically refining copper concentrates instead of exporting them worldwide would reduce total emissions per unit of value added produced in the domestic

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[10] For the Climate Agreement in Paris, COP21, Chile submitted its Intended Nationally Determined Contribution, in which it commits to reduce in 30% its levels of CO2 emissions per GDP unit by 2030, compared with its levels in 2007 (1.02 tCO2e/1,000,000 CLP 2011 GDP) (Government of Chile, 2015).

economy, which would be a change in the right direction in terms of Chile's contribution to the global efforts against global warming and climate change (OECD, 2016).

Moreover, Chile has very favorable conditions for photovoltaic power generation in areas where mining is located—Chilean mining is concentrated in regions I to IV, where solar radiation factors are around 4.5 Kcal/m^2/day, which is, for example, around 18 to 20 times the factors shown by Northern Europe. This is in addition to the interconnection, in 2017, of the two major power systems of the country (the Central Interconnected System (SIC) and the Norte Grande Interconnected System (SING)), which has reduced the price of energy and improved the ability to enter non-conventional renewable energy to the electric national system (National Electric Coordinator, 2019; Ministerio de Energía, 2015). This may imply that refining in Chile the copper concentrates currently exported by the country instead of refining them elsewhere as it is done today would prevent releasing additional carbon emissions into the global atmosphere to those we calculate in this work. Here we do not include any computation of this possible additional reduction of GHG emissions released to the global atmosphere.

The next section presents the methodology employed for our estimations, and section 2.3 analyses the international trade of Chile´s copper concentrates and describes the sources of the data used for our empirical estimations. Section 2.4, presents and discusses our empirical results, and in section 2.5 we present our conclusions and policy proposals.

2.2 METODOLOGY

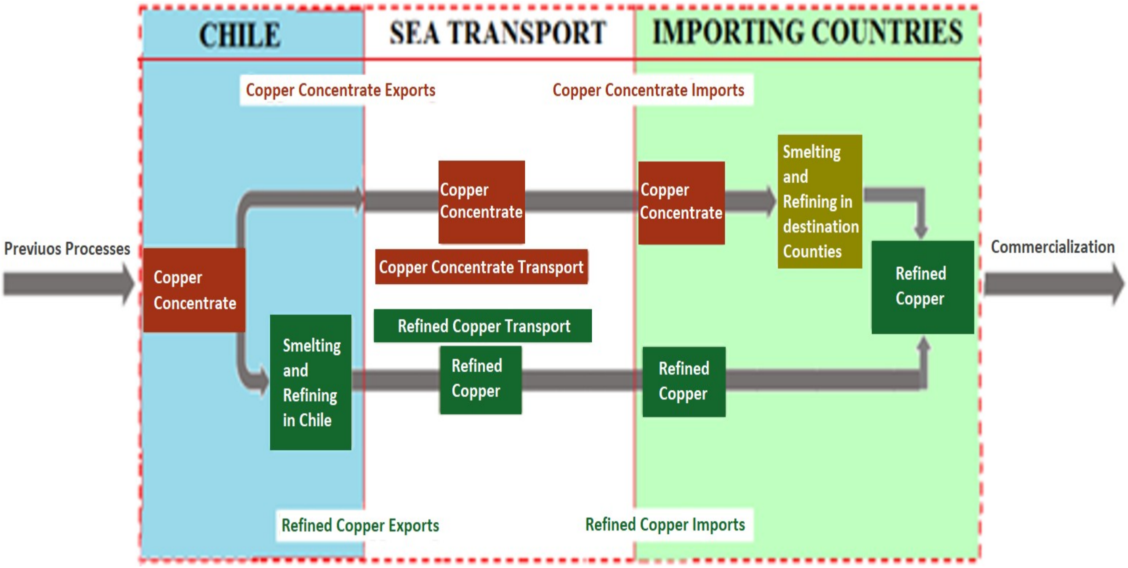
The methodology we use to estimate the net reduction of GHG emissions resulting from a Chile's policy of not exporting copper concentrate and replacing them by refined copper exports considers the two relevant components of the life cycle analysis (LCA) of these two copper products. The first one corresponds to the GHG emissions from the sea shipping of these products when they are exported from Chile, and the associated reduction in the total GHG emissions generated from the fuel oil burned by the freight-ships transporting for more than 15.5 million km (9.6 million miles), around 6.6 million tons of gangue incorporated in the copper concentrates currently being exported from Chile, every year. Burning this diesel oil would be avoided if instead of these cooper concentrates Chile exports only the refined copper included in those concentrates.

The second relevant component of the LCA of the two copper products under analysis corresponds to the GHG emissions generated by the metallurgic processes of these two products, and the resulting difference, i.e. the associated increase or reduction, in the GHG emissions per ton of refined copper produced from Chilean copper concentrates provoked by smelting and refining those copper concentrates in Chile instead of smelting and refining them in the countries where they are processed today after importing them from Chile. After calculating these two components, the final total net reduction in GHG emissions resulting from the relevant changes in the life cycles of these two copper products, occurring if Chile adopts the trade policy analyzed here, will be the result of adding (subtracting) to the reduction in GHG calculated in the first component the reduction (increase) in GHG emissions calculated in the second component.

The part of the life cycle analysis for refined copper involved in calculating the second component corresponds to the one beginning once the copper concentrates have been produced and still are in Chile before being exported. The previous processes these concentrates have already gone through (mine extraction, crushing, grinding, flotation, thickening, filtration, internal transport, etc.) also generate GHG emissions that are emitted to the global atmosphere. However, the amount of these GHG emission does not change with a hypothetical decision of Chile to export copper as copper concentrates instead of as refined copper (after processing the copper concentrates domestically). In other word, this part of the life cycle of copper concentrates as well as of refined copper do not change because of the trade policy.

Thus the initial product for our comparative analysis is the copper concentrate produced and still located in Chile, ready to be exported abroad or be smelted and refined in Chile; and, the final product, on the other hand, corresponds to the refined copper obtained from the copper content of the copper concentrates that has already been converted in refined cooper in Chile, and has also been exported to and it is already located in the same countries currently importing the copper concentrates exported from Chile. Figure 1 presents a schematic illustration of that part of the life cycles for producing refined copper or copper concentrates to be exported we are referring to here (enclose by the discontinuous red line in the figure).

Figure 1
Relevant components of the life cycles of Chile´s exports of copper concentrate and refined copper to which changes in GHG emission are estimated



Source: Own elaboration.

The methodology employed here has been designed to guarantee that reductions of the GHG emissions resulting from the Chile's hypothetical trade policy we are evaluating here are never overestimated. This guarantees that the estimations we obtained always correspond to minimum or "floor" values of the true GHG reductions that will occur in a real-world realization of the trade policy analyzed. Additionally, we do not estimate GHG emissions associated with the domestic transportation of copper concentrates from the arriving port to the corresponding refining facilities in the countries importing concentrates from Chile, because there is no data available to calculate them. I any case, it is evident that these emissions are very much lower than the emissions associated with the sea transportation of these copper concentrates, as well as with the emissions generated in their smelting and refining process.

2.2.1 *Amount of Gangue Incorporated in Chile's Copper Concentrates*

For any country "l" importing copper concentrates from Chile, the weight of the gangue content incorporated in these concentrates, E_l, can be estimated by subtracting from the total weight of these copper concentrates, measured in metric tons, the weight of the copper content in these concentrates, also measured in metric tons. Therefore, the weight of the gangue incorporated in these copper concentrates transported from Chile to the country "l" importing these concentrates is formally defined as:

$$E_l = \sum_j \sum_k \cdot E_{j,k,l} \qquad [1]$$

where,

$E_{j,k,l}$ = weight in metric tons of the gangue at origin port j in Chile and destination port k in the importing country l

$$E_{j,k,l} = C_{j,k,l} \cdot (1 - \lambda_{j,k,l}) \qquad [2]$$

where,

$C_{j,k,l}$ = the total weight of the copper concentrates shipped to port "k" in country "l" from the origin port "j" in Chile;

$\lambda_{j,k,l}$ = percentage of copper in the cooper concentrate exported from origin port j in Chile to the destination port k in the importing country l

Thus, the total weight of the gangue transported during 2014 from Chile to the L countries that imported copper concentrates from Chile that year is calculated as:

$$H = \sum_{l=1}^{L} E_l \qquad [3]$$

2.2.2 *Diesel Fuel Burned That Could Be Avoided by the Analyzed Policy*

A_l is defined as the total amount of diesel oil burned due to the sea transportation of the gangue exported from Chile to country l when the freight-vessel travels through the Panama Canal. Freight-ships using the Panama Canal are of a smaller size than those that do not use the Panama Canal; and, as a result, their average oil consumption is lower per distance traveled. Thus, we calculate A_l using the following expression:

$$A_l = \frac{a}{g \cdot h} \cdot \sum_j \sum_k \left(d_{j,k,l} \cdot E_{j,k,l} \right) \qquad [4]$$

where,

g = correction factor for calculating vessel's actual cargo capacity from its technically defined full capacity

a = fuel consumption of a vessel using the Panama Canal

h = correction traveling factor, for calculating actual travelled distances from origin-port to destination-port calculated without considering intermediate stops

$d_{j,k,l}$ = direct nautical distance (with no intermediate stops) between Chilean origin-port j and destination-port k in importing country l

B_l is defined as the total amount of oil burned due to the transportation of gangue incorporated in the copper concentrates exported from Chile to country l, when the freight-ships do not travel through the Panama Canal:

$$B_l = \frac{b}{g \cdot h} \cdot \sum_j \sum_k \left(d_{j,k,l} \cdot E_{j,k,l} \right) \qquad [5]$$

where,

b = fuel consumption of vessels that do <u>not</u> pass through the Panama Canal

Z is defined as the total oil burned from the transportation of gangue incorporated in copper concentrates exported from Chile to the rest of the world in 2014:

$$Z = \sum_{l} \left(A_l + B_l \right) \qquad [6]$$

2.2.3 Avoidable GHG Emissions from Sea Shipping to Each Importing Country

Using the carbon emission factor for oil combustion provided by IPCC (2014) for the different types of ships that transport copper concentrates from Chile, it is possible to obtain an expression for the GHG emissions generated (expressed in CO2-eq tons) by importing country "l" from the gangue transported through the Panama Canal –C_l– plus the gangue transported through routes different to the Panama Canal –D_l:

$$C_l = f \cdot A_l \qquad [7]$$

$$D_l = f \cdot B_l \qquad [8]$$

where,

f = factor of diesel fuel-related carbon emissions

2.2.4 GHG Emissions from Smelting and Refining Copper Concentrates in Chile and in those Countries Importing Them from Chile

Using equation [2], in equation [9] we obtain an expression formally defining the amount of copper content that arrives to the importing country l, R_l, incorporated in the copper concentrates imported from Chile:

$$R_l = \sum_{j} \sum_{k} C_{j,k,l} \cdot L_{j,k,l} \qquad [9]$$

To estimate the GHG emissions generated from smelting and refining the copper concentrates we use a factor of emission specific to each country, depending on the smelting and refining technology each country has. Then, there are 2 basic cases for which it is necessary to calculate smelting and refining GHG emissions: 1. if the concentrates are refined in Chile; and, 2. if the concentrates are refined in any of the countries importing copper concentrates from Chile. Therefore, we define as U_l to the amount of GHG emissions generated if copper concentrates imported from Chile by county "l"are smelted and refined in country "l" and, as T to the total amount of GHG emissions generated if all copper concentrates exported from Chile are smelted and refined in Chile; and, in equations [10] and [11] we show the expressions to calculate them:

$$U_l = R_l \cdot S_l \qquad [10]$$

where,

S_l = country l's GHG emission factor from smelting and refining copper concentrates

$$T = S_{ch} \cdot \sum_{l=1}^{L} R_l \qquad [11]$$

where,

S_{ch} = Chile's GHG emission factor from smelting and refining copper concentrates.

2.2.5 Avoidable Net Total GHG Emissions from Chile´s Policy of Refining Copper Concentrates Domestically and Exporting Only Refined Copper

Using equations [7] and [8], it is possible to calculate the total amount avoidable GHG emissions resulting from not transporting the gangue incorporated in copper concentrates from Chile to the countries importing these concentrates.

$$W = \sum_{l=1}^{L} (C¿¿l¿+D_l)¿¿ \qquad [12]$$

As explained before, to obtaining the final total avoidable carbon emissions is it necessary to estimate the change in GHG emissions provoked because the smelting and refining of copper concentrates is switched to Chile from the countries importing these concentrates from Chile. This change can be positive or negative (and increase or a decrease in the GHG generated), depending on the relative size of S_{ch} and S_l. In fact, and as it follows from equations [10] and [11], if $S_{ch} < S_{chl}$, refining copper concentrates in Chile will generate less GHG emissions that refining them in the countries that currently import them from Chile. The opposite will occur if $S_{ch} > S_{chl}$.

More formally, defining as V the total GHG emissions generated from smelting and refining Chile's copper concentrates in the importing destination countries, then the following expression allows to calculate it:

$$V = \sum_{l=1}^{L} U_l \qquad [13]$$

Finally, it is possible to define Y as the total amount of avoidable GHG emissions from smelting and refining copper concentrates in Chile instead of abroad; and, therefore, using equations [11], [12] and [13] the expression for Y is:

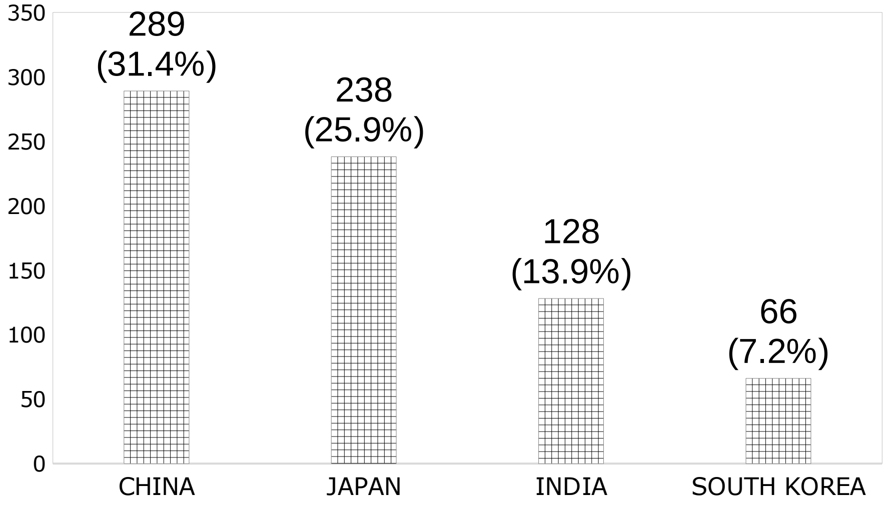
$$Y = W + (V - T) \qquad [14]$$

2.3 TRADE OF CHILE´S COPPER CONCENTRATES AND DATA SOURCES

For doing our most relevant empirical estimations we use data for 2014, which is the most recent year for which there is official data on copper concentrate exports with the detailed information on every exported shipment required for our calculations. The database of the Central Bank of Chile (2015) shows that, in 2014, 919 shipments of exported copper concentrates were sent abroad from Chile and provides, for each of them, the following information relevant to our study: 1. the exporting company or entity; 2. the total gross amount of the copper concentrate (including moisture); 3. the percentage of copper content in the concentrates (copper mass over gross amount of concentrate mass); 4. origin port in Chile; 5. importing country; and, 6. destination port in the importing country.

Figure 2 shows that China, Japan, India and South Korea received the largest numbers of copper concentrate shipments imported from Chile. They jointly received 721 shipments, or 78.5%, of the total shipments exported from Chile in 2014. Most of these shipments were sent abroad from only 4 Chilean ports that dispatched 680 shipments altogether, or 74% of all shipments: Caleta Coloso (239 shipments with 26%); Ventanas (196 shipments with 21.3%); Patache (135 shipments with 14.7%); and, Los Vilos (110 shipments and 12%).

Figure 2
<u>Chile</u>: Number of copper concentrate shipments exported to the 4 main importing countries; 2014
(number of landings)



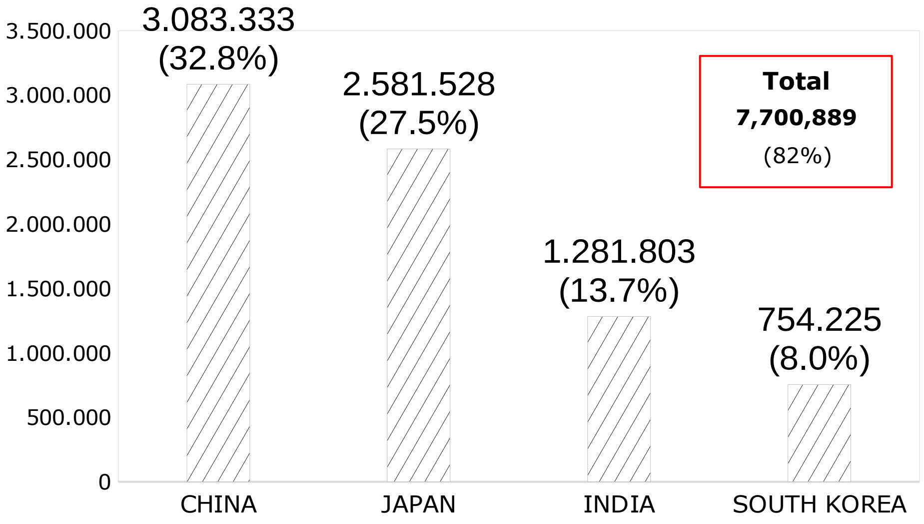
Source: Own elaboration, using information from the Central Bank of Chile (2015).

