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A review of the future impact of climate change in Chile: economic output and other outcomes

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Abstract

I review several studies for the future impact of climate change during the twenty-first century, making a comprehensive summary of the effects estimated for Chile. Several studies suggest that Chile is likely to suffer mild effects in terms of GDP growth, labor productivity, and mortality costs from climate change in the twenty-first century. However, there is substantial uncertainty around these estimates, with at least one study predicting significant GDP losses due to adaptation difficulties. I compute a principal component factor that summarizes the information from six different measures of GDP loss as a single variable, showing a low principal component value for Chile. Furthermore, several studies find that Chile may face non-GDP-related problems from climate change, such as air pollution, fire hazards, drought, water stress, biodiversity loss, ecosystem damages, and human migration. Finally, according to several indexes, Chile is still only in the middle of the table in terms of policy, infrastructure, and climate readiness. Chile is also below several developed countries in terms of government expenditure on environmental protection and environmental taxes, while at the same time presenting a high value of fossil fuel subsidies. Therefore, there is substantial room to improve economic and environmental policies to fight climate change.

Keywords Economic growth · Global warming · Latin America · GDP losses from climate change

JEL Classification 044 · 054 · Q51 · Q59 · R11

1 Introduction

Climate change is predicted to negatively affect the economic growth of almost all countries (OECD 2015; Kahn et al. 2021). The Latin American and Caribbean countries will be strongly affected by climate change due to their oceanic location, their proximity to the Equator, and their dependence on the agriculture and fishing sectors (Vergara et al. 2013; Barcena et al. 2019). Due to its worst impact on the

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poorest countries and the poorest households, climate change will be a significant threat to economic growth and attempts to reduce income inequality in Latin American countries (Barcena et al. 2019; Cavallo and Hoffmann 2020). Furthermore, climate change has a direct impact on the achievement of 16 of the 17 Sustainable Development Goals (SDGs) and the fight against climate change presents several synergies to the targets of all the 17 SDGs (Nerini et al. 2019), affecting health, poverty, hunger, inequality, and ecosystem preservation, among others (Nerini et al. 2019; Zhenmin and Espinosa 2019).

This paper provides a broad review of the economic impact of climate change in Chile, considering a wide range of multinational studies on different economic effects, with a special focus on GDP losses (Burke et al. 2015; Kahn et al. 2021) and physical risks (OECD 2015; McKinsey 2020). This is a relevant topic as middle-income countries, such as Chile, need to catch up with the environmental policies of the advanced economies and the literature lacks a comprehensive review of the impacts of climate change for Chile and other Latin American countries. I start by showing that Chile had a small rise in temperature since 1900 when compared to the other Latin American and Caribbean countries[1] and OECD members.[2] A review of forecasts for the twenty-first century from other studies shows that Chile is expected to experience a smaller degree of temperature increase and sea level rise than other countries. Therefore, although exposed to sea level rise, fires, and floods through its coastal geography, Chile's environment may experience smaller weather changes relative to the rest of the globe (World Bank 2013, 2021).

I then compare the effects of climate change on the Chilean GDP relative to other countries from four major studies: Burke et al. (2015), Kalkuhl and Wenz (2020), Kahn et al. (2021), Roson and Sartori (2016). All these studies include weather effects from temperature and precipitation on GDP. The first three studies use similar GDP data for a large number of countries and then estimate the sensitivity of GDP growth to weather. The classic study of Burke et al. (2015) considers country-specific fixed-effects and quadratic time trends, while estimating a quadratic function for the weather effects and time shocks that are common across countries. Kalkuhl and Wenz (2020) improve upon this study by a significant expansion in sample size (since the study considers observations for the regions of each country, rather than just country aggregates) and by accounting for changes in the temperature of each country over time. Kahn et al. (2021) take a different approach by considering the lags of the countries' growth rates and weather changes besides country fixed effects, rather than considering quadratic time trends which may be implausible as approximations for longer time periods. Finally, I consider the Roson and Sartori study, which measures the loss of GDP from climate change by summing the effect on GDP of five components: sea level rise, agricultural productivity, heat effects on labor productivity, human health, and tourism flows.

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[1] The Latin America and the Caribbean (LAC) region includes 19 countries: Argentina, Bahamas, Brazil, Chile, Colombia, Costa Rica, Curacao, Dominican Republic, Ecuador, El Salvador, Haiti, Honduras, Jamaica, Mexico, Paraguay, Peru, Saint Kitts And Nevis, Trinidad and Tobago, Uruguay.

[2] The OECD includes 37 member countries, of which 3 countries (Chile, Colombia, Mexico) are part of the LAC region: Australia, Austria, Belgium, Canada, Chile, Colombia, Czech Republic, Denmark, Estonia, Finland, France, Germany, Greece, Hungary, Iceland, Ireland, Israel, Italy, Japan, Korea, Latvia, Lithuania, Luxembourg, Mexico, Netherlands, New Zealand, Norway, Poland, Portugal, Slovak Republic, Slovenia, Spain, Sweden, Switzerland, Turkey, the UK, the USA.