Figure 3 shows that the same 4 importing countries –China, Japan, India and South Korea– received the largest amounts of copper concentrate exported from Chile, 7,700,889 metric tons altogether, representing 82% of the total amount of metric tons of copper concentrates exported from Chile in 2014.

Figure 3
<u>Chile</u>: Amount of copper concentrate exported from Chile to

the 4 main importing countries; 2014

(tons)



Source: Own elaboration, using information from the Central Bank of Chile (2015)

More details regarding the shipments of Chile´s copper concentrate to the destination countries in 2014 are presented below in Appendices A, B and C.

2.3.1 Copper Content of Copper Concentrates

Using data on the shipments of copper concentrates exported in 2014, and the copper content reported by the National Customs Service for each shipment, we estimated that the average copper content of the copper concentrates exported from Chile that year was 30%. Also, 13 of the 18 companies exporting copper concentrates that year, or 72.2% of all of them, exhibited a copper content of their shipments between 25% and 30%.

2.3.2 Origin-Destination Ports Matrix of Chile´s Exported Copper Concentrates in 2014

We identified a total of 97 different origin-destination maritime routes by which the shipments of exported copper concentrates were sent from Chile to the rest of world in 2014. For each one of these routes, we calculated the direct nautical distance involved, using the computer tool "Distances and Times" (Sea Rates, 2017). We also determined whether each of these routes included or not crossing through the Panama Canal.

Appendix D below shows in detail the 97 routes, reporting their distances in kilometers, the amount of gangue transported through the route, and whether the route crossed the Panama Canal or not. It is worth noting that these routes were analyzed as if they were direct trips from the origin Chilean port to the final destination port, which is not actually the case, as vessels, more often than not, do make stopovers in their routes. This is analyzed with more detail in Section 2.3.4 below.

Table 2 shows the routes using and not using Panama Canal., their average distances, the total amount of gangue transported for each route and the percentage of gangue content.

Table 2

Chile: Distance traveled, total amount of gangue transported and % of total copper concentrates transported, by type of shipping route; 2014

ITEM	ROUTES THROUGH THE PANAMA CANAL	ROUTES NOT CROSSING THE PANAMA CANAL
AVERAGE NAUTICAL DISTANCE	14,271 km	15,940 km
TRANSPORTED GANGUE	768,601 tons	5,807,982 tons
% OF TOTAL COPPER CONCENTRATE TRANSPORTED	12%	88%

Source: Own elaboration, using information from the Central Bank of Chile (2015) and Sea Rates (2017)

2.3.3 Freight-Ships Transporting Copper Concentrates from Chile

As of 2014, ships with gross tonnage over 52,000 tons were not allowed to use the Panama Canal route; therefore, we assumed here that copper concentrates exported from Chile through this route were transported on ships of the "Panamax" type. On the other hand, the maritime routes that do not cross the Panama Canal do not imply capacity limitations on ship tonnage. With the purpose of avoiding any possible overestimation when we estimate the reduction in GHG emissions generated by Chile´s hypothetical trade policy under analysis, we assume that the representative ship for the routes not crossing the Panama Canal corresponds to a large, efficient fright-vessel of the "MSC Oscar" type from the Mediterranean Shipping Company, with a gross tonnage of 193,000 tons.

Table 3 shows the relevant features of both types of freight-ships used to perform the calculations of this study, obtained from Alphaliner (2011) and Access (2014) for the case of the "Panamax" vessels, and from ABB (2015) and MSC (2017) for the "MSC Oscar" ships.

Table 3
Key technical characteristics of the freight-ships transporting copper concentrates exported from Chile

TECHNICAL CHARACTERISTIC	TYPE OF FREIGHT SHIP	
	MSC Oscar	Panamax
GROSS TONNAGE	193,000 tons	52,000 tons
FUEL TYPE	Diesel	Diesel
FUEL CONSUPTION	>280 liters per km	>95 liters per km

Source: Own elaboration, with information from Alphaliner (2011), Access (2014), ABB (2015) and MSC (2017)

2.3.4 Technical Correction Factors

Fuel consumption rates of freight-ships may be affected by several conditions, especially in long trips, causing that their actual fuel consumption rates are lower than their potential (most efficient) fuel consumption rates. Therefore, for our fuel consumption estimations we have followed Access (2014) and considered that the average actual fuel consumption rates of the freight-ships transporting copper concentrates exported from Chile are 80% of their potential most efficient rates. As a result, for our calculations the average fuel consumption rate used for the ships of the "Panamax" type is 114 liters per km travelled, and for ships of the "MSC Oscar" type is 336 liters per km travelled.

The technical specifications of the gross tonnage of the freight-ships shown in Table 5 must be corrected to obtain the actual cargo capacity of each type of vessel. Hence, following Enertrans (2008) and Trozzi (1999) we employ here a correction factor of 55% to calculate the actual cargo capacity of each type of freight-ship.

Additionally, to calculate the travel distance involved in every shipment of copper concentrates, we have estimated the nautical distance traveled as in a direct trip from the corresponding port in Chile to the final destination port. However, freight-ships very often do not travel directly from the port of origin to the final port but they make intermediate stops, which increases the actual travel distance, especially for vessels passing through the Panama Canal. To incorporate this in our estimations, we have used a correcting factor expressed as the ratio of the estimated direct nautical distance over the actual traveled distance. As proposed by Enertrans (2008), Trozzi, (1999) and Access (2014), for those ships passing through the Panama Canal we have used a ratio of 0.7 (and a ratio of 0.6 to estimate and alternative scenario), and for the ships not using the Panama Canal we used a ratio of 0.8 (and a ratio of 0.7 to estimate and alternative scenario).

Finally, we calculate the amounts of the different greenhouse gases (CO2, methane, nitrous oxide, ozone, etc.) emitted to the global atmosphere from the oil burned by the freight-ships transporting the copper concentrates exported from Chile in terms of their equivalent tons of CO2. To perform the involved transformation, we use the converting factor calculated by the Intergovernmental Panel on Climate Change, which is 2.8 tons of CO2-eq per cubic meter of oil burned (IPCC, 2014).

2.3.5 GHG Emissions from Smelting and Refining Copper Concentrates

As explained before, to calculate the total amount of GHG emissions avoided by smelting and refining the copper concentrates in Chile instead of exporting them, it is also necessary, in addition to calculate the emissions avoided from the ship transportation of the gangue incorporated in the copper concentrates, to calculate the difference in total GHG generated by the smelting and refining processes when they are done in Chile compared to when they are done in those countries currently importing those concentrates from Chile.

If smelting and refining these concentrates in Chile generates less GHG than doing it abroad, then the calculated difference will be an additional contribution to the GHG reduction generated from avoiding the sea transportation of the gangue incorporated in the copper concentrates. On the contrary, if smelting and refining the concentrates in Chile generates more GHG emission than smelting and refining them abroad, the calculated difference will reduce the net total reduction in GHG emissions implied by Chile´s decision of exporting refined copper instead of copper concentrates.

To do these estimations, we analyzed the group of 10 countries that jointly imported more than the 98% of the copper concentrates exported by Chile in 2014. We gathered detailed information on the GHG emissions generated by the copper smelting and refining technologies of these countries and Chile. In Table 6, we present the information obtained for each of these countries’ metallurgic technologies, in terms of the direct GHG tons of CO2-eq of GHG they emit per ton of refined copper. As shown in the table, the average pollution rate for the technologies of the 11 countries in the table is 0.63 tons of CO2-eq per ton of refined copper; and Spain and Chile exhibit the less polluting technologies of the group, with 0.41 and 0.44 tons of CO2-eq per ton of refined copper, respectively, and are the only two countries in the group with best environmental technologies, i.e. with GHG emission generator factors between one and less than two standard deviations below the average factor. Moreover, Brazil, Bulgaria and Germany are, in the group of countries exhibiting the second less polluting technologies, i.e. with GHG emission generator factors up to less than one standard deviation below the average factor; China, Japan, South Korea, Finland and Sweden are in the group of countries whose technologies are less than one standard deviation more polluting than the average; and India is the only country of the group with a technology that is more polluting than the latter group, with a pollution rate of 1.09 tons of CO2-eq per ton of refined copper. For the estimations involving the other 12 countries importing and refining the remaining 2% of Chile's exported copper concentrates we used the average environmental efficiency rate of 0.63 tons of CO2-eq per ton of refined copper (which includes Chile´s environmental efficiency rate)[11].

Table 4
GHG emission generation factors of the metallurgic technologies to smelt and refine copper concentrates in countries importing copper concentrates from Chile

COUNTRY	GHG EMISSION GENERATION FACTOR	SOURCE
	(ton CO2-eq / ton Cu)*	
CHILE	0.44	Cochilco (2018)
CHINA	0.65	ESG (2017)
JAPAN	0.75	JX Nippon Mining & Metals Corp. (2017)
INDIA	1.09	Hindalco (2017)
SOUTH KOREA	0.71	USGS (2017)
BRAZIL	0.54	Paranapanema (2018)
SPAIN	0.41	Atlantic Copper (2017)
BULGARIA	0.46	Dundee (2018)
GERMANY	0.52	Aurubis (2018)
FINLAND	0.69	Boliden (2017)
SWEDEN	0.67	Boliden (2017)

(*) average value for 2016-2017.
Source: Own elaboration.

2.4 RESULTS

2.4.1 GHG Emissions Avoided from Copper Concentrate Sea Shipping

2.4.1.1 Sensitivity Analysis Scenarios for the Estimations

As noted in the previous section, two key parameters are involved in the estimation of the amount of the GHG emissions that could be reduced if copper concentrates are refined in Chile instead of being exported as such. The first of them is the correcting factor used to estimate the actual distance travelled by the ships transporting each shipment of copper concentrate exported from Chile, starting from an estimate of this distance from the origin Chilean port to the final destination port without considering the usual intermediate stopovers made by the

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[11] The purpose of including Chile's environmental efficiency in this average is, once again, to eliminate any risk of overestimating the reduction in GHG emissions resulting from the Chile´s hypothetical trade policy under analysis.

ships. The second of these key parameters corresponds to the oil consumption rate per kilometer travelled by the two kinds of freight-ships involved. Therefore, in order to perform sensitivity an analysis in our estimations we use two different values for each of these two key parameters. Thus, we calculate 4 different scenarios of the net total reduction of GHG emissions resulting from refining Chilean copper concentrates domestically and exporting their copper content as refined copper afterwards. Table 5 shows the combination of the values of the 2 key parameters used for each one of the 4 sensitivity scenarios estimated.

Table 5

Structure of the 4 scenarios used for the sensitivity analysis of the estimations of the net total reduction in GHG emissions resulting from refining Chilean copper concentrates domestically instead of exporting them as copper concentrates

SENSITIVITY ANALYSIS SCENARIO	SHIPPING DISTANCE CORRECTING FACTOR		FUEL USE FACTOR	
	Panamax Ship	MSC Oscar Ship	Panamax Ship	MSC Oscar Ship
	(%)		(diesel fuel liters / km)	
A	60	70	95	280
B	70	80	95	280
C	60	70	114	336
D	70	80	114	336

Source: Own elaboration.

2.4.1.2 GHG Emissions Avoided from Gangue Sea Shipments

For each of the 4 scenarios described in Table 5 we calculate the CO2-eq tons of all GHG emissions generated by the sea transport of the gangue included in the copper concentrates exported from Chile in 2014. We estimate the amount of these emissions for the 919 shipments sent to every destination port in each one of the 22 countries that imported Chilean copper concentrates that year. Evidently, the amounts of these emissions corresponds to the GHG emission that would had been avoided if, in 2014, Chile would had exported refined copper instead of copper concentrates, avoiding in this way the sea shipping of the gangue contained in the copper concentrates exported. Table 6 shows the estimations obtained for each one of our four sensitivity scenarios, presenting the amounts of total GHG emissions that would have been avoided and the amounts of diesel fuel that would have not been burned.

Table 6

Avoided GHG emissions and not burned diesel fuel in four scenarios for sensitivity analysis

SENSITIVITY ANALYSIS SCENARIO	**GHG EMISSIONS AVOIDED**	**DIESEL FUEL BURNING AVOIDED**
	(ton of CO2-eq)	(ton)
A	1,682,946	601,052
B	1,445,551	515,911
C	2,017,783	721,262
D	1,903,388	619,093
AVERAGE	1,762,417	614,330

Source: Own estimations.

Column 2, in turn, shows that the amounts of GHG emissions generated by this burned fuel were, for the four scenarios estimated, between 1,445,551 and 2,017,783 tons of CO2 equivalent. Column 3 of Table 6 shows that the total volume of diesel oil burned to transport the gangue content included in the copper concentrates exported from Chile was, in 2014, between 515,911 and 721,262 tons, which could be avoided. The estimations for each one of 22 countries that imported those Chilean copper concentrates in 2014 are presented in Appendix E.

2.4.2 GHG Emissions Avoided if the Metallurgic Processes to Smelting and Refining Chile´s Copper Concentrates Were Carried Out in Chile Instead of Abroad

To estimate the final total net GHG emissions involved in the hypothetical Chile´s decision of exporting refined copper instead of copper concentrates, it is necessary to add to (to subtract from) the figures presented in Table 6, the reduction (the increase) in GHG emissions resulting from the metallurgic processes of smelting and refining the copper concentrates in Chile instead of in the 22 countries importing the concentrates from Chile. Our estimations show that the smelting and refining of copper concentrates in Chile instead of in the importing countries in fact provokes a net reduction in GHG emissions. The reason of this, as it is explained by the GHG emission factors of the different countries reported in Table 4 above, is that the environmental efficiency of Chile´s copper smelting and refining processes is higher than the efficiencies exhibit by the 9 of the 10 countries importing 98% of Chile´s copper concentrates and it is also 30.2% higher than the average for those 10 efficiency. This is the underlying explanation of our estimations indicating that if all copper concentrates exported by Chile in 2014 would had been smelted and refined in Chile the total amount of GHG emission generated by the metallurgic processes involved would had been 1,235,872 tons of CO2-eq, which means 781,496 tons less than the CO2-eq tons of GHG that were produced by those 22 countries –2,017,368 tons– when they smelted and processed the copper concentrates they imported from Chile that year.

Appendix F below shows the GGH emissions produced by each one of the 22 countries that imported copper concentrates from Chile, in 2014.

2.4.3 Total GHG Emissions to the Global Atmosphere Avoided from Refining Copper Concentrates in Chile and Exporting Their Copper Content as Refined Copper

When we add both GHG emission reductions we have estimated, resulting from the hypothetical trade policy of Chile under analysis, we obtain a net total reduction of GHG emissions liberated to the global atmosphere of between 2,227,047 and 2,799,279 tons of CO2-eq. Indeed, as shown in column 2 of Table 7, we have obtained an estimate for each one of the 4 scenarios we have developed here for the sensitivity analysis of our calculations, and the average reduction estimated for the 4 scenarios is 2,543,913 tons. Moreover, to illustrate the relative magnitude of these estimates, they are presented in column 3 of the table as percentages of Chile´s total annual GHG emissions, for the year 2014 (105 million tons of CO2-eq (MMA, 2018)). The figures shown indicate that the avoided GHG emissions were equivalent to a minimum of 2.2% (scenario B) to a maximum of 2.8% (scenario C) of Chile’s total annual GHG emissions of 2014, and that the average for the 4 sensitivity scenarios was equivalent to 2.5%. Additionally, as it is shown in column 4 of the table, the avoided GHG emission estimated were equivalent to a minimum of 4.9% (scenario B) to a maximum of 6.1% (scenario C) of Chile’s net annual GHG (48.5 million tons of CO2-eq, MMA (2018)) , and that, in this case, the average for the 4 sensitivity scenarios was equivalent to 5.6%.

Table 7

Chile: GHG emissions to the global atmosphere avoided by a hypothetical policy to completely replace its 2014 copper concentrate exports by refined copper exports, expressed in tons of CO2-eq and as percentages of Chile's annual Total and Net GHG emissions; estimations for four scenarios of sensitivity analysis

SENSITIVITY ANALYSIS SCENARIO	AVOIDED GHG EMISSIONS TO THE GLOBAL ATMOSPHERE		
	ABSOLUTE VALUE	AS PERCENTAGE OF CHILE´S ANNUAL	
		TOTAL GHG EMISSIONS	NET GHG EMISSIONS
	(ton of CO2-eq)	(%)	
A	2,464,442	2.4	5.4
B	2,227,047	2.2	4.9
C	2,799,279	2.8	6.1
D	2,684,884	2.6	5.9
AVERAGE	2,543,913	2.5	5.6

Source: Own elaboration with data from MMA (2018) and own estimates.

Thanks to a suggestion of an anonymous referee of this journal we significantly improved our estimates of the embodied emissions generated in the whole production process of Chile's copper concentrate and refined copper exports reported here, by extending them through a more encompassing life cycle analysis. To do that, we used some of our findings from a parallel ongoing research that attempts to estimate the carbon footprint of the Chilean economy, and uses an input-output methodology (see López et al., 2016). In Table 8, we use again some of these parallel findings in order to better illustrate the relative magnitude of our estimates of Chile´s avoided GHG emissions to the global atmosphere reported in Table 7. In fact, column 2 of Table 8 presents our estimates of the GHG emissions to the global atmosphere avoided expressed now, as percentages of the direct (as opposed to the indirect) GHG emissions generated by the mining sector of Chile in the year 2014 (5.5 million tons of CO2-eq, Cochilco (2018)). These percentages indicate that the avoided GHG emissions estimated here were between a minimum of 40.5% (for scenario B) and 50.9% (for scenario C) of Chile's mining sector direct annual GHG emissions; and, that they represented 46.3% of the average GHG emissions generated by the 4 scenarios of the sensitivity analysis performed here.

On the other hand, in columns 3, 4 and 5 of Table 8, we show our estimates of the avoided GHG emissions expressed in this case, as percentages of the indirect GHG emissions generated by the mining sector of Chile in the year 2014 (17.2 million tons of CO2-eq, based in López et al., 2016). These estimated percentages are separated in the three sub-sectoral components employed in the input-output analysis of Chile's national account system: electricity and gas; transport; and, manufactures. As the relative sizes of the three sub-sectors are quite different, the estimated percentages are also quite different. In fact, considering the averages for the 4 sensitivity scenarios employed here, these estimated percentages go from the lowest, of 31.8%, for the GHG emissions generated by the sub-sector of electricity and gas; to the intermediate of 207%, for the GHG emissions generated by the transport sub-sector; to the highest, of 290.2%, for the GHG emissions generated by the sub-sector of manufactures. Nevertheless, in spite of their ample range, these percentage proportions clearly indicate that the contribution that Chile would made by completely replacing its current exports of copper concentrates by refined copper exports would be significant from several points of view, and with relevance not only for its mining sector but also from a national perspective.

Table 8

Chile: GHG emissions to the global atmosphere avoided by a hypothetical policy to completely replace its 2014 copper concentrate exports by refined copper exports, expressed as percentages of Chile's mining sector GHG emissions; estimations for four scenarios of sensitivity analysis

SENSITIVITY ANALYSIS SCENARIO	GHG EMISSIONS AVOIDED AS PERCENTAGE OF CHILE MINING SECTOR'S GHG EMISSIONS			
	DIRECT	INDIRECT EMISSIONS		
	EMISSIONS	ELECTRICITY & GAS	TRANSPORT	MANUFATURES
	(%)	(%)		
A	44.8	30.8	200.8	281.1
B	40.5	27.8	181.5	254.1
C	50.9	35.0	228.1	319.3
D	48.8	33.5	218.8	306.23
AVERAGE	46.3	31.8	207.3	290.2

Source: Own elaboration with data from MMA (2018), López et al. (2016), and own estimates.

2.5 CONCLUSIONS AND POLICY PROPOSALS

Of all the GHG emissions that Chile emitted to the global atmosphere in 2014, 2,227,047 to 2,799,279 tons were generated from two sources related to its copper exports. First, by the diesel oil burned to transport Chile´s copper concentrates exported to the 22 countries who imported them. Second, by the environmentally dirtier processes used afterwards in those 22 countries to smelt and refine those copper concentrates, compare with the same metallurgic processes used in Chile. Obviously, these large amounts of GHG emissions are not insignificant. For example, they represented around 50% of all the direct GHG emissions released that year by the entire copper mining sector of Chile, the largest copper producing country, who produces 30% of all the copper annually produced in the world. On the other hand, they were also equivalent to 5.6% of the amount of GHG emissions that Chile would have needed to mitigate that year to make its economy fully carbon neutral, and to 2.5% of the total amount of GHG emitted by Chile that year. Therefore, if these more than 2,500,000 tons of CO2-eq GHG would had been mitigated instead of released to the atmosphere, they would had made a valuable contribution to the world´s efforts to reduce climate change and global warming that year. Moreover, Chile could make a contribution like this, every year in the future, by adopting a trade policy of not exporting copper concentrates any longer, replacing them by refined copper exports.

Chile committed to the 2015 Paris Agreement a 30% reduction of its CO2 emissions per unit of GDP by 2030, relative to its levels in 2007. This involves going from 1.02 to 0.71 tons of CO2-eq per million Chilean Pesos of GDP in 23 years (Government of Chile, 2015). Given the importance of the mining sector in Chile´s total GDP, these figures imply that the sector should play a significant role in reducing the country´s GHG emission per million Chilean pesos of GDP. One way of doing this contribution would by refining all its copper domestically instead of continuing with exporting copper concentrates. The latter results from the fact that the GHG intensity per million Chilean pesos of GDP of the domestic copper refining processes is 0.8 CO2-eq tons of GHG per million Chilean pesos of GDP, which is less than the intensity of the entire mining sector of 0.92 (as estimated by Lopez et al., 2016).

The International Maritime Organization (IMO) of the United Nations estimated that, in 2012, the GHG emissions from international shipping accounted for 2.2% of anthropogenic CO2 emissions and that, by 2020, such emissions will grow between 50% and 250% (IMO, 2015). To join the world effort to reduce climate change and global warming, IMO is committed to reducing GHG emissions from international shipping and, as a matter of urgency, aims to phase them out as soon as possible in this century (MEPC, 2018).

To pursue these objectives, the IMO defined its Initial Strategy, one of whose levels of ambitions is to peak GHG emissions from international shipping as soon as possible and to reduce the total annual GHG emissions by at least 50% by 2050, compared to 2008. Moreover, IMO is committed to pursue efforts towards phasing out international shipping GHG emissions as a point on a pathway of CO2 emissions reduction consistent with the Paris Agreement temperature goals (MEPC, 2018). There is no doubt then, that Chile could make a substantive contribution in line with these IMO´s objectives by reducing the GHG emission generated from the sea shipping of its annual exports of copper concentrates, substituting them by refined copper exports.

On the other hand, the growing evidence indicating that the international efforts committed in the 2015 Paris Agreement would not be sufficient to slowing down global warming with the required speed pushed the IPCC to launch, at the end of 2018, its Special Report on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emission pathways. In this report the IPCC urges the global community to strengthen current efforts to attaining pathways to limit global warming to 1.5°C instead of 2°C, because, with high confidence, the pathways reflecting the ambitions of the Paris Agreement would not limit global warming to 1.5°C, even if supplemented by very challenging increases in the scale and ambition of emissions reductions after 2030 (IPCC, 2018). Moreover, at the UN Climate Action Summit, held in New York on last September 21-23, the UN Secretary-General, António Guterres, asked to all world leaders to propose concrete, realistic plans to enhance their nationally determined contributions by 2020, in line with reducing greenhouse gas emissions by 45% over the next decade, and to net zero emissions by 2050.

To meet these tough challenges, the world maritime transport sector can make a significant contribution, because 80% of the world´s merchandise transport is made by sea. This is why, in the Climate Action Summit of last September, the Secretary General of the International Maritime Organization, Kitack Lim, committed this UN organization´s efforts to attempt to reduce in 40% the CO2 intensity of sea transport by 2030, relative to 2008, and to reach 70% towards 2050. To honor these commitments, it would be convenient that the IMO plays a more active role to generate incentives to motivate all countries to implement initiatives for reducing the GHG generated by their international shipping activities.

A proposal to attain this would be to determine that the amounts of GHG emissions mitigated by a country as a result of reducing the sea shipping of its exports can be accounted as part of its future national determined contribution (NDC). An internationally agreed policy like this would create large incentives for all countries to reduce the GHG emissions generated by the sea shipping of their exports; which, in the case of the mining sector of Chile studied here, implies eliminating its exports of copper concentrates. The latter would reduce the GHG intensity of Chile´s mining sector in more than the 30% reduction in the GHG intensity per million Chilean Pesos of GDP already committed by the country to the Paris Agreement. Of course, this would be beneficial to Chile but, more relevant than that, this recognition of the GHG emissions reductions from sea shipping would align the incentive of all countries with the world efforts to reduce global GHG emissions.

On November 29, 2019, the Assembly of the IOM reelected Chile as a member of the IMO´s Council, the executive organ responsible for supervising the work of the Organization. This occurred only three days before the COP 25 to the United Nations Framework Convention on Climate Change (UNFCCC) will convene in Madrid, Spain, under the Presidency of Chile, and in which the safeguard of global oceans as well as the reductions in GHG emission to the atmosphere will be relevant issues. Both of these facts represent opportunities for Chile to promote in the international arena the necessary changes to increase the current existing incentives for countries to reduce GHG emissions from the sea transportation of their exported merchandises by obtaining their recognition as part of their NDCs.

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2.7 APPENDIXES

Appendix A

<u>Chile</u>: Amount of exported gangue and equivalent refined copper by shipping port; 2014

PORT OF ORIGIN	GANGUE	EQUIVALENT REFINED COPPER
	(ton)	
ANTOFAGASTA	125,406	54,651
ARICA	3,614	1,426
CALDERA	373,409	154,552
CALETA COLOSO	1,726,577	802,787
CHANARAL/ BARQUITO	28,334	12,223
COQUIMBO	323,605	118,428
LOS VILOS	795,854	441,228
MICHILLA	600,274	192,742
PATACHE	1,088,245	432,818
PUERTO ANGAMOS	29,745	15,452
SAN ANTONIO	3,599	1,394
VALPARAISO	3,844	1,278
VENTANAS	1,474,077	579,884
TOTAL	**6,576,584**	**2,808,861**

Source: Own elaboration.

Appendix B

<u>Chile</u>: Copper Concentrate exported, and equivalent refined copper content, by exporter; 2014

EXPORTER	COPPER CONCENTRATE	EQUIVALENT REFINED COPPER CONTENT
	(ton)	(%)
ANGLO AMERICAN NORTE S.A.	545,387	28.3%
ANGLO AMERICAN SUR S.A.	1,164,460	28.1%
CIA.CONT. MINERA CANDELARIA	527,961	29.3%
CIA.MIN.DONA INES COLLAHUASI S	975,676	28.5%
CIA.MINERA TECK CARMEN DE ANDA	276,049	27.0%
CODELCO CHILE	1,102,253	28.9%
EMPRESA NACIONAL DE MINERÍA	15,744	36.1%
GLENCORE CHILE S.A.	57,751	27.6%
MINERA CENTINELA	43,542	25.9%
MINERA CERRO DOMINADOR S.A.	1,475	22.2%
MINERA ESCONDIDA LTDA	2,529,363	31.7%
MINERA ESPERANZA	749,473	24.2%
MINERA LAS CENIZAS S.A.	10,053	26.1%
MINERA LOS PELAMBRES	1,237,082	35.7%
SCM MINERA LUMINA COPPER CHILE	57,661	26.0%
SIERRA GORDA SCM	14,773	28.6%
SOC. CONTRACTUAL MINERA ATACAMA	5,857	27.7%
TRAFIGURA CHILE LTDA	70,883	25.9%
TOTAL	**9,385,444**	**30.0%**

Source: Own elaboration.

Appendix C

Chile: Gangue and equivalent refined copper, by destination country; 2014

DESTINATION COUNTRY	GANGUE	EQUIVALENT REFINED COPPER
	(ton)	
GERMANY	163,055	62,443
BRAZIL	324,490	137,271
BULGARIA	168,454	71,322
CANADA	653	203
CHINA	2,166,088	917,245
SOUTH KOREA	528,609	225,616
SPAIN	319,326	130,299
PHILIPPINES	14,538	7,466
FINLAND	66,659	25,217
GEORGIA	722	372
NETHERLANDS	3,787	1,671
HONG KONG	2,874	1,481
INDIA	892,103	389,699
JAPAN	1,798,180	783,348
MALAYSIA	844	380
MEXICO	7,818	3,834
NAMIBIA	29,558	14,185
PERU	8,493	3,506
SWEDEN	45,945	17,821
TAIWAN	31,494	13,990
THAILAND	2,147	1,106
VIETNAM	747	385
TOTAL	**6,576,584**	**2,808,861**

Source: Own elaboration.

Appendix D

Chile: Domestic and destination ports, gangue transported, maritime route and travelled distance of copper concentrated shipments; 2014

PORT OF ORIGIN	PORT OF DESTINATION	GANGUE CONTENT	NAUTICAL DISTANCE	MARITIME ROUTE
		(ton)	(km)	Panama Canal = 1 No Panama Canal =0
ANTOFAGASTA	CALLAO	600	1,639	0
ANTOFAGASTA	HUELVA	7,559	12,150	1
ANTOFAGASTA	KAOHSIUNG	4,316	19,008	0
ANTOFAGASTA	KEELUNG	5,933	18,887	0
ANTOFAGASTA	MANZANILLO	3,064	6,221	0
ANTOFAGASTA	OTHER PARTS OF INDIA	30,248	19,174	0
ANTOFAGASTA	OTHER PARTS OF PANAMA	1,223	4,108	0
ANTOFAGASTA	OTHER PARTS OF CHINA	20,094	18,681	0
ANTOFAGASTA	OTHER PARTS OF NAMIBIA	22,243	11,407	0
ANTOFAGASTA	OTHER PARTS OF NETHERLANDS	3,787	13,072	1
ANTOFAGASTA	OTHER PARTS OF JAPAN	3,670	16,932	0
ANTOFAGASTA	OTHER PARTS OF SWEDEN	9,450	14,502	1
ANTOFAGASTA	PORI	9,431	14,689	1
ANTOFAGASTA	VARNA	3,787	15,852	1
ARICA	OTHER PARTS OF CHINA	3,614	18,318	0
CALDERA	HUELVA	117,580	12,342	1
CALDERA	OTHER PARTS OF INDIA	40,688	18,828	0
CALDERA	OTHER PARTS OF BRAZIL	7,350	7,680	0
CALDERA	OTHER PARTS OF CHINA	66,065	14,926	0
CALDERA	OTHER PARTS OF KOREA	15,428	18,224	0
CALDERA	OTHER PARTS OF JAPAN	113,929	17,121	0
CALDERA	OTHER PARTS OF SWEDEN	12,370	14,694	1
CALETA COLOSO	OTHER PARTS OF INDIA	376,853	19,161	0
CALETA COLOSO	OTHER PARTS OF BRAZIL	106,376	8,014	0
CALETA COLOSO	OTHER PARTS OF CHINA	643,367	18,676	0
CALETA COLOSO	OTHER PARTS OF KOREA	208,607	18,027	0
CALETA COLOSO	OTHER PARTS OF JAPAN	383,552	16,927	0
CALETA COLOSO	OTHER PARTS OF TAIWAN	7,821	18,882	0

PORT OF ORIGIN	**PORT OF DESTINATION**	**GANGUE CONTENT**	**NAUTICAL DISTANCE**	**MARITIME ROUTE**
		(ton)	(km)	Panama Canal = 1 No Panama Canal =0
CHANARAL/ BARQUITO	KAOHSIUNG	1,514	18,899	0
CHANARAL/ BARQUITO	OTHER PARTS OF INDIA	11,919	18,883	0
CHANARAL/ BARQUITO	OTHER PARTS OF CHINA	7,704	18,775	0
CHANARAL/ BARQUITO	OTHER PARTS OF JAPAN	4,235	17,043	0
CHANARAL/ BARQUITO	VARNA	2,962	15,978	1
COQUIMBO	ILO	4,215	1,450	0
COQUIMBO	OTHER PARTS OF INDIA	34,420	18,483	0
COQUIMBO	OTHER PARTS OF BULGARIA	35,756	16,312	1
COQUIMBO	OTHER PARTS OF PANAMA	3,530	4,607	0
COQUIMBO	OTHER PARTS OF GERMANY	83,642	14,037	1
COQUIMBO	OTHER PARTS OF BRAZIL	16,430	7,336	0
COQUIMBO	OTHER PARTS OF CHINA	29,090	18,794	0
COQUIMBO	OTHER PARTS OF KOREA	8,478	18,230	0
COQUIMBO	OTHER PARTS OF JAPAN	42,669	17,171	0
COQUIMBO	OTHER PARTS OF SWEDEN	15,975	15,001	1
COQUIMBO	PORI	49,400	15,188	1
LOS VILOS	HUELVA	27,811	12,649	1
LOS VILOS	OTHER PARTS OF INDIA	40,877	18,483	0
LOS VILOS	OTHER PARTS OF BULGARIA	41,432	16,312	1
LOS VILOS	OTHER PARTS OF GERMANY	14,301	14,037	1
LOS VILOS	OTHER PARTS OF BRAZIL	21,221	7,336	0
LOS VILOS	OTHER PARTS OF CHINA	139,747	18,794	0
LOS VILOS	OTHER PARTS OF KOREA	55,490	18,230	0
LOS VILOS	OTHER PARTS OF PHILIPPINES	14,538	18,236	0
LOS VILOS	OTHER PARTS OF JAPAN	440,437	17,171	0
MICHILLA	HUELVA	33,660	12,150	1
MICHILLA	OTHER PARTS OF BULGARIA	8,319	15,813	1
MICHILLA	OTHER PARTS OF GERMANY	25,318	13,538	1
MICHILLA	OTHER PARTS OF BRAZIL	8,264	8,027	0
MICHILLA	OTHER PARTS OF CHINA	158,012	18,681	0