A graphical analysis shows that the Burke et al. (2015), Kalkuhl and Wenz (2020), and Roson and Sartori (2016) predict a low impact of climate change on the Chilean GDP during the twenty-first century, with estimates of the GDP loss for 2100 in the RCP 8.5 scenario[3] of − 32% (Burke et al. 2015), + 0.3% (Roson and Sartori 2016), and + 6.1% (Kalkuhl and Wenz 2020). However, the study of Kahn et al. (2021) predicts Chile to be one of the most affected countries by climate change, with GDP losses for the year 2100 of 5.2% and 11.1%, respectively, for the RCP 2.6 and RCP 8.5 scenarios. This result can only be explained by fundamental parametric differences in the model of Kahn et al. (2021), which presents a negative correlation with the GDP loss forecasts of the other three studies. Estimating the principal component factor (Rencher and Christensen 2012) from the GDP loss forecasts of all these four studies for the years 2030, 2050, and 2100, I show that Chile is one of the countries forecasted to be least affected by climate change for the twenty-first century, whether in terms of the entire country sample or relative to its GDP per capita. The principal component factor model based on all the studies predicts that Chile will be among the 5% of the least affected countries by climate change in all the years 2030, 2050, and 2100.

I then review the impact of climate change on GDP and other outcomes from a range of academic and policy studies. Chile is estimated to have a low sensitivity of the local weather to fluctuations in global temperature (Collins et al. 2013; Krusell and Smith 2020; Kahn et al. 2021). This work is also related to studies of the economic impact of climate change in other countries, such as studies for the USA (Hsiang et al. 2017) and China (Duan et al. 2022). Kolstad and Moore (2020) provide a summary of the different datasets and methodologies for estimating the economic effects of climate change, discussing the advantages and disadvantages of the different approaches. Most past studies of climate change at the multinational level give estimates for Chile with either a low negative (OECD 2015; McKinsey 2020; Cruz and Rossi-Hansberg 2021) or even a positive economic impact (Burke et al. 2015; Krusell and Smith 2020). Furthermore, several studies forecast a small or even negative increase in mortality and health costs for Chile due to climate change (OECD 2015; Carleton et al. 2020). Also, Chile may also face increasing costs in terms of its ecosystem preservation (Vergara et al. 2013; OECD 2015; McKinsey 2020), higher water stress (Gerten et al. 2011; McKinsey 2020), and human migration from neighboring countries (OECD 2015; Cruz and Rossi-Hansberg 2021; Gaska 2021).

This work is organized as follows: Section 2 summarizes the studies included in this review and discusses the forecasts for the weather changes in Chile during the twenty-first century. Section 3 compares the forecasts for the GDP loss from climate change in Chile and other countries, with a particular focus on the OECD and Latin American and Caribbean countries. Section 4 reviews the estimates of the impact of climate change on GDP from structural economic models and from labor productivity studies. Section 5 summarizes the effect of climate change on other outcomes in Chile, such as agriculture, labor productivity, mortality, and ecosystem changes. Finally, Section 6 concludes with a summary of the results and its implications.

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[3] Climate studies consider several scenarios given by Representative Concentration Pathways (RCP) published by the IPCC 2014. RCP 2.6 denotes the best possible scenario in which climate change is completely controlled. RCP 4.5 assumes that the global temperature rise is likely to fall below 2.0 °C. RCP 8.5 is considered the worst scenario, in which no country implements policies to control climate change.

2 A review of climate change estimates for Chile

To summarize the information sources in this review, Table 1 lists the 29 major articles cited in this work, which present environmental indicators for a wide range of countries. The studies are separated into 5 different categories, with 9 articles in the academic peer-reviewed category, 5 articles in the academic non-peer-reviewed category, 8 items in the policy category (from international institutions such as the World Bank, OECD and United Nations), 5 items in the research institute category, and 2 items in the business category. Therefore, there are several trusted sources included in this review, with academic articles (peer and non-peer reviewed) representing almost half of the items listed.

Past studies show that Chile so far has received little impact from climate change in terms of temperature. Krusell and Smith (2020) estimate that Chile has one of the lowest sensitivity ratios to global temperature, with a sensitivity coefficient of just 0.5 on a scale from 0.4 to 5.2; therefore, Chile's temperature is forecasted to change little and gradually for the next century. As shown in Fig. 1, Chile experienced a temperature increase of just 0.0017 °C and 0.0102 °C per year during the periods of 1900–2014 and 1960–2014, respectively (Kahn et al. 2021) . These values are among the lowest temperature rises in the world during this period, with Chile being in the 10th and 25th percentiles of the countries with the lowest rate of temperate increase for the periods 1900–2014 and 1960–2014, respectively. Notice that the rate of temperature increase in 1960–2014 is 6 times bigger than for 1900–2014; therefore, climate change has accelerated worldwide over the last 50 years and the same is true for Chile. In fact, taking the ratio of the rates of increase in both periods $b_{1960–2014}/b_{1900–2014}$, the data shows that Chile is among the top 10% of the countries that accelerated their temperature increase rate over the last 50 years. In the previous century, Chile also experienced a small impact from climate change in terms of blue and green water availability (Gerten et al. 2011) or water availability in food producing units (World Bank 2013).

In relation to future weather change forecasts, Table 2 shows that Chile may experience a low (Roson and Sartori 2016) or moderate sea level rise (World Bank 2013; Barcena et al. 2019), although the temperature increase during the twenty-first century is expected to be smaller than the rest of the world (Collins et al. 2013). Furthermore, a multivariate

Table 1 Studies included in this review

Type of article	Authors and year of reference
Academic (peer reviewed) 2016	Gonzalez and Velasco (2008), Eboli et al. (2010), Gerten et al. (2011), Diffenbaugh and Giorgi (2012), Burke et al. (2015), Roson and Sartori (2016), Kalkuhl and Wenz (2020), Kahn et al. (2021), Dasgupta et al. (2021)
Academic (non-peer reviewed)	Collins et al. (2013), Carleton et al. (2020), Krusell and Smith (2020), Cruz and Rossi-Hansberg (2021), Gaska (2021)
Policy	World Bank (2013), Vergara et al. (2013), IPCC (2014), OECD (2015), Burek et al. (2016), IL0 (2019), Barcena et al. (2019), Dasgupta (2021)
Research institute	ND-GAIN (2018), Germanwatch (2019), Patterson et al. (2020), CIE (2021), Swiss Re (2021)
Business	HSBC (2018), McKinsey (2020)

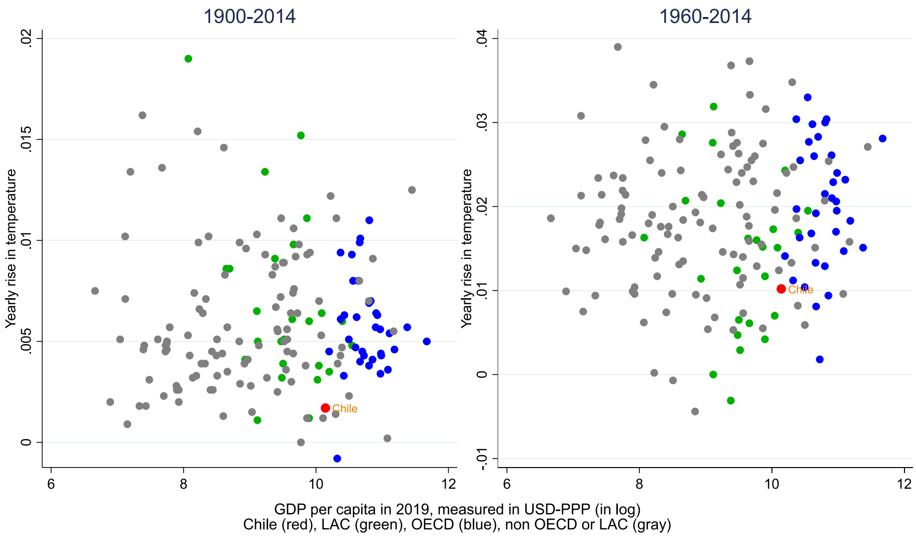

Fig. 1 Trends in yearly rise of temperatures by country in different periods (Kahn et al. 2021)

measure of climate change exposure estimated by Diffenbaugh and Giorgi (2012)[4] expects a moderate level of climate change for Chile under the RCP 4.5 scenario, but it may be negatively affected in a more serious scenario (RCP 8.5). Using a different methodology, Germanwatch (2019) finds that, during the period 1999–2018, Chile suffered less from climate change (rank 93 in 169 countries), with fewer fatalities (rank 121 in 169 countries) and low GDP costs (rank 83 in 169 countries). An analysis of the climate change impact over the previous decade for 67 countries by HSBC (2018) also found that Chile is one of the economies that is the least vulnerable to the costs imposed by climate change, in terms of its ability to manage the physical risks, energy transition risks, and the resources available to respond to climate change. However, HSBC (2018) also finds that Chile was one of the 14 most sensitive economies to the physical risk induced by extreme climate events during the period 2007–2016.

3 Climate change's potential impact on the Chilean GDP

I compare the effects of climate change on the Chilean GDP relative to other countries from four major studies: Kahn et al. (2021), Burke et al. (2015), Kalkuhl and Wenz (2020), Roson and Sartori (2016). All these studies consider GDP loss forecasts for each country under an RCP 8.5 scenario, with the exception of Kahn et al. (2021), which report GDP losses for both the RCP 2.6 and RCP 8.5 scenarios.

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[4] The climate indicators are absolute change in mean surface air temperature, fractional change in mean precipitation, fractional change in interannual standard deviation of de-trended surface air temperature, fractional change in interannual coefficient of variation of de-trended precipitation, frequency of occurrence of seasons above the baseline maximum seasonal surface air temperature, frequency of occurrence of seasons below the baseline minimum seasonal precipitation, and frequency of occurrence of seasons above the baseline maximum seasonal precipitation.

Table 2 Review of estimates from multinational studies of the climate change impact for Chile in terms of temperature, precipitation, and sea level rise

Authors	Time horizon	Outcome	Estimated impact for Chile
Collins et al. (2013)	2081–2100	Temperature	0.5 to 0.75 °C increase per 1 °C in global temperature
Collins et al. (2013)	2081–2100	Precipitation	− 3 to − 6% rainfall per 1 °C in global temperature
World Bank (2013)	2100	High temperature months (in %)	0 to 10% (RCP 2.6) 0 to 10% (RCP 2.6)
World Bank (2013)	2100	Sea level rise	0.7 m (RCP 2.6), 1.0 m (RCP 8.5)
World Bank (2013)	2071–2099	Precipitation	− 10 to − 15% (RCP 2.6) − 30 to − 35% (RCP 8.5)
Roson and Sartori (2016)	2062	Sea level rise	− 0.0002% of GDP (RCP 8.5)
Barcena et al. (2019)	2010–2040	Sea level rise	+ 2.4 mm per year
Barcena et al. (2019)	2040–2070	Sea level rise	+ 3.4 mm per year
Diffenbaugh and Giorgi (2012)	2016–2035	Climate change[a)]	0.85 (RCP 4.5), 0.95 (RCP 8.5)
Diffenbaugh and Giorgi (2012)	2045–2065	Climate change[a)]	1.35 (RCP 4.5), 1.50 (RCP 8.5)
Diffenbaugh and Giorgi (2012)	2080–2099	Climate change[a)]	1.45 (RCP 4.5), 2.60 (RCP 8.5)