PORT OF ORIGIN	PORT OF DESTINATION	GANGUE CONTENT	NAUTICAL DISTANCE	MARITIME ROUTE
		(ton)	(km)	Panama Canal = 1 No Panama Canal =0
MICHILLA	OTHER PARTS OF KOREA	67,247	18,032	0
MICHILLA	OTHER PARTS OF JAPAN	299,455	16,932	0
PATACHE	HUELVA	33,275	11,781	1
PATACHE	OTHER PARTS OF INDIA	158,173	19,490	0
PATACHE	OTHER PARTS OF BULGARIA	19,850	15,445	1
PATACHE	OTHER PARTS OF GERMANY	31,773	13,169	1
PATACHE	OTHER PARTS OF CHINA	495,796	18,491	0
PATACHE	OTHER PARTS OF KOREA	55,770	17,664	0
PATACHE	OTHER PARTS OF JAPAN	293,609	17,664	0
PUERTO ANGA MOS	BUSAN CY (PUSAN)	533	17,910	0
PUERTO ANGA MOS	CALLAO	3,678	1,517	0
PUERTO ANGA MOS	HONG KONG	2,874	19,593	0
PUERTO ANGA MOS	HONG KONG – TAIWAN	1,831	19,593	0
PUERTO ANGA MOS	HONG KONG - THAILAND	716	19,593	0
PUERTO ANGA MOS	KEELUNG	1,199	18,857	0
PUERTO ANGA MOS	MONTREAL	653	9,890	1
PUERTO ANGA MOS	OTHER PARTS OF CHINA	7,202	18,652	0
PUERTO ANGA MOS	OTHER PARTS OF NAMIBIA	7,315	11,517	0
PUERTO ANGA MOS	OTHER PARTS OF GEORGIA	722	16,532	1
PUERTO ANGA MOS	OTHER PARTS OF MALAYSIA	844	19,676	0
PUERTO ANGA MOS	OTHER PARTS OF THAILAND	1,431	20,763	0
PUERTO ANGA MOS	OTHER PARTS OF VIETNAM	747	20,316	0
SAN ANTONIO	KEELUNG	1,095	18,560	0
SAN ANTONIO	OTHER PARTS OF CHINA	2,504	18,778	0
VALPARAISO	OTHER PARTS OF CHINA	3,844	18,773	0
VENTANAS	DAIREN	46,942	19,129	0
VENTANAS	HUELVA	92,371	12,913	1
VENTANAS	OTHER PARTS OF FINLAND	7,829	15,401	1
VENTANAS	OTHER PARTS OF INDIA	198,924	18,167	0
VENTANAS	OTHER PARTS OF BULGARIA	63,417	16,576	1

PORT OF ORIGIN	PORT OF DESTINATION	GANGUE CONTENT	NAUTICAL DISTANCE	MARITIME ROUTE
		(ton)	(km)	Panama Canal = 1 No Panama Canal =0
VENTANAS	OTHER PARTS OF GERMANY	8,021	14,300	1
VENTANAS	OTHER PARTS OF BRAZIL	164,850	7,019	0
VENTANAS	OTHER PARTS OF CHINA	462,638	18,799	0
VENTANAS	OTHER PARTS OF KOREA	117,590	18,302	0
VENTANAS	OTHER PARTS OF JAPAN	264,105	17,265	0
VENTANAS	OTHER PARTS OF SWEDEN	8,150	15,265	1
VENTANAS	OTHER PARTS OF TAIWAN	7,784	18,616	0
VENTANAS	SHANGHAI	31,455	18,799	0

Source: Own elaboration.

Appendix E

Chile: GHG emissions generated by the sea transportation of the gangue content of copper concentrates exported, by importing country and for four scenarios for sensitivity analysis; 2014

IMPORTING COUNTRY	SCENARIO FOR SENSITIVITY ANALYSIS			
	A	B	C	D
	(ton of CO2-eq)			
GERMANY	23,747	20,779	28,497	24,935
BRAZIL	37,334	32,001	44,801	38,401
BULGARIA	30,132	26,365	36,158	31,638
CANADA	68	60	82	72
CHINA	609,663	522,569	731,596	627,082
SOUTH KOREA	148,157	126,991	177,788	152,390
SPAIN	41,028	35,900	49,234	43,080
PHILIPPINES	4,110	3,522	4,931	4,227
FINLAND	10,650	9,319	12,780	11,182
GEORGIA	126	110	151	132
NETHERLANDS	522	457	627	548
HONG KONG	873	748	1,048	898
INDIA	261,665	224,284	313,998	269,141
JAPAN	491,224	421,049	589,469	505,259
MALAYSIA	257	221	309	265
MEXICO	626	536	751	643
NAMIBIA	5,239	4,490	6,287	5,389
PERU	196	168	236	202
SWEDEN	7,205	6,304	8,646	7,565
TAIWAN	9,209	7,894	11,051	9,472
THAILAND	678	581	814	697
VIETNAM	235	202	282	242
TOTAL	**1,682,946**	**1,445,551**	**2,017,783**	**1,903,389**

Source: Own elaboration.

Appendix F

Chile: GHG emissions generated from smelting and refining copper exported concentrates at the 22 importing countries; 2014

IMPORTING COUNTRY	COPPER PROCESSED	EMISSIONS RATE	GHG EMISSIONS
	(ton refined Cu)	(ton CO2-eq / ton Cu)	(ton CO2-eq)
CHINA	917,245	0.65	596,209
JAPAN	783,348	0.75	587,511
INDIA	389,699	1.09	424,772
SOUTH KOREA	225,616	0.71	160,187
BRAZIL	137,271	0.54	74,126
SPAIN	130,299	0.38	49,513
BULGARIA	71,322	0.46	32,808
GERMANY	62,443	0.52	32,470
FINLAND	25,217	0.69	17,400
SWEDEN	17,821	0.67	11,940
TAIWAN	14,185	0.64	8,898
NAMIBIA	13,990	0.64	8,775
PHILIPPINES	7,466	0.64	4,683
PERU	3,834	0.64	2,405
MEXICO	3,506	0.64	2,199
NETHERLANDS	1,671	0.64	1,048
HONG KONG	1,481	0.64	929
THAILAND	1,106	0.64	694
MALAYSIA	385	0.64	241
CANADA	380	0.64	239
GEORGIA	372	0.64	233
VIETNAM	203	0.64	128

Source: Own elaboration.

3 **ESSAY III**. SMELTING AND REFINING COPPER IN CHILE: THE IMPORTANCE OF LOCAL POLLUTANTS[12]

Abstract

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[12] This work was carried out as a continuation of the one presented in chapter II, at the request of my supervisor Ramón López. The objective is to incorporate the dimension of local pollutants, which is not addressed in the paper of the previous chapter. Sturla, G. "Smelting and refining copper in Chile: The importance of local pollutants". *Working Papers Department of Economics*. School of Economics and Business, University of Chile. SDT 501. August 2020.

This work aims to illustrate the importance of local pollutants in the copper smelting and refining process. While there is a benefit to the global atmosphere of smelting and refining all copper in Chile, as shown by Sturla et al. (2020), it is necessary to take into account that, if such a policy is implemented, the country will have to bear a high pollution burden. Thus, this work addresses aspects that cannot be left out of a policy for copper concentrate: i) recognize the problem, ii) identify the most important pollutants, iii) review national and international literature, iv) identify problems associated with health and the environment, v) show the example of a slaughter area in Chile, and vi) refer to some estimated costs for the identified impacts. The work has a more informative than conclusive role, fundamentally as an input for a public policy for Chilean copper.

Keywords: Copper Mining, Local Pollutants, Health, Environmental, Slaughter Areas, Public Policy.

JEL Classification: Q32, Q42, Q56,

3.1 INTRODUCTION

Smelting and refining all the copper ore in Chile on the one hand helps to reduce global greenhouse gas (GHG) emissions (Sturla et al., 2020), but on the other hand, by concentrating this process in one country (in spite of 12 countries), greatly affects the local population and environment through concentrating the pollutants. Due to these effects, it is necessary to carry out a detailed analysis of the local pollutants involved and their potential negative impacts, since that impact should be taken into account in public policies surrounding copper.

Copper smelters and refiners are an important source of toxic pollutants for both humans and the environment. These pollutants include arsenic, which is an extremely toxic and dangerous element. Others are sulphur dioxide, which is an indirect greenhouse gas, and nitrogen oxides, which are direct greenhouse gases. Exposure to different gases and unwanted elements in the ecosystem can cause serious damage to the human body, from headaches to genetic damage, cancer, or poisoning. This is especially a concern when it comes to children since are the most sensitive to these pollutants due to their size and that they are growing. Many countries like Mexico and Chile have had this sort of issue. Another factor is the reduction of biodiversity in the affected environment. There can be contamination of the water with heavy metals or phenomenon such as acid rain. Toxins can also show up in agricultural produce, which obviously affects the consumers of such produce. Soil can be made practically unusable, and the air can become toxic. In addition, it contributes to climate change with the emission of greenhouse gases. The main local pollutants are Copper, Sulphur Dioxide, Nitrogen Oxides, Lead, Arsenic, Cadmium, Mercury, Zinc and Selenium.

In Chile the most important smelters and refineries are Chuiquicamata and Potrerillos from the state-owned Codelco, which are also refineries; Caletones of Codelco, Altonorte of Glencore, Chagres of Anglo American, which is also a sulfuric acid plant; Hernán Videla Lira of Enami; and lastly, Ventanas of Codelco, also a refinery and a sulfuric acid plant, an emblematic case of contamination.

Of course, copper producers are not alone in creating pollution. Ventanas, for example, is located in an industrial area with coal thermoelectric plants, chemical industries, along with other industry. They have contaminated the Quintero-Puchuncaví area to such an extent that it has been declared, by environmental groups, as a slaughter area. According to many studies carried out in the area over several years, there are many toxic and polluting elements in soil, area, and most importantly in the sea — fishing is another important industry in the area. The methods of study have varied widely atmospheric samples, soil samples, sea sediment samples, rainwater samples, and household dust, showing that pollution has affected all aspects of local life. Those that have caused adverse effects on marine life and human life, even raising the potential risk of children living in the area to have cancer.

Beyond quality of life, environmental pollution causes economic damage that can be quantified from health and remediation expenses. People getting sick costs additional health resources and is a loss of productivity; cleaning toxins out of the local environment is often quite expensive and time consuming. Of interest to this paper is the possibility to estimate the costs of specific pollutants, allowing us to evaluate the costs of copper smelting.

We start this paper going over each of the main local pollutants associated with the smelting and refining processes. Specifically, we focus on their effects on the environment and public health as documented in the literature, through notably most of that research comes from other locations. Secondly, we review the most important smelters and refineries in Chile along with other fixed emission sources. Subsequently, we discuss the specific case of the Quinteros-Puchuncaví is carried out. As mentioned earlier it is an industrial area considered as a "slaughter area" due to the multiple sanitary and environmental problems that have arisen in the area. Industries like the Ventanas smelter, four coal thermoelectric, ENAP maritime terminal, chemical industries like Oxiquim and many other industries are in the area. Then, we discuss some aspects about the economic costs associated with the industrial pollution and the specific pollutants, using international research on health and environmental pollution. Finally, we discuss the elements that need to be taken into account for an adequate analysis of the costs of increased copper smelting and refining in Chile.

3.2 LOCAL POLLUTANTS

3.2.1 Copper (Cu)

Only a small number of plants can live in copper rich soils, so copper can seriously impact agriculture depending on soil acidity of the soil and the presence of organic matter. It has a negative impact on the activity of microorganisms and earthworms. The decomposition of organic matter can decrease due to this. Animals can also absorb concentrations of copper that harm their health. Copper has been found to have a negative impact on soil in the Ventanas smelter area by causing a decrease in organic matter (Calisto, 2014). The same study also found copper impacting marine life. When examined, marine sediments from Quintero Bay, Chile, metal concentrations were found the suggest an anthropogenic origin related with copper which are most likely associated with by the copper smelter (Parra, et al., 2015). Also, in Quintero Bay, leaf samples were analyzed with a clear trend to increase the concentration of Cu with the proximity to the industrial complex (Gorena, et al., 2020).

3.2.2 Sulphur Dioxide (SO_2)

Sulphur dioxide is a colorless and toxic gas with an irritating odor and is a waste product generated from obtaining concentrates in the copper smelter. This pollutant reacts with humidity in the air and oxidizes in the atmosphere forming H_2SO_4 and lowering the pH of the rain, e.g. "acid rain." Rain and snow deposit, it in the soil, a process degrades soil and the plants on it. Near the Caletones copper smelter, the soils have high levels of aluminum (González, 2011). The main sources of contamination in the Karabash geotechnogenic system are atmospheric emissions of copper smelter, one of the main components of which are sulfur dioxides. This results in acid rain with anomalous concentrations of heavy metals and metalloids, which are withdrawn from atmosphere and accumulated in the forest floor and upper soil (Gashkina, et al., 2014). In the town of Bor, Serbia, situated in the immediate vicinity of one of the largest copper smelters in Europe, environmental pollution resulting from the SO_2 gas, PM_{10} particles, arsenic, and copper are several times above the limit values prescribed by EU Directives which seriously endangers human health in this part of Europe. Because of the location of the smelter plant there is also a risk of pollution on a wider scale even in other countries such as Romania and Bulgaria (Nikolic, et al., 2009).

3.2.3 Nitrogen Oxides (NO_x)

Nitrogen oxide (NO) is a colorless, highly reactive gas that contributes to global warming. Another contributing gas is nitrogen dioxide, a toxic and irritating yellow brown gas. Like sulfur dioxide, they are created from obtaining concentrates in the copper smelter. This pollutant reacts with humidity in the air and oxidizes in the atmosphere forming H_2SO_4 and lowering the pH of the rain. It is deposited in ecosystems by rain and snow creating soil and plant degradation. Near Caletones copper smelter, the soils have high levels of aluminum (González, 2011).

3.2.4 Lead (Pb)

Lead is a highly polluting and toxic heavy metal and is often the result of mining operations of minerals that include lead in their chemical composition. Many copper mining areas from the Glogow Copper Smelter Protected Forest in Poland to other smelter locations in Poland, Russia, and the Karabash area have high lead levels in nearby soil ((Kostecki, et al., 2015; Kabala, et al., 2001; Smorkalov, et al., 2011; Tatsii, et al., 2017). High lead levels have also been found in the blood of children living near smelters in Mexico as well as in the soil (Carrizales, et al., 2005). Along with humans, lead can also affect marine life, effects on Lake Serebry bream's kidneys are suggested to be due to cadmium and lead (Gashkina, et al., 2014).

3.2.5 Arsenic (As)

Arsenic is an extremely toxic metalloid normally found in the form of sulphide. It is a smelter waste from minerals that are contaminated with it, which is often the case with copper. Near a copper smelter in Bor, Serbia, the suspended particulate content of As was found to be consistently above the annual limit (Tasic, et al., 2017). In Huelva a copper smelter caused it to be one of the most arsenic particulate matter contaminated areas in Europe in 2001 and 2002 (Sánchez de la Campa, et al., 2007). Copper smelter workers are often exposed to high levels of arsenic, which results in health impacts. Chronic arsenic exposure involves increased risk to various forms of cancer and numerous non-cancer conditions, such as diabetes, skin diseases, chronic cough, and toxic effects in the liver, kidneys, cardiovascular system, and the peripheral and central nervous systems (Halatek, et al., 2014). Modeling of carcinogenic risk showed that dust ingestion was the most important pathway from arsenic, followed by inhalation (Fry, et al., 2020).

3.2.6 Cadmium (Cd)

Cadmium is one of the most toxic heavy metals. It is often found as a pollutant near copper smelters such as the one in Bor, Serbia, as well as other locations mentioned (Tasic, et al., 2017; Smorkalov, et al., 2011; Tatsii, et al., 2017). Cadmium has been found not only in soil and water but also in rice and vegetables grown near a copper smelter in China, and the hair and urine of local residents (Buyun Du, et al., 2020).

3.2.7 Mercury (Hg)

Mercury is an extremely toxic heavy metal and comes from the production of blister copper. Almost 400 kg of mercury is ejected into the atmosphere during production of 100.000 tons black copper at the Karabash copper smelter, leading to high contamination in atmospheric dust, soil, and lake sediment in the area (Tatsii, et al., 2017). In Fuyang, Zhejiang Province, secondary copper smelter China, the levels of soil mercury in the vicinity of the smelters have been substantially elevated following local smelting activities. The total accumulation of Hg in the topsoil of the study area of 10.9 km^2 is approximately 365–561 kg and of which 346–543 kg might be contributed by anthropogenic (Yin, et al., 2009).

3.2.8 Zinc (Zn)

Zinc is on its own a valuable metal, but is often found with copper, and thus is a copper smelting pollutant. Like the other minerals mentioned, it is often found polluting soil and water near copper smelters.

3.2.9 Selenium (Se)

Selenium is a nonmetal pollutant that is spread by dust from copper smelters. Like the others it has been found polluting in areas near smelters. Of particular interest, selenium concentrations in rainwater, soils and *alfalfa* at various sites from three different zones of Valparaíso, Chile, near the Ventanas Smelter (De Gregori, et al., 1999).

3.3 CHILEAN SMELTERS AND REFINERIES

3.3.1 Smelters

Figure 1 shows the seven largest Chilean smelters, of which five are state-owned companies such as Codelco and Enami. Notably the two with highest smelting capacity are state-owned, specifically Caletones and Chuquicamata, which are part of Codelco. Three of the seven are located in or near a slaughter area; these are Chagres, Hernán Videla and Ventanas.

Figure 1. Chilean smelters. Smelter owner, capacity of smelting in thousand tons, and if it is in or near a slaughter area.

Smelters	Owner	Capacity (ktpy)	Slaughter Area
Chuquicamata	Codelco	1.400	No
Caletones	Codelco	1.370	No
Altonorte	Glencore	1.160	No
Potrerillos	Codelco	680	No
Chagres	Anglo American	660	Yes
Hernán Videla L.	Enami	450	Yes
Ventanas	Codelco	430	Yes

Source: Own elaboration, based on Ramírez (2019).

3.3.2 Refineries

Figure 2 shows the three largest Chilean refineries are owned by the state through Codelco. One of them, the controversial Ventanas refinery of Codelco, is located in a slaughter area,

Figure 2. Chilean refineries. Refinery owner, capacity of refining in thousand tons and if it is in or near a slaughter area.