[a)] This is a multivariate measure of climate change with an Euclidean distance of the change in seven climate indicators (including extreme temperature and precipitation) for four weather seasons. The Euclidean scale goes from 0.5 (low climate change) to 3.0 (high climate change)

These studies consider different datasets and models for estimating climate change's impact on GDP across countries. Burke et al. (2015) consider a model of the growth of GDP per capita as a quadratic function of yearly temperature and precipitation plus country fixed effects, year fixed effects (shocks at the international level), and a country-specific quadratic time trend. Kalkuhl and Wenz (2020) give coefficient panel estimates with a similar model, but with added controls for changes in the temperature of each country over time. These new parameters take into account that some countries or latitudes may have more difficulty adapting to the new temperatures. Furthermore, Kalkuhl and Wenz (2020) also estimate a model with pure cross-sectional data, which may capture climate change costs excluded from the panel estimates, such as GDP losses that have already occurred in the past. Kahn et al. (2021) take a different approach by considering the lags of the countries' growth rates and weather changes besides country fixed-effects, rather than considering quadratic time trends (which may be implausible as approximations for longer time periods). Finally, I consider the Roson and Sartori study, which measures the loss of GDP from climate change by summing the effect on GDP of five components: sea level rise (calibrated based on a methodology from the IPCC 2014), agricultural productivity (calibrated with a methodology from the IPCC 2014), heat effects on labor productivity (based on a methodology from Kjellstrom et al. 2009), human health (based on a methodology from Bosello et al. 2006), and tourism flows (based on a methodology by Hamilton et al. 2005).

The Burke et al. (2015) and Kahn et al. (2021) models were estimated using GDP data from the World Development Indicators of the World Bank. Kalkuhl and Wenz (2020) made use of a wide range of GDP data to expand their sample to include the regions of each country. The Roson and Sartori (2016) estimates were obtained from the Global Trade Analysis Project dataset. In terms of the weather information, Burke et al. (2015) used the Terrestrial Air Temperature and Precipitation Monthly and Annual Time Series, Kahn et al. (2021) and Kalkuhl and Wenz (2020) both used the Climate Research Unit (CRU) of the University of East Anglia, and Roson and Sartori used the Weatherbase website. According to Kahn et al. (2021), the CRU weather dataset is comparable to the Terrestrial Air Temperature and Precipitation Monthly and Annual Time Series dataset used by Burke et al. (2015) and several previous studies, as well as being consistent with data published by the Goddard Institute for Space Studies (GISS) at the National Aeronautics and Space Administration (NASA) and the National Center for Environmental Information (NCEI) at the National 0ceanic and Atmospheric Administration (N0AA). Therefore, both the GDP and weather datasets are comparable across all the four studies.

Table 3 Different models of GDP growth and weather

Article	Model	Time sample
Burke et al. (2015)	$g_{i,t} = \beta\left(T_{i,t}, T_{i,t}^2\right) + \alpha_i + \alpha_t + (t, t^2)$	1960–2014
Kalkuhl & Wenz (2020): panel	$g_{i,t} = \beta\left(T_{i,t}, T_{i,t}^2\right) + \alpha_i + \alpha_t + \left(t, t^2\right) + \theta(\Delta T_{i,t}, T_{i,t}\Delta T_{i,t})$	1900–2014
Kalkuhl & Wenz (2020): cross-section	$y_i = \sum_{k=1}^{b} \beta_{k,i} B_k(T_i) + \gamma X_i + \alpha_c$	1900–2014
Kahn et al. (2021)	$g_{i,t} = \sum_{l=1}^{p} \beta_l \Delta T_{i,t-l} + \sum_{l=1}^{p} \gamma_l g_{i,t-l} + \alpha_i$	1900–2014
Roson and Sartori (2016)	$y_{i,t}\left(T_i^{RCP-8.5}\right) - y_{i,t}\left(T_i\right) = f_{SeaLevelRise} + f_{Agriculture} + f_{LaborProductivityLoss} + f_{Health} + f_{TourismFlows}$	2004, 2007, 2011 (3 cross-sections)

Table 4 Correlation matrix of the GDP loss measures in 2100 (70 countries) in %

Country GDP loss measure	PCF	BHM	KWpanel	KWcs	Kahn 2.6	Kahn 8.5	RS
Principal component factor	100						
Burke et al. (2015)	80.6	100					
Kalkuhl and Wenz (2020): panel	72.8	65.1	100				
Kalkuhl and Wenz (2020): cross-section	−10.6	−1.9	44.9	100			
Kahn et al. (2021): RCP 2.6	−51.9	−9.0	−16.8	11.6	100		
Kahn et al. (2021): RCP 8.5	−59.6	−26.4	−17.9	39.5	62.7	100	
Roson and Sartori (2016)	83.6	67.5	47.9	−20.5	−21.4	−38.6	100

Note that Kalkuhl and Wenz (2020) report two different measures of GDP loss, which are obtained from the panel and cross-sectional models (Table 3). Kahn et al. (2021) also report two GDP loss measures, which correspond to the scenarios of RCP 2.6 and RCP 8.5. Using the 6 variables available from Kahn et al. (2021), Burke et al. (2015), Kalkuhl and Wenz (2020), and Roson and Sartori (2016), I obtain the principal factor index variable by fitting the vector f of factors to the observed x vector of 6 variables of GDP losses by country: $x = f\omega' + e$, with the variance of × being given by $\sum = \omega\gamma\omega' + \mu$ (Rencher and Christensen 2012). The columns of ω are computed as the leading eigenvectors, scaled by the square root of the appropriate eigenvalue (Rencher and Christensen 2012). For simplicity, I only retain the first common factor as an index that drives all the 6 variables. This principal component factor is standardized to have mean zero and standard deviation of one across all countries in each horizon period (2030, 2050, 2100).

Table 4 summarizes the correlation coefficients between the principal component factor and the 6 measures of country GDP losses for 2100 obtained from the different articles. The results show that the factor component is positively correlated with the Burke et al. (2015), the panel estimates of Kalkuhl and Wenz (2020), and the Roson and Sartori (2016) measures, with the correlation ranging between 72.8 and 83.6%. The Burke et al. (2015), the panel estimates of Kalkuhl and Wenz (2020), and the Roson and Sartori (2016) measures also present high levels of positive correlation between themselves, with coefficients ranging from 47.9 to 67.5%. However, the factor component has a low negative correlation with the cross-section estimates of Kalkuhl and Wenz (2020) and an even more negative correlation with the Kahn et al. (2021) measures, with the correlation going from −10.6 to −59.6%. It is also noticeable that the Kalkuhl and Wenz (2020) panel forecasts have a small negative correlation with the Kahn et al. (2021) measures, while the Kalkuhl and Wenz (2020) cross-sectional estimates have a small positive correlation with the Kahn et al. (2021) measures. Therefore, it appears as if all the GDP loss measures are highly correlated among themselves, except for the Kahn et al. (2021) measures and the Kalkuhl and Wenz (2020) cross-sectional estimates.

A graphical analysis (Figs. 2, 3, 4 and 5) shows that the Burke et al. (2015), Kalkuhl and Wenz (2020), and Roson and Sartori (2016) predict a low impact of climate change on the Chilean GDP during the twenty-first century, with estimates of the GDP loss for 2100 in the RCP 8.5 scenario of −32% from Burke et al. (2015) (Fig. 2), +0.3% from Roson and Sartori (2016) (Fig. 5), +4.8% for the panel estimate of Kalkuhl and Wenz (2020) (Fig. 3), and +6.1% for the cross-sectional estimate of

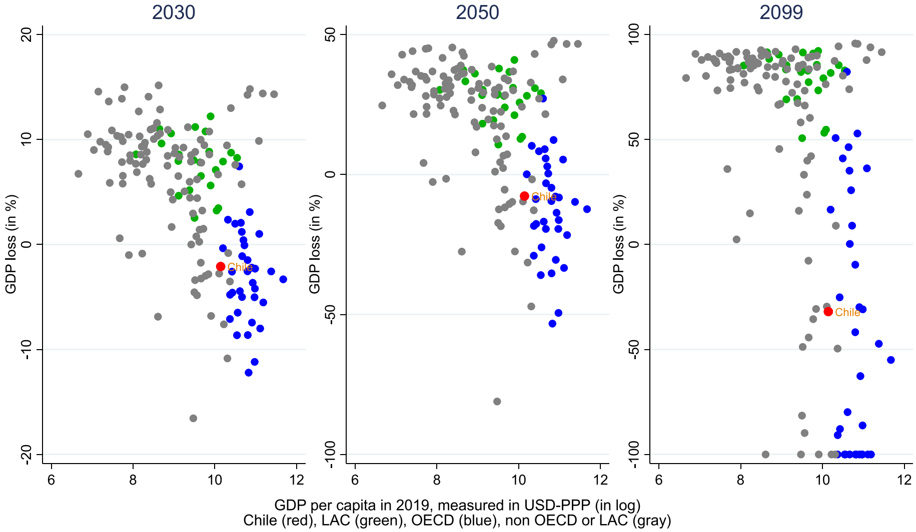

Fig. 2 GDP losses from climate change according to income per capita (Burke et al. 2015)

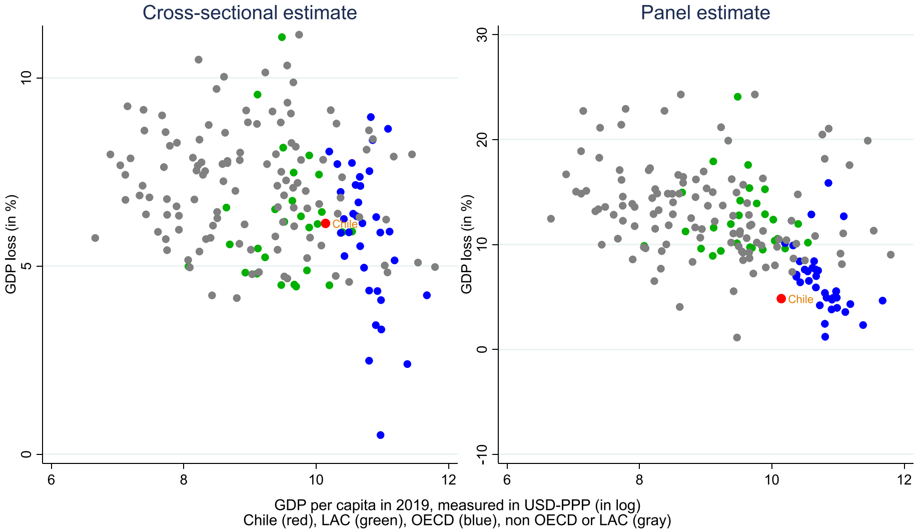

Fig. 3 GDP losses from climate change according to income per capita (Kalkuhl and Wenz 2020)

Kalkuhl and Wenz (2020) (Fig. 3). Looking at different horizons, Burke et al. (2015) predict an increase in GDP pc for Chile of 2.1%, 7.7%, and 32% by 2030, 2050, and 2099, respectively (Fig. 2). The principal component factor shows that Chile is one of the countries expected to be least affected by climate change in the twenty-fist century, whether in terms of the entire country sample or relative to its GDP per capita. It is relevant to note that all these measures predict a significant decline in GDP from climate change across most countries, which further reinforces the positive results