Refinery	Owner	Capacity (ktpy)	Slaughter Area
Chuquicamata	Codelco	540	No
Potrerillos	Codelco	130	No

Ventanas	Codelco	410	Yes

Source: Own elaboration, based on Ramírez (2019).

3.3.3 Other Pollutant Sources

Figure 3 shows other fixed pollutant sources in Chile such as oil refineries and coal thermoelectric plants. Most of these sources are located in or near slaughter areas; only one of the fourteen coal thermoelectric and one of the three oil refineries are not located in these areas.

Figure 3. Other Chilean fixed sources. Shows type source, the name(s) of the source, the owner(s), if it is in or near a slaughter area and the source power in megawatts.

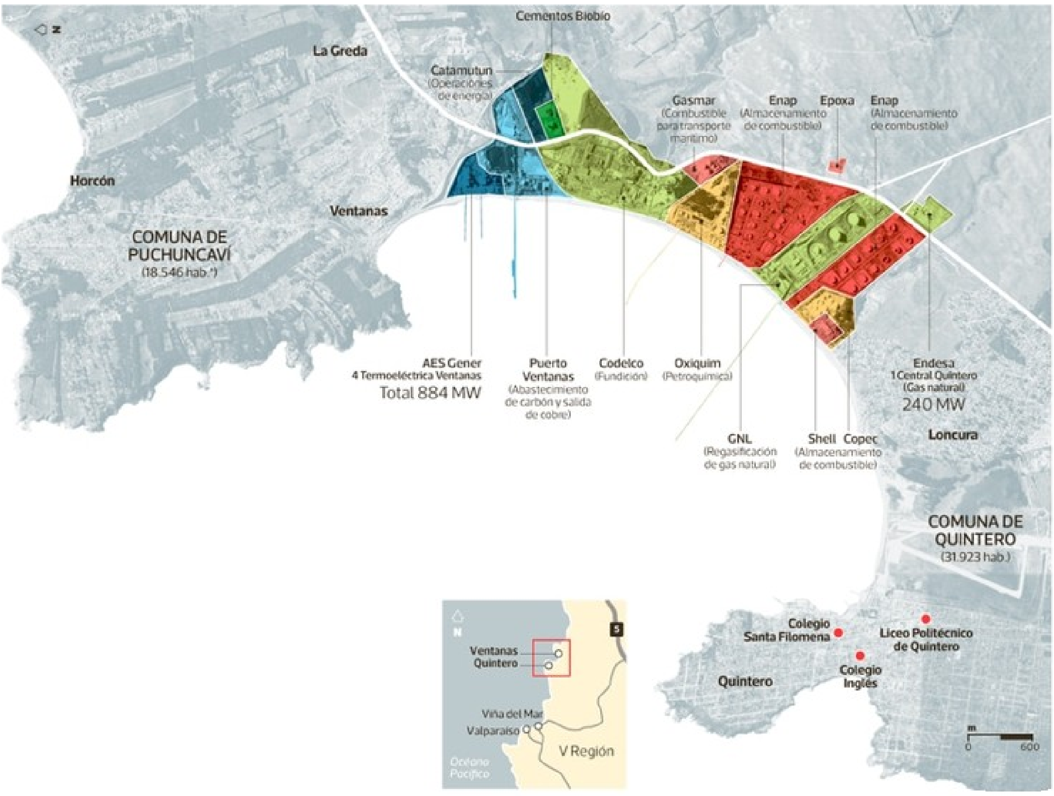
Source	Name	Owner	Slaughter Area	Power (Mw)
Oil Refinery	Aconcagua	Enap	Yes	-
Oil Refinery	Concepción	Enap	Yes	-
Oil Refinery	Gregorio	Enap	No	-
Thermoelectric	Tarapacá	Enel & Gas Atacama	No	158
Thermoelectric	Tocopilla U12-13-14-15	Engie	Yes	438
Thermoelectric	Norgener NT01-02	Aes Gener	Yes	275
Thermoelectric	CT Atacama	Engie & Andina	Yes	178
Thermoelectric	Mejillones CTM1-2	Engie	Yes	333
Thermoelectric	Angamos ANG1-2	Aes Gener	Yes	558
Thermoelectric	Cochrane CCH1-2	Aes Gener	Yes	550
Thermoelectric	Hornitos	Engie & Hornitos	Yes	178
Thermoelectric	IE1	Engie	Yes	375
Thermoelectric	Guacolda 1-2-3-4-5	Aes Gener	Yes	701
Thermoelectric	Ventanas	Aes Gener	Yes	322
Thermoelectric	Nueva Ventanas	Aes Gener	Yes	249
Thermoelectric	Bocamina I-II	Enel	Yes	445
Thermoelectric	Santa María	Colbún	Yes	342

Source: Own elaboration, based on Carmona (2018).

3.4 THE QUINTERO-PUCHUNCAVÍ SLAUGHTER AREA

It is an industrial area considered as a slaughter area due to the multiple sanitary and environmental problems that have arisen in the area. Polluters include the Ventanas smelter, four coal thermoelectric plants, the ENAP maritime terminal, chemical industries like Oxiquim, along with many other industries. Figure 4 shows the Quintero-Puchuncaví industrial complex and some of the industries located in the area, which are close to many schools. These are; Catamutun, Cementos Biobío, Ventana's Port, Gasmar, Oxiquim, Enap, Epoca, GNL, Shell, Copec and Endesa. Codelco appears in green with an approximately area of 5 km^2, corresponding to the Ventanas smelter and refinery, which has a smelting and refinery capacity of 430 and 410 thousand tons per year.

Figure 4. Map of Quintero-Puchuncaví industrial complex. It shows some industries and schools located in the zone.

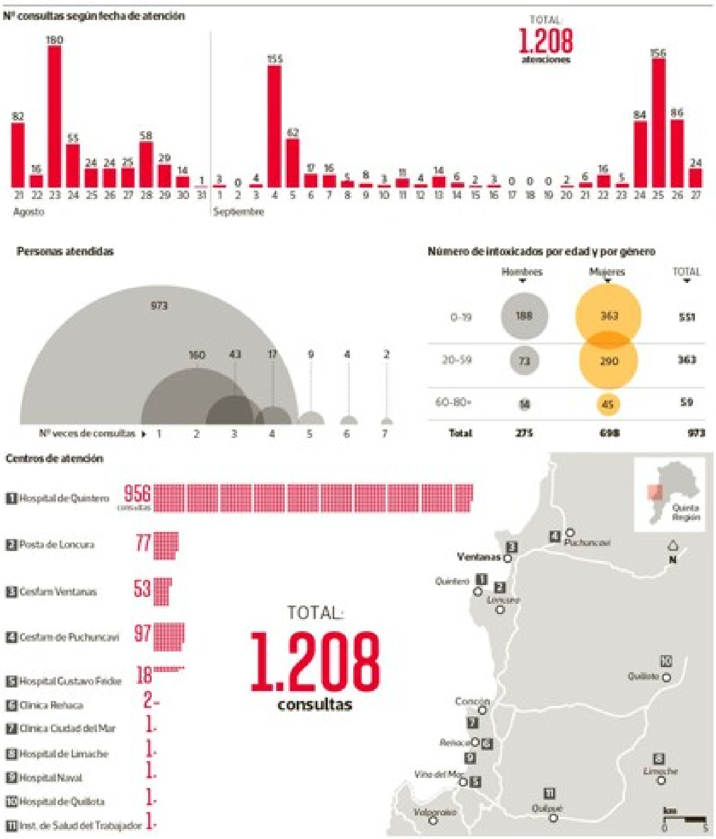


Source: Sandoval, et al. (2018).

Due to the exposure of different pollutants in the area, the population may suffer from many health difficulties. Headache, vomiting, tachycardia, and respiratory issues are some of the reactions that residents of the sector could present due to exposure to toxic gases. Cases of mothers with spontaneous abortions have been reported, along with fetal and infant health issues including growth retardation, cognitive and intellectual deficits, microcephaly, and craniofacial malformations. Regarding arsenic, long-term exposure increases the risk of developing bronchopulmonary, bladder, kidney and urinary tract cancer, liver and skin, risk of myocardial infarction and strokes. This carcinogenic risk is particularly high for children between 1 and 5 years old, along with other genetic damage (Tapia-Gatica, et al., 2020). Tapia-Gatica (2020) specifically assessed the non-carcinogenic and carcinogenic health risks due to exposure to trace elements in soil and indoor dust in Puchuncaví valley. Indoor dust was more important than soil in terms of human exposure to trace elements because it was so polluted and the amount of time people spend at home. Carcinogenic risk due to arsenic exposure was above the threshold value in the population of young children (from 1 to 5 years old) in all studied areas, including the controls, and in children (from 6 to 18 years old) in the exposed area. Such risk values are classified as unacceptable by the US Environmental Protection Agency, requiring some target intervention from the Chilean government (Berasaluce, et al., 2019). The environmental effects in the area are very intense, highlights the year 2018, according to Figure 5:

- Number of queries: 1,208
- People served: 973
- Intoxicated men: 275
- Intoxicated women: 698

Figure 5. Environmental effects at 2018 year in Quintero-Puchuncaví zone. It shows queries by number, people served by age and gender, and queries by medical center.



Source: Cerda (2018).

Figure 6 shows an analysis of cases of poisoning where the main symptoms were:

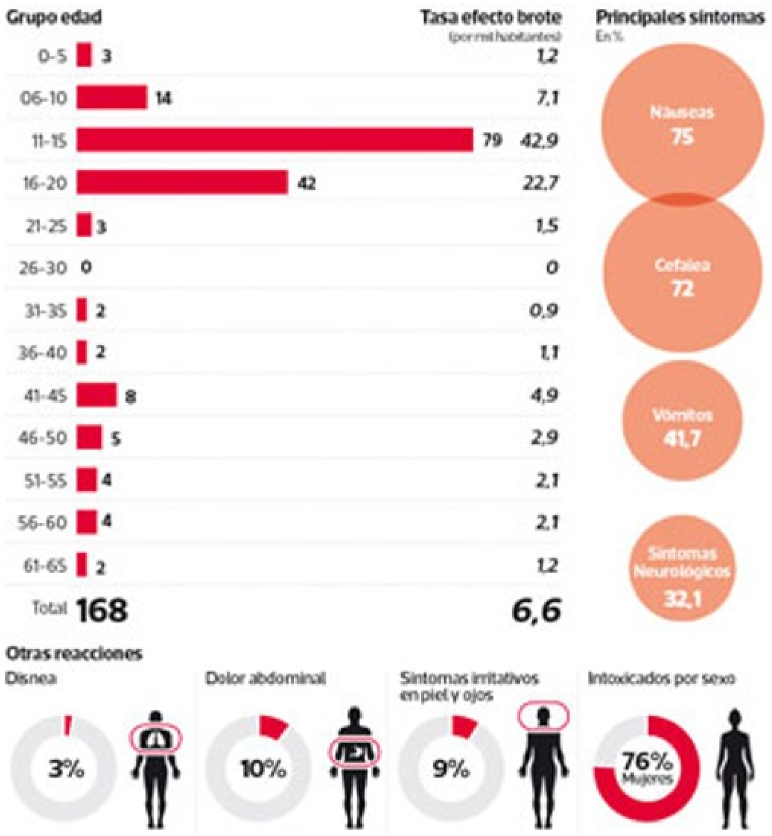
- Sickness: 75%
- Headache: 75%

- Vomiting: 42%
- Neurological systems: 32%

The age range with the most symptoms was 6-20 years, representing 80% of the total cases.

- Other symptoms correspond to:
- Dyspnea: 3%
- Abdominal pain: 10%
- Skin and eye irritation: 9%

Figure 6. Analysis of cases of affected people, by age and gender.



Source: Solorio (2018).

Air quality is one of the environmental problems that most directly affects the population. There are pollutants like; SO_2, particulate matter (MP_{10}), Pb, As, Mo, V and Cd. Water quality is also great concern and discussion since it affects local industries such as preservation, fishing, research, tourism, and real estate. Contamination of Cu, As and Cd has been found in 100% of the species near the Ventanas smelter.

There has been a decrease in biodiversity due to the presence of heavy metals, as well as copper. Hg, Cu, Cd, Zn, Pb, Cr, As, suspended solids, oils, fats in marine life, and change water pH. This leads to changes in water temperatures as well. An important percentage of the soil is contaminated with Cd, Cu, Pb, Cr, As, Ni and Se as a result of particulate matter pollution. There is strong erosion of the soil and, consequently, a decrease in organic matter. Soil acidity also causes plants to have difficulties absorbing nutrients and increases the solubility of certain metals (Cu and Zn) causing a toxic effect on plants (Calisto, 2014). Based on the estimated concentrations of exchangeable Cu, 10, 15 and 75% of the study area exhibited a high, medium and low risk of phytotoxicity, respectively (Tapia-Gatica, et al., 2020). There are other toxic compounds present such as toluene, methichloroform (banned since 2015) and nitrobenzene. Different contaminants were found in analyzed soil samples at high concentrations, specifically Cu, Cd, As, Ni, Pb V and Zn. The risk ratio values were higher for children than for adults both due to ingestion and dermal absorption. Pb was the most polluting based on all the studied contamination indexes, followed by Cu, As, Cd and Zn. (Tume, et al., 2019). Marine sediments from Quintero Bay were analyzed, the metal concentrations found suggest an anthropogenic origin related with Cu, Se, Mo, As, Sb and Pb. The heavy metal-bearing particles such as Cu, Zn, As and Pb are most likely associated with by the copper smelter (Parra, et al., 2015). The results of a study on the chemical composition of rainwater as an environmental pollution factor in the surroundings of the Puchuncaví-Ventanas industrial complex showed elements emitted by anthropogenic activities significantly polluted the rainwater of the area studied. The risk assessment showed that as content in rainwater is above the WHO guideline value for drinking water at some points in the study area (Cereceda-Balic, et al., 2020).

The aims of one research project were to assess the usefulness of a specific tree species as a biomonitor. The leaf samples were taken from five selected sites, located between 0.8 to 15 km away from the spelter. Leaf concentration of As, Ca, Cd, Cu, Dy, Er, Gd, K, Li, Mg, Mn, Mo, Na, Nd, P, Pb, Pr, S, Sb, Ti, Yb and Zn showed statistically significant differences between sampling sites. Increased concentrations of Cu, Sb, S, As, Cd and Pb were found depending on geographic closeness to the smelter. The high values of Cu and As were observed near the industrial area exceed phytotoxic levels. This provided the greatest variance the component related to industrial activity specific to copper smelters and refineries (Gorena, et al., 2020). The main results of atmospheric samples to evaluate pollution levels found long-term patterns of atmospheric deposition. The samples gave elements deposition values (Al, As, Ba, Cd, Co, Cu, Fe, K, Mn, Pb, Sb, Ti, V and Zn) in the insoluble fraction of the total atmospheric deposition. Results showed that again areas closer to the smelter were more polluted (Rueda-Holgado, et al., 2016).

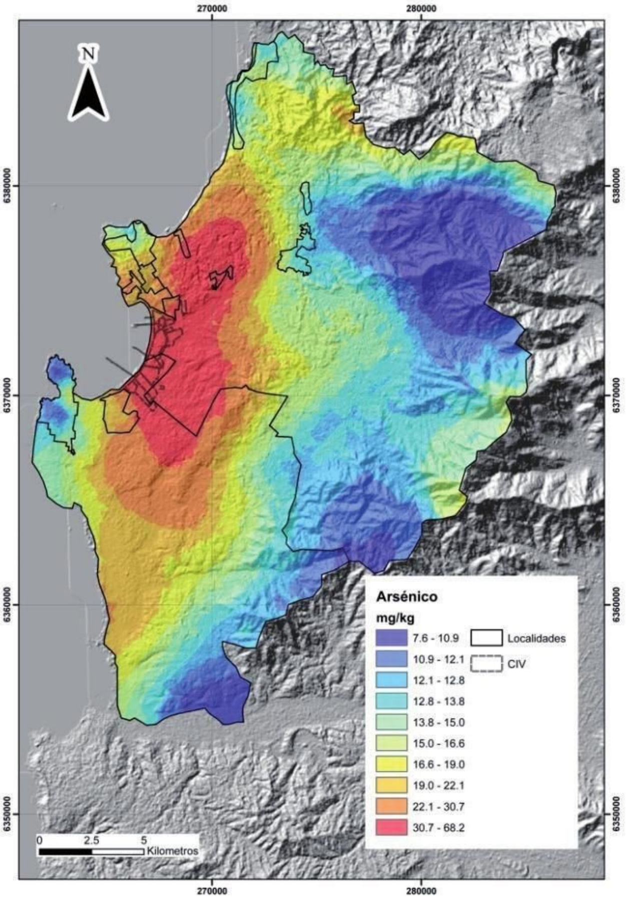
Neaman et al. (2009) analyzed soils exposed to emissions from the Ventanas copper smelter. Using perforated plastic bottles in the soil and testing based on how often it rained, they studied soil pH, free $Cu2^+$ activity, and total dissolved copper. Topsoil (up to 30 cm) had lower pH and higher copper concentrations compared to soil lower in the ground of up to 10 times more copper concentration and 2.6 lower pH.

Salmanighabeshi, et al (2015) also investigated soil pollution by elemental contaminants and compared ecological risk indexes related to industrial activities for the case study of Puchuncaví-Ventanas. Selected elements (As, Pb, Cd, Ni, Hg, V, Mn, Zn, Sr, Sb, Cr, Co, Cu, K, and Ba) were analyzed during a long-term period (2007–2011). The results suggested that a copper smelter and a coal-fired power plant complex were major pollution sources.