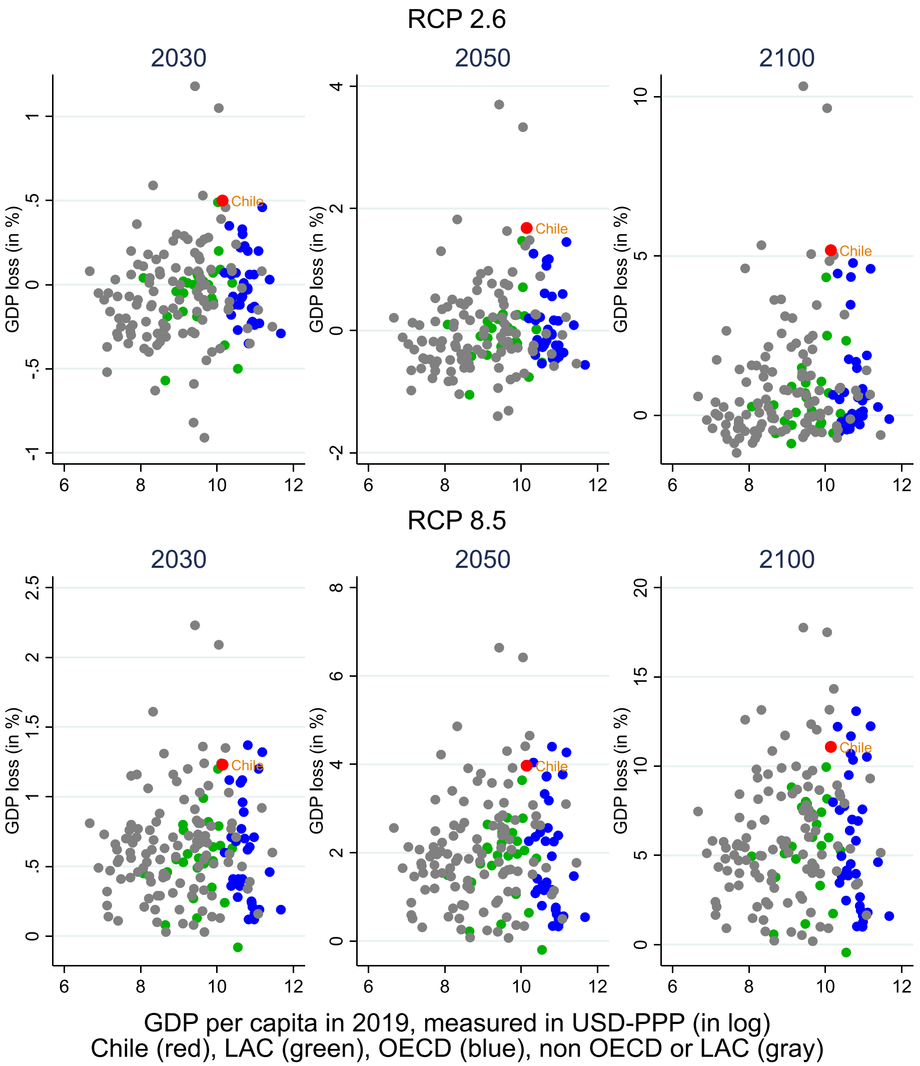

Fig. 4 GDP losses from climate change according to income per capita (Kahn et al. 2021)

obtained for Chile in these studies.[5] From the 26 countries of Latin America and the Caribbean (LAC) in the empirical study of Burke et al. (2015), Chile is the only country with a positive impact on GDP from climate change, with the median LAC country suffering a loss of 7.9%, 28.1%, and 82.2% in GDPpc by 2030, 2050, and 2100, respectively. In this respect, the study of Burke et al. (2015) gives estimates for Chile

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[5] For instance, Burke et al. (2015) predict a strong decline of GDPpc from climate change for most countries. Relative to a no climate change scenario, their study predicts that climate change's impact on World GDP pc implies a reduction of 0% or more with a 71% probability, a reduction larger than 10% with a 63% probability, a reduction larger than 20% with a 51% probability, and a reduction larger than 50% with a 12% probability.

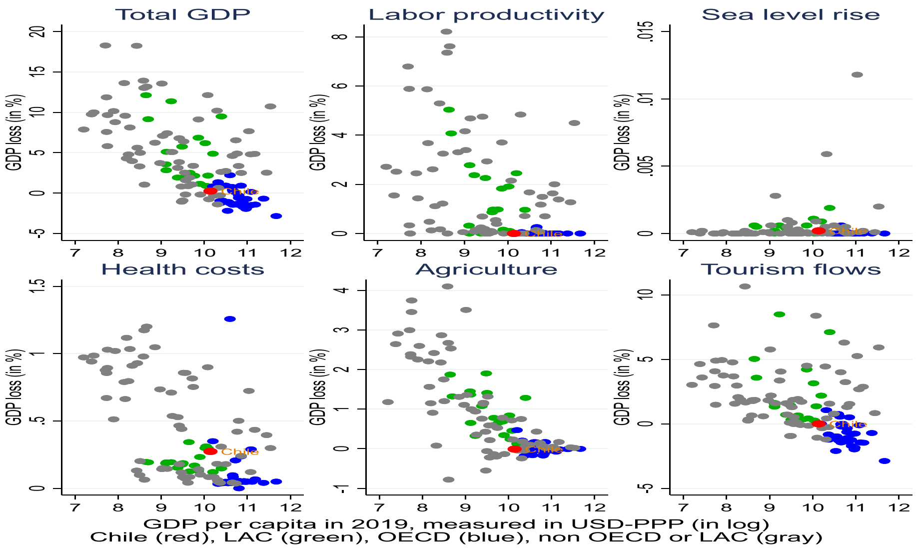

Fig. 5 GDP losses from climate change according to national income per capita and physical risk source (Roson and Sartori 2016)

more similar to the developed OECD countries, which show a negative GDP loss (that is, a gain in GDP). The median OECD country has an expected GDPpc loss of − 2.2%, − 8.0%, and − 31.4% by 2030, 2050, and 2100, respectively. Chile may have some common weather aspects with the European countries that still have low temperatures and are geographically distant from the Equator (Burke et al. 2015).

However, the study of Kahn et al. (2021) predicts Chile to be one of the most affected countries by climate change, with significant GDP losses by 2100 for both the RCP 2.6 and RCP 8.5 scenarios (Fig. 4). This study predicts that climate change will reduce GDP in Chile by 0.5%, 1.7%, and 5.2% for the years 2030, 2050, and 2100, respectively, for the RCP 2.6 scenario and by 1.2%, 4%, and 11.1% for RCP 8.5 scenario in the same years. Kahn et al. (2021) forecast of GDP loss for Chile in 2100 for the RCP 8.5 scenario is almost double the value of 6.1% from Kalkuhl and Wenz (2020) (Fig. 3) and 37 times the value of 0.3% given by Roson and Sartori (2016) (Fig. 5). This result for Chile confirms the correlations shown in Table 4, which show that the Kahn et al. (2021) model provides very different forecasts from the other 3 studies.

In terms of the relative GDP losses in 2100, Chile is on the 25th, 18th, 40th, and 8th percentiles from, respectively, Roson and Sartori (2016), Burke et al. (2015), cross-sectional Kalkuhl and Wenz (2020), and panel Kalkuhl and Wenz (2020), for the forecasts of the least affected countries by climate change. However, Chile is among the top countries damaged by climate change in the Kahn et al. (2021) study, which shows Chile to be in the top 98th and 92th percentiles of the countries affected by climate change in 2100 for the RCP 2.6 and RCP 8.5 scenarios, respectively. The principal component factor analysis on Fig. 6 predicts that Chile will be among the 5% of the least affected countries by climate change in all of the years 2030, 2050, and 2100.

The principal factor component results by country for the years 2030, 2050, and 2100 are publicly available in this website (Madeira 2022), including both the final dataset and

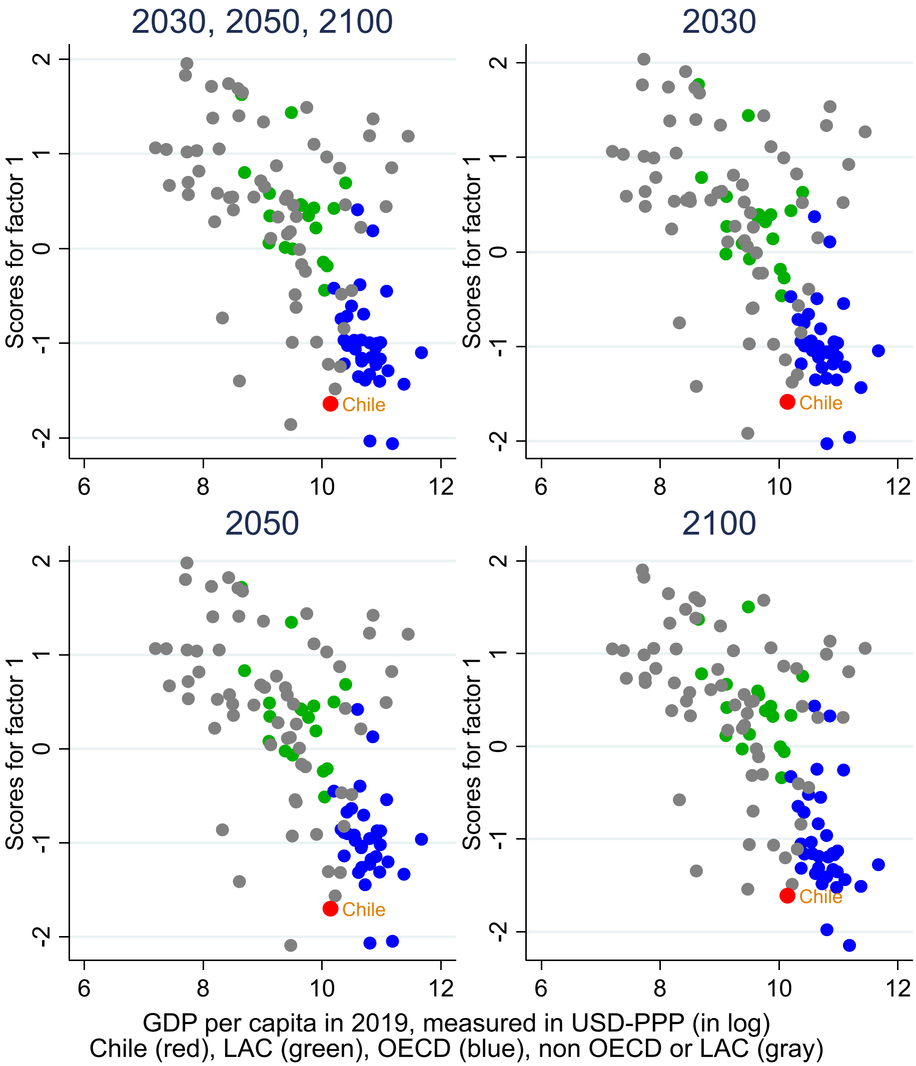

Fig. 6 Principal component factor from the GDP losses implied by climate change in several models (Burke et al. 2015; Kalkuhl and Wenz 2020; Kahn et al. 2021; Roson and Sartori 2016)

the software codes that process the data and implement the analysis in this section: https://data.mendeley.com/datasets/nm9ckg6kgv/1.