According to Codelco itself, the pollutants related to Ventanas smelter are SO_2, particulate matter and As, but Pb, Zn, Ni and others may also be involved.

When we specifically look at arsenic in Figure 7, again concentrations of this toxic element increase as get closer to the industrial complex with ranges between 30 and 68 mg/kg. The scope of the significant concentrations is approximately 20 km from industrial complex in every direction.

Figure 7. Arsenic (As) spatial distribution, in milligrams per kilogram of sample.



Source: Poblete, et al. (2018).

3.5 SOME ASPECTS OF ECONOMIC COSTS

Environmental pollution causes damage to the economy that can be quantified from health and environmental remediation expenses. Costs could be due to say heavy metals leaching during food waste composting or the treatment and lost wages costs of arsenic contamination of drinking water. It is possible to estimate expenses resulting from environmental pollution based on concentrations of specific pollutants.

3.5.1 Environmental costs

Heavy metals in leachate during food waste composting may produce different degrees of pollution hazards and further induce environment costs when the concentrations of heavy metals exceed the dis-charging quality standards. Chu et al (2019) estimates the heavy metal environmental costs from food waste composting in Minhang food waste treatment plant located in northern Shanghai. Major findings of this study are the pollution hazard rate of Cd amounts to 94.03%, and the environmental costs caused by heavy metals in leachate during food waste composting amount to US$ 0.52 per ton. This magnitude of environmental costs is meaningful and significant, considering that it is equivalent to 2.97% of Shanghai's food waste treatment charges.

Understanding the potential for reducing air pollution emissions and the associated costs is a prerequisite for designing cost-effective control policies. In one study, a model was updated to estimate the abatement potential and the marginal cost of multiple pollutants in China. The associated control cost of such reductions was estimated at CNY 92.5 and CNY 469.7 million for SO_2 and NO_x respectively. Notably it also found that regions with high GDP tend to have higher total abatement costs. End-of-pipeline technologies tended to be a cost-effective way to control pollution in industry processes, while such technologies were less cost effective in fossil fuel related sectors compared to renewable energy. The marginal reduction cost curves developed in this study can be used as a crucial component in an integrated model to design optimized and cost-effective control policies (Zhang, et al., 2020).

The negative health effects of mercury poisoning have been documented for both chronic and acute exposure. Today, exposure to Hg is largely diet or occupationally dependent. Hylander, et al. (2006) puts a tentative monetary value on Hg polluted food sources in the Arctic, where local, significant pollution sources are limited, and relates this to costs for strategies to avoid Hg pollution and to remediation costs of contaminated sites in Sweden and Japan. The cases studied are relevant for point pollution sources globally and their remediation costs ranged between 2,500 and 1.1 million US dollars per kilogram of Hg isolated from the biosphere.

Holland (2019) reviews the environmental risks to human health associated with the primary and secondary production of copper, rare earth elements, and cobalt. The environmental cost range of air pollution in Europe is from 3.7 to 40.2, 12.3 to 124.3 and 14.2 to 88.4 thousand euros per ton of NO_x, PM_{10} and SO_2, respectively. In the worst case, the estimate of the costs of air pollution for a ton produced of primary and secondary copper is a total of 53,870 euros.

3.5.2 Health costs

Mahanta et al. (2016) estimates the health costs of arsenic contamination of drinking water in Assam, India, where nearly one million people were affected. Using data collected through a primary survey of 355 households in 2013, it estimates health costs due to arsenic contamination. The estimates show that the average annual health cost of a 1 microgram increase in arsenic concentration per liter of drinking water is about INR 4 per household. Furthermore, if the average level of arsenic concentration was reduced to the safe limit of 50 microgram per liter, the average annual welfare gain for a household is estimated to be INR 862 (USD 14). Projecting these figures to the entire arsenic-affected population of Assam, the annual health costs of a 1 microgram increase in arsenic concentration per liter are estimated to be about INR 0.76 million (USD 0.01 million), and the welfare gains from reducing the level of arsenic concentration to the safe limit are estimated to be INR 153 million (USD 2.49 million). The results also indicate that these health costs and welfare gains vary significantly across different levels of arsenic concentration and across districts.

Another study estimates the health damages due to arsenicosis among people residing in two districts of Bihar, India. Arsenic field test kits were used to test the arsenic level in drinking water. The water test results indicate that 18.3% of the sample contained 50 ppb of arsenic, and 5.12% of the sample had levels between 300 and 500 ppb. Water source pollution, doctor visits, work loss, and arsenic concentration levels are all found to significant and positively related to arsenicosis, and awareness is significant but negatively related to arsenicosis. Per-capita income, sanitation, awareness, and depth of water sources are significant and positively related to defensive activities, i.e., water purification. The annual wage loss, cost of treatment, and cost of illness for sample households are estimated as INR 2437.92 ($45.83), INR 5942.40 ($111.72), and INR 8380.32 ($157.55), respectively. The annual cost of illness for the society is estimated as INR 265.97 million ($5 million) (Thakur, et al., 2019).

3.6 CONCLUSION

From the reviewed information it is found that the main local pollutants are SO_2, NO_x, Pb, As, Cd, Cu Hg, Zn and Se. Those elements have effects on people's health, from respiratory illnesses to cancer. Also, on the environment, the presence of heavy materials in the vicinity of smelters, generates air pollution, with both particulate matter and greenhouse gases; water pollution; and reduction of biodiversity.

In the case of Chile, there are a total of 7 smelters, 3 of which are also refiners, and 2 of which are sulfuric acid plants. In 2018, they produced a total of 1,246 thousand tons of molten copper and 2,461 thousand tons of refined copper in 2018. They are concentrated in the center of Chile, and in the Atacama and Antofagasta Regions in the north. Especially, in the area of the Ventanas smelter, there have been a high number of environmental and health problems with the ecosystem has been affected by gases and polluting elements. to the extreme of being declared a slaughter area.

Any public policy that involves increasing copper refining and smelting in Chile must consider these aspects: the environmental impact and the health of the population. Regarding cost valuation, international research gives some suggestions regarding environmental and health costs. It is important to bear in mind that this has been presented in the form of "some aspects," given the complex and specific locality of this valuation process; the objective has been to shed insights on this issue. This does not mean that these processes cannot be developed to add more value to copper and reduce global GHG emissions, however, any such development should be located in accordance with a land use policy considering the health and local environmental impacts described here along with their costs.

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4 **ESSAY IV**. EFFICIENT WATER ALLOCATION WHEN CLIMATE IS CHANGING: AN INTERDISCIPLINARY APPROACH[13]

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[13] Sturla, G.; López, R. and Figueroa B., E. "Efficient Water Allocation When Climate Is Changing: An Interdisciplinary Approach". *Working Papers Department of Economics*. School of Economics and Business, University of Chile. SDT 489. September 2019. http://econ.uchile.cl/es/publicacion/efficient-water-allocation-when-climate+is-changing-an-interdisciplinary-approach

Abstract

This study analyzes the effects of rising water supply variability provoked by climate change on the welfare of a society whose economy heavily depends on water availability. Several studies recommend that communities should impose policies that ensure a minimum level of water allocation for human consumption. We compare two contracts, one where society allocates to the firm a fixed proportion of the annual water-runoff; and the other one, where due to the uncertainties of climate change, the community instead allocates to human consumption a fixed annual amount of water-runoff. We consider a risk-averse community. We show that, unless water supply is absolutely fixed, a higher variability and scarcity of water supply does not necessarily imply that society is better off choosing a contract that assures a minimum water for human consumption. Depending on the characteristics of water supply frequency distribution, particularly the third moment, it is possible that society would not benefit by switching to the fixed allocation contract for human consumption. We illustrate the main analytical results using data and runoff climate change projections from a water basin located in the central region of Chile, showing that in this case the community is better-off sticking to the current contract.

Key words: Water economics, Climate change, Runoff variability, Water policies.

JEL Classification: Q54, Q25, Q58

4.1 INTRODUCTION

Allocating and protecting natural resources for both productive purposes (i.e. mining, agriculture, forestry, aquaculture and so on) and human consumption are critical for a healthy functioning of ecosystems and human well-being (Stern, 2007; Figueroa and Calfucura, 2010).

In the last decades, economic growth based on the exploitation of natural resources has been widely questioned due to the cumulative degradation of natural capital, the large levels of pollution generated, and the lack of suitable policies (SCOS, 2019; OECD, 2013; World Bank, 2011; Stern, 2007). There is a general awareness of the need to reorient the objectives of economic growth; this is not related only to the health of the planet, but also to the economy itself. Development is unthinkable without purposely designing specific policies for the use of renewable and non-renewable natural resources (López & Figueroa, 2016; Taylor et al, 2014). This is why several of the seventeen United Nations´ Sustainable Development Goals defining the 2030 agenda for achieving global sustainable development are directly concerned with improving the use, management and protection of natural resources (UN, 2018).

In this context, economic analysis has been important in considering natural capital as a factor of production, as well as making a distinction between clean and dirty industries and considering the irreversibility of the stock of natural capital (López & Yoon, 2014; López & Yoon, 2016). The transition to a clean economy is complex, as it depends on characteristics of each country and the actual needs of the world economy (ECLAC, 2016; OECD, 2016).

A key natural resource that illustrates much of the above concerns is water, which is in part a renewable resource (rivers, aquifers, lakes) as well as a non-renewable one (rock and surface glaciers, icefields). On the other hand, water is a factor of production that is essential to practically all industries and has a fundamental value as consumption good.

Water is the primary resource through which climate change influences Earth’s ecosystem, thus affecting the livelihood and well-being of societies (UN-Water, 2010). The most sensitive element to climate change has probably been its effect on water availability and its increasing variability (Levitus, 2009; Hansen et al., 2010). The heterogeneous nature of water, both in terms of its physical properties, either spatial or temporal, has turned it into a permanent concern nowadays, when we are faced to a specific scenario of anthropogenic climate change (IPCC, 2014; IPCC, 2007; Schmidt, G). Water scarcity affects more than 40% of the global population and is projected to rise; and, over 1.7 billion people are currently living in river basins where water use exceeds recharge (UN, 2018). Moreover, higher temperatures and extreme, less predictable, weather conditions are projected to affect availability and distribution of, 2014, snowmelt, river flows and groundwater, and further deteriorate water quality; additionally, more floods and severe droughts are predicted. Changes in water availability will also affect health and food security and have already proven to trigger refugee dynamics and political instability (UN-Water, 2019a). Under present climate variability, water stress is already high, and climate change adds even more urgency for action. Moreover, without improved water resources management, the progress towards achieving the Sustainable Development Goals are seriously jeopardized. In fact, adaptation to climate change is mainly about better water management (UN-Water, 2019b).

Spatial distribution and extreme natural events are important factors impinging upon the availability and quality of water (Wan Alwi, 2008). In this sense, one should raise many complex questions requiring interdisciplinary analyses such as the one made in this study. This way of thinking allows picturing the water allocation problem taking into consideration fundamental elements that have not been satisfactorily added to economic models so far, including the timeframe of records for decision making, trade-offs between variability and resource preservation, productive role and human consumption assurance (Lenzen et al., 2007).

In this context of increased uncertainty, there is a remaining certainty: increased water stress and meeting future demands will undoubtedly require increasingly tough decisions about how to allocate water resources between competing water uses. Such as for human consumption versus irrigation, for human direct use versus production goals, for home use versus ecological flow, etc., including for climate change mitigation and adaptation. Moreover, to create a sustainable future, business as usual is no longer an option and water management needs to be scrutinized through a lens that focus on the increased climate variability in a planet whose climate is affected by human activities and the resulting global warming (UN-Water,2019c).

Dealing with the increased uncertainty caused by global climatic conditions needs a policy framework that deals explicitly with the new water problems (Hansen et al., 2012; ECLAC, 2016). The tools currently available allow reducing the risks on key aspects, such as human consumption, where general circulation models gain significance, as they allow making runoff forecasts in different regions (IPCC, 2014).

When discussing problems of water scarcity, it is important to consider that this is not only linked to the physical availability of the resource. Aspects such as the lack of appropriate infrastructure or inefficient public policies, can lead to serious problems of scarcity in areas where there is enough water, even considering climate change projections (Barbier, 2019).

In this study, an interdisciplinary analysis is performed to provide insights on the most efficient policies that ensure water allocation for human consumption, using an economic model that explicitly takes into consideration the crucial role of the variability of water runoff as treated in hydrological models. To illustrate the results obtained using the conceptual model and their implications, we present an empirical application to a water basin of the southern Central part of Chile.

Studying the case of Chile is interesting on several grounds. World Bank (2011) is the most significant study on Chile's water, which discusses multiple components regarding resources and provides an accurate diagnosis. It emphasizes the need for a national water policy that captures the heterogeneous nature of the country's climate and that takes future scenarios into account. Several studies emphasize the need for economic and social approaches (Garreaud, 2011), in consideration of the fact that 70% of Chile's current environmental conflicts are directly related to water (INDH, 2012). Various studies on the economics of water and climate change in Chile have been performed (CEPAL, 2009; Figueroa and Calfucura 2010; Vicuña et. al, 2012). These studies have had a significant impact; however, none of them has addressed the close link between climatic variability, economic production and water allocation for human consumption.

In the model proposed here, we consider a society hosted in a hydrological catchment, which bases its economy in its water resource, and it has property rights over it, which allows society to charge for the use of the water resource by a firm using it. The firm produces goods employing labor and water as inputs. Society ´s income comes from labor income of workers employed by the firm and from the extraction of part of the firm´s economic rent through taxation (Wessel, 1967). The relationship between the society and the firm is defined by a contract, which rules the sharing of the water resource between them. Two types of contracts are analyzed: 1) the firm is bestowed the use right over a fixed proportion of the annual water resources available and the rest is allocated to human consumption; and, 2) society assures a fixed amount of water for its own consumption needs and the remaining water, if exists, is allocated to the firm.

A common hypothesis which is implicitly or explicitly imbedded in water policies of different countries is that, under conditions of increased water scarcity and variability, caused for example by climate change, contracts akin to the second one of the two contracts just mentioned should be preferable to those similar to the first one (IPCC, 2014; World Bank 2011). The main objective of this paper is to theoretically and empirically assess this hypothesis.

An important issue in deciding water policies is the institutional context. A key institutional factor is the existence of water trading systems which allow communities to buy or sell water to other communities. (Meinzen-Dick et al., 2002; Gazmuri & Rosegrant, 1996). This is important because water scarcity is not homogenous within countries or regions even in conditions of water stress caused by climate change. Water surplus regions coexist with water scarce ones, often separated by not too great distances. This renders the possibility of water trade among communities. (Dinar & Saleth, 2005; Grey & Sadoff, 2007; Vatn, 2010). Moreover, many countries have the capacity to desalinize sea water which brings another opportunity to water-scarce regions to buy desalinized water. Of course, the cost of purchasing water from other regions or from desalinizing plants can be quite steep, which is a feature that is considered by the ensuing model. (Meinzen-Dick et al., 2002; Ahmed et al., 2017; Baawain, 2015).

The model in this paper assumes that water trade is feasible, allowing water scarce communities to purchase water, albeit at high prices. It is the option of water trading that brings into question the conventional advice to first assure water for human consumption and then allow the residual water to be used for productive purposes. This assumption makes the model more relevant to middle income and developed countries which often have the institutional conditions that allow water trading among communities and/or have the capacity to produce water desalination. The conventional advice may be correct for poor countries that do not have these capacities.

There are many experiences in the world of water exchange within the same basin and between nearby basins, countries such as the United States, Australia, Canada, Spain, Chile and India show the active role of water rights markets which has allowed the water transfer between basins, conditioned by the regulatory framework and the existing infrastructure (Maestu, 2013). Climate change has accelerated the pressure for the mobility of water resources in countries with high hydro-climatic heterogeneity (Rayl, 2016). The case of Spain has been recognized as one of the most successful experiences of interregional water trade in the world (De Stefano & Llamas 2012). Chile has high climate heterogeneity and a market for flexible exploitation rights; in its northern zone, in a context of severe water scarcity and low Government participation as a regulator, the purchase of water, previously used for agricultural and domestic purposes, by mining localities is quite common (Bitran et al., 2014).

4.2 THE MODEL

Assumptions:

- The model considers a small and open local or regional economy (represented by the water basin).

- The total water annually available from natural local sources is assumed to be exogenously given. It is determined by a climatic factor where the future is represented with different states of nature.
- Society in the region or basin can buy water from elsewhere at a cost which can be considerable.[14]
- The production function of the firm located in the region uses labor and water as inputs and exhibits constant returns to scale.
- When the firm's labor demand is less than the basin's labor supply, the surplus workers may find employment in another basin.
- If the labor demand is greater than the basin's labor supply, the firm may hire workers from outside the basin. The salary is constant, so it will be considered $w = 1$.[15]
- Population in the basin is fixed.
- Society has a well-defined concave utility function.

Contract 1

- The firm must pay to the community, in the form of a local tax, a fixed proportion of its income net of labor costs obtained every year.
- The firm must hire labor from the basin and can only hire people from outside the basin after full employment is reached in the basin.
- The firm fully uses every year their fixed portion of the total runoff.

Contract 2

- Conditions of Contract 2 are identical to Contract 1 except that the firm can only use the surplus water after the water consumed by society instead of a fixed portion of the total water available.

Parameters:

$\bar{L}$ = Fixed number of workers in the basin.

α = Coefficient associated with the water factor in the production function

$1-\alpha$ = Coefficient associated with the labor factor in the production function

β = Portion of the firm's income net of labor cost which is paid to society every year for use of the society's water

θ = Fraction of annual volume allocated to the firm in the form of water use rights

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[14] This assumption reflects the fact that water availability is not homogenous across all regions or basins; even in very dry years some communities may experience substantial water surplus part of which could be sold to other communities that are experiencing water shortage. Also, this assumption is consistent with the fact new technologies allow the extraction of water from non-conventional sources such as sea water via desalinization at more reasonable costs.

[15] That is, the labor market in the basin is integrated with the rest of the country so that the society is a wage taker.

$1-\theta$ = Fraction of annual volume allocated as use for human consumption rights

a = Exogenous cost of supplying water from other sources (e.g., from desalinization of sea water).

C_h = Volume of water needed for human consumption, assumed fixed.

Endogenous Variables (Contract j=1,2)

R_j = Optimal income of the firm net of labor cost.

L_j = Optimal labor demand.

V_j = Expected utility of the society.

Exogenous Variables (states of nature i =1, …, I)

p_i = Probability that the volume of water is the one associated to the state i of nature.

q_i = Probability that the volume of water for human consumption in the state i of nature is lower than the water needed for human consumption.

N_i = Total water volume associated to the state i of nature.

Objective of a benign policymaker or planner

The key objective of the analysis below is to ascertain which of the two contracts would maximize Society's expected utility. Importantly, we do not necessarily assume that society maximizes its expected utility, rather we try to mimic the choice of a policy advisor or planner who has all the information needed to solve the expected utility maximization problem.

4.2.1 Firm´s optimization problems

4.2.1.1 Contract 1

The community allows the firm to use a fixed proportion θN of the total water available and therefore there is a volume $(1-\theta)N$ of water left for consumption of the community. If $(1-\theta)N < C$ then the community must purchase water for its consumption at a price per unit equal to a. The firm's production is assumed to be a Cobb-Douglas function of water (θN¿ and labor (L_1¿

The income of the firm net of labor cost is:

$$R_1 = ¿ \qquad [1]$$

The firm maximizes the income using labor as a variable. Noting that by choosing the appropriate units of labor we can assume that w =1, we have:

$$máx_{L_1} ¿ \qquad [2]$$

By solving the optimization problem, the firm's labor demand is obtained:

$$L_1 = [1-\alpha]^{\frac{1}{\alpha}} \theta N \qquad [3]$$

By replacing the optimal labor demand [3] in the firm income function [1], we get the optimal income net of labor cost for the firm:

$$R_1 = A\theta N \qquad [4]$$

Where $A \equiv ¿$

Given that $\alpha < 1$ we have that $0 < A < 1$. Thus, the net income of the firm is proportional to the amount of water available to the firm.

4.2.1.2 Contract 2

In the case of Contract 2 the community first assures itself full consumption from the local water availability sources and allows the firm to use the remnant available.

For Contract No. 2, the firm uses the total water volume available minus the water for human consumption which in this case is a fixed amount. If such remnant is positive then the income of the firm net of labor cost is,

$$R_2 = ¿ \qquad [5]$$

The firm maximizes its net income using labor as a variable:

$$máx_{L_2} ¿ \qquad [6]$$

By solving the optimization problem, we get the firm's labor demand,

$$L_2=[1-\alpha]^{\frac{1}{\alpha}}(N-C_h) \qquad [7]$$

By replacing the optimal labor demand [7] in the firm´s income [5], we get the optimal income net of labor cost for the firm in a period:

$$R_2=A\cdot(N-C_h) \qquad [8]$$

4.2.2 Society's expected utility

The analysis considers the expected value for I states of nature. Although each state of nature corresponds to a series of time, the theoretical analysis focuses on one period, without loss of generality. In the empirical analysis, time is explicitly considered.

4.2.2.1 Contract 1

Society's total income has three components: the labor income; the portion β of the firm´s rent that society obtains via a tax; and the cost of ensuring human consumption of water in years of deficit. Assuming that q is the probability that the total volume of local water is lower than the volume needed for human consumption, society's income under Contract 1 for estate of nature i is:

$$S_{1,i}=w\overline{L}+\beta R_1-q_i a[C_h-(1-\theta)N_i] \qquad [10]$$

For simplicity, we can omit without loss of generality the labor income, which will always be the same for all contracts; then replacing [3], [4] and [9] in [10] we have:

$$S_{1,i}=\beta A\theta N_i-aq_i\cdot\left[C_h-(1-\theta)N_i\right] \qquad [11]$$

Thus, the expected value of the utility of the community is,

$$V_1=\sum_{i=1}^{I}p_i\cdot u\left[\beta A\theta N_i-q_i a\cdot\left[C_h-(1-\theta)N_i\right]\right] \qquad [12]$$

Where $u(S)$ is the utility function of the community, assumed to be increasing and strictly concave.

4.2.2.2 Contract 2

The analysis here is similar to the one for Contract 1, but in this case, there is no cost associated to ensure human consumption of water. Then, from the previous analysis, we have derived the expressions [13] and [14] below for the society's income at state i and its expected utility.

$$S_{2,i}=\beta A\left(N_i-C_h\right) \qquad [13]$$

$$V_2=\sum_{i=1}^{I} p_i \cdot u\left[\beta A\left(N_i-C_h\right)\right] \qquad [14]$$

4.3 ANALYSIS OF THE ALTERNATIVE CONTRACTS

4.3.1 Comparison under uncertainty

Since $u>0$, $u'>0$ and the probabilistic structure of runoff is the same under both contracts, for a given state of nature i, Contract 1 will yield higher income than Contract 2 if:

$$\beta A\theta N_i-a q_i \cdot \left[C_h-(1-\theta)N_i\right]>\beta A\left(N_i-C_h\right) \qquad [15]$$

To perform an uncertainty analysis considering the expected utility for the I states of nature, we use a third order Taylor approximation of the utility function around the income´s mean, μ_S. Then we express the expected utility function in terms of three first central moments of income as follows:

$$E\left[u(S)\right]\cong E¿$$

Thus, we have:

$$E\left[u(S)\right]\cong u(\mu_S)+\frac{u''(\mu_S)}{2}\sigma_s^2+\frac{u'''(\mu_S)}{6}\gamma_s \qquad [16]$$

Whereσ_{si}^{2} and γ_{Si} $(i=1,2¿$ are the variance and third moment[16] of the income under contracts 1 and 2, respectively. A key issue is that the moments of the income distribution are, in turn, determined by the moments of the distribution of the water runoff. Climate change thus affect the distribution of water runoff, leading to concomitant changes in the income distribution moments, which in turn affect the expected utility under each of the contracts in a differential way. From (16) it is clear that, given that the utility function is identical for both contracts, the level of the expected income (the first moment of the distribution) and hence of the expected water runoff level affect the expected utility under each contract identically. Therefore, for the purpose of comparing the two types of contract we need to focus only on the higher order moments of the distribution. The differential effect of climate change under each contract concerns only the second and third moments of the distribution of water runoff and hence second and third order moments of the resulting income distribution.

Central Proposition. Contract 2 should be preferred to contract 1 if and only if:

$$\sigma_{s2}^{2}-\sigma_{s1}^{2}+\frac{1}{3}\frac{u^{'''}}{u^{''}}\left[\gamma_{S2}-\gamma_{S1}\right]<0 \qquad [17]$$

Where, $u^{'''}/u^{''}$, is the so-called "prudence coefficient" (Kimball, 1990) (with $u^{'''}$and $u^{''}$ representing the third and second derivates, respectively).

Proof.

Using equation [16] we have the expected utility for both contracts:

$$E\left[u(S_1)\right]\cong u(\mu_S)+\frac{u''(\mu_S)}{2}\sigma_{s_1}^{2}+\frac{u'''(\mu_S)}{6}\gamma_{s_1}$$

$$E\left[u(S_2)\right]\cong u(\mu_S)+\frac{u''(\mu_S)}{2}\sigma_{2}^{2}+\frac{u'''(\mu_S)}{6}\gamma_{s_2}$$

The Contract 2 should be preferred to contract 1 when:

$$E\left[u(S_1)\right]-E\left[u(S_2)\right]<0$$

---

[16] Note that γ is the third central moment of the income distribution, which is different from the income skewness (or its coefficient of skewness) which is equal to $\gamma/\sigma^{(3/2)}$. It is important to keep in mind this difference for our analysis below regarding the relevance of the income's asymmetry to deciding whether contract one or contract two is preferred. In order to be able to separate the effects of the variance and the asymmetry of income on this decision, we use the third moment instead of the coefficient of skewness.

Or equivalently (Taylor approximation of the utility function around the income´s mean, μ_S):

$$\frac{u''(\mu_S)}{2}\sigma^2_{s_1}+\frac{u'''(\mu_S)}{6}\gamma_{s_1}-\frac{u''(\mu_S)}{2}\sigma^2_2-\frac{u'''(\mu_S)}{6}\gamma_{s_2}<0$$

Multiplying by $\frac{2}{u''(\mu_S)}$ the above equation and factorizing we have that Contract 2 should be preferred to contract 1 if and only if:

$$\sigma^2_{s2}-\sigma^2_{s1}+\frac{1}{3}\frac{u'''}{u''}\left[\gamma_{S2}-\gamma_{S1}\right]<0$$

☒

In the following analysis for the sake of simplicity we assume a strictly concave Cobb-Douglas utility function, $u(\mu_S)=\mu_S^{\varepsilon}$, where $1>\varepsilon>0$ is a fixed parameter. Then we have that the prudence coefficient is,

$$\frac{u'''}{u''}=\frac{\varepsilon-2}{\mu_S}<0.$$

Now, using (17) and evaluating it at the runoff mean we have that contract 2 is preferred to contract 1 if and only if,

$$\sigma^2_{s2}-\sigma^2_{s1}<\frac{1}{3}\frac{(2-\varepsilon)}{(\overline{N}-C_h)A\beta}\left[\gamma_{S2}-\gamma_{S1}\right] \qquad [18]$$

The main justification used by the proponents of contract 2 is to reduce the variance of the income received by society each year. Thus, the case of interest consists of the one in which $\sigma^2_{s2}<\sigma^2_{s1}$ and, from the inequality obtained in [18]. Clearly, if the distribution of income and water runoff were merely normal, contract 2 should indeed always be preferred to contract 1. However, since there is no *a priori* reason to assume a normal distribution, we consider the case of a more general distribution which has non-zero higher order moments. Assuming that the third order moment is non-zero, we obtain the following two propositions.

Proposition 1

Assume $\sigma^2_{s2}<\sigma^2_{s1}$, if the income third moment associated with contract 2 is greater or equal than that associated with contract 1, $\gamma_{S2}\geq\gamma_{S1}$, then contract 2 should be preferred.

***Proof*.**

By construction the following term of equation [18] is always positive,

$$\frac{1}{3}\frac{(2-\varepsilon)}{(\overline{N}-C_h)A\beta}>0$$

Then, if $\gamma_{S2}\geq\gamma_{S1}$, the right side of the equation [18] will be grater or equal to cero,

$$\frac{1}{3}\frac{(2-\varepsilon)}{(\overline{N}-C_h)A\beta}[\gamma_{S2}-\gamma_{S1}]\geq 0$$

Finally, considering that $\sigma_{s2}^2-\sigma_{s1}^2<0$, the inequality [18] will be satisfied for any combination of parameters and average runoff.

☒

Proposition 2

Assume $\sigma_{s2}^2<\sigma_{s1}^2$, if the income third moment associated with contract 2 is lower than that associated with contract 1, $\gamma_{S2}<\gamma_{S1}$, then the choice of the best contract is ambiguous.

Proof.

Then, if $\gamma_{S2}<\gamma_{S1}$, the right side of the equation [18] will be lower than cero,

$$\frac{1}{3}\frac{(2-\varepsilon)}{(\overline{N}-C_h)A\beta}[\gamma_{S2}-\gamma_{S1}]<0$$

Considering that $\sigma_{s2}^2-\sigma_{s1}^2<0$, the inequality [18] indicates that,

- Contract 2 will be preferred to contract 1 if only if,
  $$\sigma_{s2}^2-\sigma_{s1}^2-\frac{1}{3}\frac{(2-\varepsilon)}{(\overline{N}-C_h)A\beta}[\gamma_{S2}-\gamma_{S1}]<0$$
- Contract 1 will be preferred if only if,
  $$\sigma_{s2}^2-\sigma_{s1}^2-\frac{1}{3}\frac{(2-\varepsilon)}{(\overline{N}-C_h)A\beta}[\gamma_{S2}-\gamma_{S1}]>0$$

☒

Corollary 1

Ignoring the income´s third moment leads to choose contract 2, but including it in the analysis, may under certain conditions render contract 1 optimal.

Proof.

Follows directly from Proposition 1 and Proposition 2.

☒

Thus, the fact that many analyses focus exclusively on the effect of climate on increasing the runoff variance may lead them to wrong policy conclusions. The choice of the optimal is thus in general ambiguous. Moreover, it is also possible that the optimal contract choice switches over time as the endogenous weights attributed to the second and third order moments may vary over time. This is what we call the "switching effect".

4.3.2 The switching effect

The equation [18] can be expressed as,

$$\varphi_1(\sigma¿¿2¿¿S2-\sigma^2{}_{S1})¿¿ -\varphi_2\,(\gamma¿¿S2-\gamma_{S1})<0¿ \qquad [19]$$

where,

$$\varphi_1 \equiv ¿ -C_h¿A\beta$$

$$\varphi_2 \equiv \frac{1}{3}¿\,\varepsilon¿$$

The fact that φ_1 is a function of $\overline{N}$ (the total availability of water) implies that its value may change over time; on the other hand, φ_2 is constant. In a climate change context water availability may change in a non-monotonical way over time, that is, $\frac{d\overline{N}}{dt}$ could be positive or negative, depending on the geographical region in which the hydrological catchment analyzed is located.

Proposition 3

If the effect of climate change in a particular region implies that $\frac{d\overline{N}}{dt}<0$, *the reduction of* φ_1 *lowers the importance of the income's variance differential* $(\sigma¿¿2¿¿S2-\sigma^2{}_{S1})¿¿$ *and, therefore, the income´s third moment differential* $(\gamma¿¿S2-\gamma_{S1})¿$ *may acquire greater relevance on the contract decision. On the* *other hand, if the effect of climate change on the geographical region under analysis implies that* $\frac{d\overline{N}}{dt}>0$, *the income´s third moment differential loses relevance on the contract decision.*

Proof*.*

If $\frac{d\overline{N}}{dt}<0$, then from equation [19], $\frac{d\varphi_1}{dt}<0$ and $\frac{d\varphi_2}{dt}=0$.

Since φ_1 decreases and φ_2 remains constant over time, from equation [19] it is easy to see that the third moment differential acquires greater relevance along time on the contract decision.

The proof for the case $\frac{d\overline{N}}{dt}>0$ is like the opposite case.

☒

Corollary 2

In a climate change context, and in a particular geographical region where $\frac{d\overline{N}}{dt}<0$, *if the* third moment of income *under contract 2 is lower than under contract 1, it is possible to choose contract 2 in the period* $[0, t^{¿}]$ *and then switch to contract 1 in the period* $[t^{¿}+1, T]$. *Therefore, the temporal income´s third moment differential could produce a switching effect in the society's contract decision.*

Thus, the conventional wisdom advising communities to choose contract 2 may be right in the early phases of climate change. However, for regions experiencing a continuous decline in precipitation it is possible that this choice ceases to be optimal beyond a certain point in time.

4.4 EMPIRICAL ANALYSIS

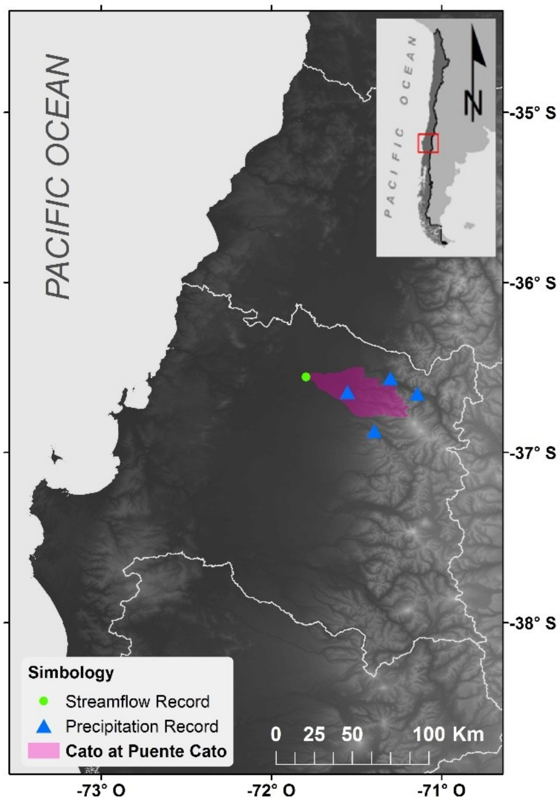
4.4.1 Runoff projections

In this section, we illustrate the analysis regarding the optimality of either of the two contracts under study applying the model to data from the catchment "Cato at Puente Cato", located in the Central South Region of Chile (Figure 1). We use data of runoff projections for the period 2020-2050 arising from climatological models, and representative values of the key parameters.

The central south region of Chile corresponds to a very sensitive zone in terms of the effects of climate change, whose impacts are amplified because this region concentrates intensive economic activities in the use of water, like mining, hydroelectricity, agricultural, forestry, tourism, etc. (Garreaud, 2011; World Bank, 2011: Rubio-Álvarez, et al., 2010). Moreover, while this region tends to experience a relatively low availability of water runoff it is not far from other catchment areas which often have significant water surplus, a situation which is expected to continue even under pessimistic climate change conditions. This validates our assumption that is possible to buy water from other regions in periods of necessity, albeit at relatively steep prices due to the high costs of transferring water from other catchment areas.

Figure 1

Chile: Cato at Puente Cato catchment location



Source: Own elaboration based on Barría et al., 2017.

It is also important to note that this case study corresponds to a geographical region in which the projected climate change effect is a significant reduction in the annual runoffs. Thus, in terms of section 3.3, we are analyzing a case in which $\frac{d\overline{N}}{dt} < 0$ (see Figure 2).

Future water availability is assessed by running a hydrological model driven by projections from global climate models (GCMs). Uncertainties in these projections arise from three main sources: the GCM used for simulating the future climatic variables (temperature and precipitation), the downscaling methodology used to translate the variables to the catchment scale, and the hydrological model used to estimate water runoff (Barría et. al 2017).

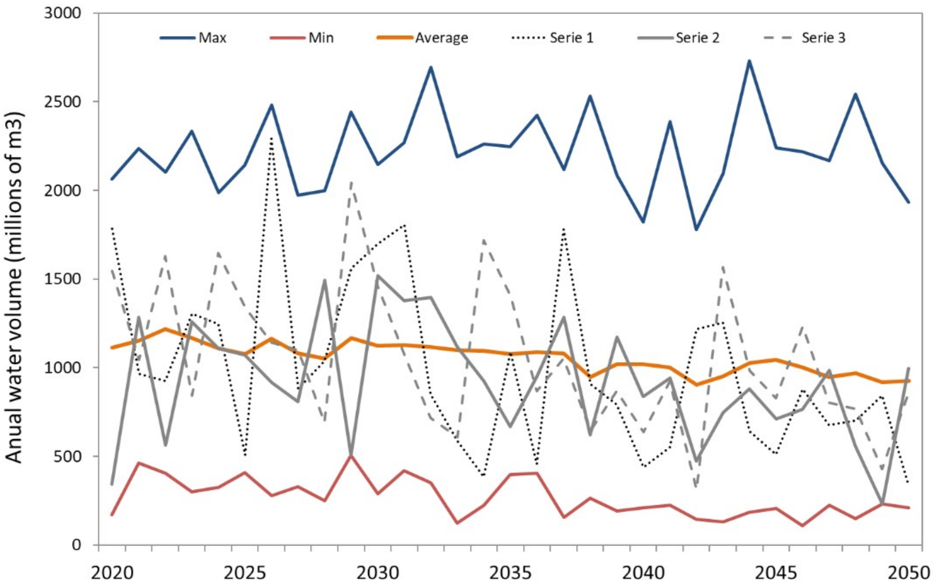
In this way, considering 83 projections of precipitation and annual temperature for the period 2020-2050 (GCMs), we can generate 83 independent series of annual runoff, using a Precipitation Evaporation Runoff model (PERM) (Barría et al. 2017; Peel et al. 2015). Each one of the independent series is assumed to have the same probability. We have used the same downscaling methodology.

Figure 2 presents the average, the maximum and the minimum value at each year, for the 83 runoff annual series generated; also, it presents only 3 time series, chosen at random from the 83-projection series.

Figure 2

Chile: Example of 3 projected runoff series for Cato catchment

(Millions of cubic meters)



Source: Own elaboration based on data obtained from Barría et al., 2017.

Figure 2 shows that the average annual runoff will decrease from 1,112 MM m^3 to 927 MM m^3 over the 2020-2050 period, an 8% reduction. This reduction of the average runoff is accompanied by an increase in the runoff variability. The latter is even noticeable in the increase range between the minimum (red line) and maximum values (blue line) of runoff associated with the 83 series shown. This reflects both the uncertainty of the projections and the fact that climate change increases extreme events, both drought and abundance of water runoff (IPCC, 2014; World Bank 2011).

In this way, there are 83 runoff values for each year (states of nature), with which it is possible to calculate for each one of the two contracts, and for each year: 83 values for the society's annual income, mean, variance and third moment, of society’s income, as well as society´s expected utility.

4.4.2 Parameters

We assume the existence of a representative agricultural firm in the basin, and a downstream town whose inhabitants work in the firm and capture a portion of the rent, via local taxes. The town dwellers consume water from the basin, but they also have the possibility of buying water from elsewhere. We consider the case of buying water from other catching regions or water desalinization as the main external sources. Below are the values used for the parameters.

A: As defined in section 3.2.1, A is a function of the parameter α.The value of α is estimated at around 0.5 for a representative agricultural firm (Kijne et al., 2003); then A takes a value of 0.25.

θ: The proportion of the total water used by the agricultural firm is 0.7. This value is based on data showing the relative proportion between human consumption and agriculture water demands in the central south region of Chile (DGA, 2017).

C_h: Annual water consumption per person is estimated at 75 m^3 (DGA, 2017). So, knowing the population in the basin we obtain the total value of human water consumption.

β: For Chile the net income tax rate applicable to firms is 0.27 (27% of the firm´s income)[17]. We assume that the central government captures half of this amount and the rest stays in the locality; then the estimated value for the parameter is 0.135.

a: Alternative cost of water purchases. This cost is estimated around 0.75 USD/m^3, considering the location of the catchment (Ahmed et al., 2017; Baawain et al., 2015). The annual water consumed per person is 75 m^3 (DGA, 2017), and for the annual income of a person we use the annual legal minimum wage for Chile of 5,000 USD[18]. Then the value of the parameter is 0.10.

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[17] https://www.leychile.cl/Navegar?idNorma=6374

[18] https://www.bcn.cl/leyfacil/recurso/sueldo-minimo,-sueldo-base-derecho-a-semana-corrida

4.4.3 Simulation results

Table 1 shows the values of the parameters used,

Table 1

Parameters used in the simulation

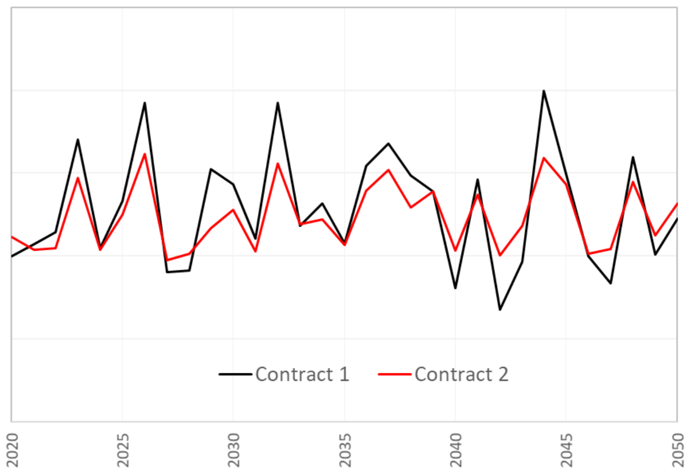
Parameter	Value
A	0.250
β	0.135
θ	0.700
a	0.100
C_h	0.300
ε	0.700

Source: Own elaboration.

Figures 3 below shows the variance of income for the 83 runoff scenarios considered for each year under contracts 1 and 2. Figure 4 shows the same data for the third order moment of income. Similarly, Figure 5 shows society´s expected utility for each year, also considering the outcome of the 83 scenarios in each year.

Figure 3

Income´s Variance

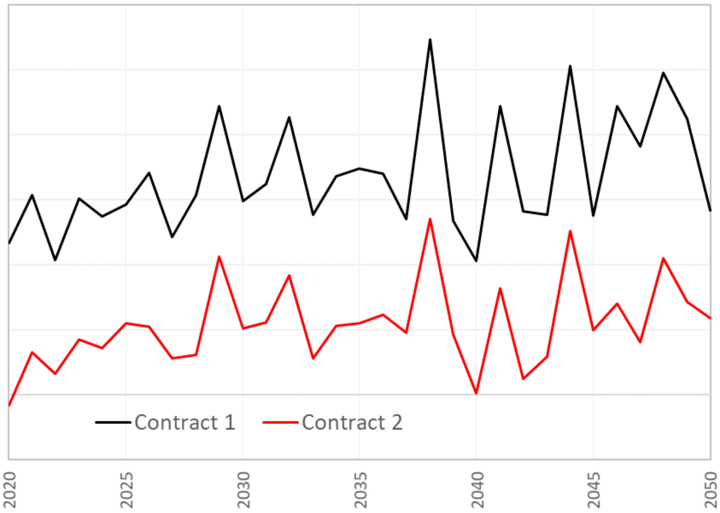


Source: Own elaboration.

Figure 3 shows that, as expected, the income variance under contract 2 in fact tends to be lower than under contract 1. While there are switching effects in some years, the income variance under contract 2 is lower than under contract 1 in about 75% of the years. Income variance under contract 1 is lower than under contract 2 in years with high water abundance when the probability of not satisfying human consumption is very low.

Figure 4

Income´s Third Moment

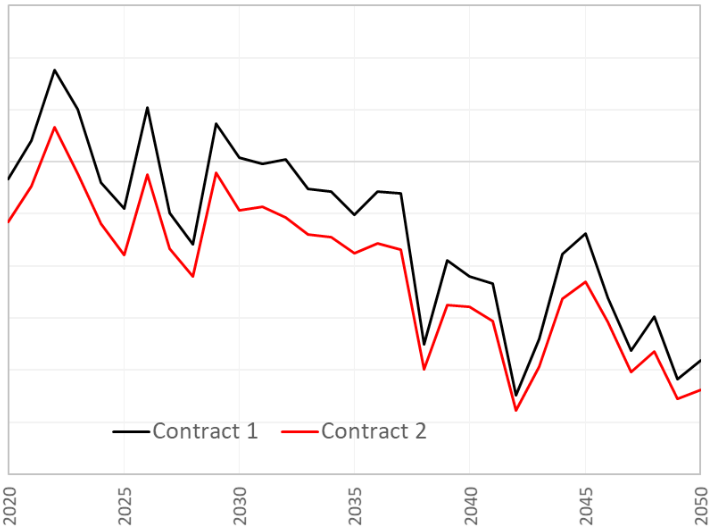


Source: Own elaboration.

Figure 4 shows that the income third moment is consistently lower under contract 2 than under contract 1 in all years. Thus, there is a trade-off between the contracts as the one that tends to exhibit a higher variance also has higher third moment. Hence, the net expected utility effect is potentially ambiguous. However, as Figure 5 shows, the expected utility is higher under contract 1 than under contract 2 in all periods. That is, the third moment effect dominates the variance effect.

Figure 5

Society's Expected Utility



Source: Own elaboration.

4.4.4 Sensitivity: An increase in alternative cost of water

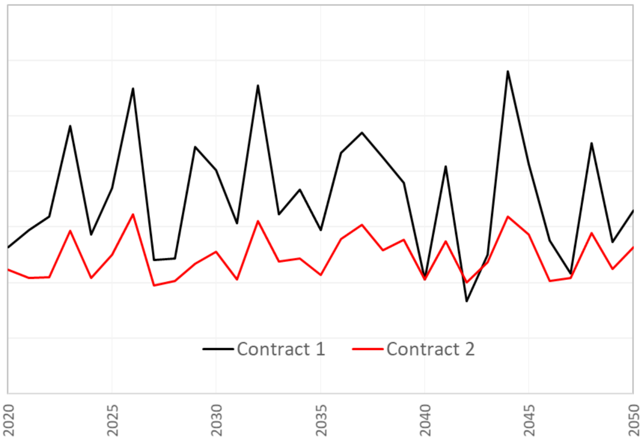
Suppose that the cost of water purchases increases by 33,3%, from 0.75 to 1.00 USD/m^3, then the value of a changes to 0.15. All other parameters in Table 1 remain the same. Figure 6 shows the new society´s expected utility.

When the cost of external water increases contract 1 becomes costlier. This reduces the expected utility differences between the contracts compared to the previous simulation. In fact, for some years the expected utility under contract 2 is now higher than under contract 1. As was seen in the theoretical analysis, contract 2 is better than contract 1 when the relative importance of the income´s variance dominates the relevance of income´s third moment.

When the alternative cost of water increases there is a substantial increase of the income variance under contract 1 (Figure 6). This is because the income variance is increasing in a. With respect to contract 2, the income variance is not affected by the value of a.

Figure 6

Income´s Variance (new simulation with a = USD 1/m^3)



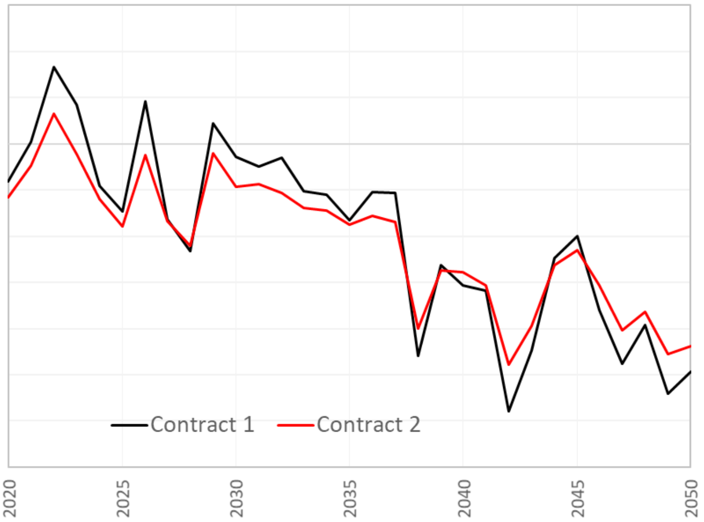
Source: Own elaboration.

On the other hand, the value of the third moment is not affected by the level of a under both contracts 1 and 2. Hence, the third moment differentials between the two contracts remain unaffected; Figure 4 is still valid in this case.

Figure 7 below shows the evolution of the expected utilities for each of the two contracts considered. As can be seen in the Figure in this case we do have a switching effect. The expected utility of contract 2 is now higher than under contract 1 for the first 15 or 16 years, of the period analyzed, but a switch does occur in the year 2035 when contract 1 becomes the preferred choice. This switching in the latter part of the period is consistent with the fact that water runoff becomes scarcer over time, which as shown in the theoretical model, eventually makes the importance of the third moment differential between the contracts to become higher vis-à-vis the second moment differential.

Figure 7

Society’s Expected Utility (new simulation with a = USD 1/m^3)



Source: Own elaboration.

4.5 CONCLUSION

Mitigation and adaptation to climate change and global warming requires urgent and large improvements in water resources management. From a national, a regional or a basin context, adaptation to climate change is in large part about better water management and requires wise decisions about the alternative use of hydrological resources, especially in those geographical areas where they are expected to be scarcer and to exhibit a greater variability (UN-Water, 2019b).

Using a multidisciplinary approach, combining modeling from economic and hydrological sciences, we have shown the importance of incorporating the expected increase in future water variability in water management and in water allocation decisions. In fact, in the theoretical model proposed here we have shown the role played by the variability (second moment) as well as by the asymmetry (third moment) of the probability distribution of the annual income of a society.

We derived the theoretical conditions under which society should prefer one of two different contracts that assign the annual available water between human consumption, on one hand, and productive activities carried out by a firm that pays to the society for the use of water, on the other hand. These conditions allow us to analyze conceptually and to test empirically a hypothesis that is commonly imbedded in water policies advices to different countries, prescribing that, under conditions of increased water scarcity and variability caused by climate change, contracts assuring human consumption provision should be preferred. We theoretically show that the choice between the two contracts considered is complex particularly in the general case in which the water runoff and hence income distribution is asymmetric. We derived the conditions under which the above prescription is indeed optimal and cases in which it is not. We used the theoretical insights from our model and we empirically apply the model using data and parameters of a catchment area located in the Central South Region of Chile, as well as data on the water runoff projections for this catchment for the period 2020-2050.

For the basin studied in Central Chile, the empirical data used, and the parameters considered in our empirical model lead to an ambiguous case in which the analyzed hypothesis in not necessarily sustained. In fact, our results indicate that contract 1 (assuring to the productive firm the provision of a given percentage of the annual water availability) should be preferred to contract 2 (assuring human consumption) in most cases, even when water scarcity and variability increase over time. This is because the effect of the symmetry of society´s income (its third moment) is determinant in this case, since it turns out to dominate the effect of the variance of society´s income under most scenarios. Thus, we provide here an empirical example that contradicts the commonly used hypothesis we are testing. That is, even though the society´s income variance is greater under contract 1 than under contract 2, this is not enough to unambiguously make contract 2 optimal (the contract that assures human consumption). However, if the cost of alternative water increases, it is possible that there is a switch effect, and contract 2 may become optimal in certain periods.

Evaluating which contract is better for society by analyzing only the variance of runoff, and therefore of society´s income, is insufficient and can lead to a wrong decision. As shown in this paper, incorporating in the analysis the third moment (asymmetry) of water runoff admits the possibility of an ambiguous case, in which it will be better to prefer a water allocation scheme in which the best way to ensure human consumption is through purchases of water outside the basin, instead of assuring the water provision from the runoff in the basing itself.

The most important lesson of the present paper is that water management policy recommendations require in-depth analyses of the water catchment area considered, as well as of the possibility and costs of water purchases from other catchment areas or from water desalinization sources that may be available. General and sweeping policy recommendations risk making serious mistakes which may negatively affect the welfare of communities.

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