4 Other estimates of the impact of climate change on GDP and labor productivity

The previous section was based on the impact of climate change on GDP estimated from reduced form econometric models, that is, models that estimate an effect of the weather on GDP as a statistical relationship and with little explanation of the channels through which such an effect appears. This section reviews some studies that estimate general equilibrium models for the effect of climate change on different countries. It is relevant to note that structural studies, such as the Integrated Assessment Models (IAMs), rely on extensive assumptions on the production functions of each economic sector and the sensitivity of damages relative to the weather.

Now I review the effects of climate change on the GDP of Chile and other countries from studies, such as (i) OECD 2015 (which is mostly based on an ENV-Linkages model that specifies a global dynamic computable general equilibrium framework with several economic sectors, regions, trade flows, and feedback effects between activity and greenhouse gas (GHG) emissions); (ii) Cruz and Rossi-Hansberg (2021) (which is based on a spatial growth model of general equilibrium with labor, capital, land, the global climate, country-specific weather,[6] plus endogenous technological innovation, international trade, migration, and carbon tax policies); (iii) Krusell and Smith (2020) (which uses a dynamic stochastic IAM with forward looking consumers and firms in each country-region, green technology, carbon taxes, plus an elaborate climate system, carbon cycle, and damages); (iv) Swiss Re (2021) (which uses a proprietary model based on Roson and Sartori 2016).

Furthermore, I also review studies with estimates of climate change's impact on labor productivity during days of extreme heat, including (i) Roson and Sartori (2016), (ii) IL0 (2019), (iii) McKinsey (2020), (iv) Dasgupta et al. (2021), and (v) CIE (2021). The idea of this approach is to obtain a robust estimate of the lower bound for the costs of climate change, which does not depend on a complex modeling approach. However, labor productivity losses are very likely to be a lower bound for the economic damages of climate change since it does not account for the damages to capital, trade disruptions, and non-linear negative effects.

Table 5 summarizes the impact of climate change on Chile and other countries from structural models of economic activity and labor productivity studies. This summary confirms that most estimates for the impact of climate change on GDP costs in Chile report low damages. The OECD 2015 reports a negative impact of 0.6% on GDP and 0.275% of GDP if mitigation policies are implemented, Cruz and Rossi-Hansberg (2021) estimates a loss of 1.9% of GDP, Krusell and Smith (2020) reports a GDP increase of 14%, and McKinsey (2020) reports a loss of just 0.1% of GDP. The reasons for these estimates are that Chile is far from the Equator, has a mild weather across many of its regions, and presents a lower sensitivity of the local weather relative to global changes. It is also worth noting that Chile was among the countries in the RoA1 region that Eboli et al. (2010) predicted would benefit from climate change in 2050 and 2100 in terms of overall GDP and also in terms of the agriculture, energy demand, health care, and tourism flow activities.[7] The Swiss Re 2021 study predicts that Chile may suffer a GDP loss by 2050 between 0.9 and 3%, but these estimates are well below the damages suffered by the worst countries in their sample (which includes only 48 countries, a minor sample relative to the more than 100 countries covered in most climate studies). Finally, the low impact of climate change forecasted for Chile in the studies summarized in Table 5 and in the previous section is consistent with the region-industry analysis of Hernandez and Madeira (2022), which shows that most industries in Chile were unaffected by climate change during the period from 1985 until 2017.

Table 5 also shows that almost all studies coincide that Chile is likely to face negligible costs in terms of labor productivity (Roson and Sartori 2016; IL0 2019; McKinsey 2020;

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[6] Cruz and Rossi-Hansberg (2020) consider that the effect of the weather in each country is a function of latitude, longitude, elevation, distance to coast, distance to ocean, distance to water, vegetation density, and albedo.

[7] According to the OECD 2015, agriculture and tourism expenditure in Chile would also benefit from climate change. However, other Chilean sectors could suffer from climate change, including energy, transports, other industries, and other services.

Table 5 Comparison of the climate change impacts on GDP from structural models estimates and from labor productivity studies in a scenario with no mitigation policies

Authors	Time horizon	Outcome	Chile	Estimated impact World: min/mean/max
OECD (2015)	2060	GDP	– 0.6%	– 4.4%/ – 1.8%/1.2%
OECD (2015)	2060	World GDP:	– 1.8% (range between – 4.4 and – 0.6%)	
Krusell and Smith (2020)	2050	GDP	+ 14%	– 21.5%/ – 2.2%/33%
Roson & Sartori (2016)	2100	GDP RCP 8.5	– 0.26%	– 18.3%/ – 3.7%/2.8%
Roson & Sartori (2016)	2100	Labor productivity	– 0.0%	– 8.2%/ – 1.3%/0%
IL0 (2019)	2030	Lost labor hours	– 0.0% (RCP 2.6)	– 2.2% (RCP 2.6)
Dasgupta et al. (2021)	2100	Total labor effect (supply × productivity)	– 1% (+ 1.5 °C)	– 7% (+ 1.5 °C)
	2100		– 2% (+ 2.0 °C)	– 11% (+ 2.0 °C)
	2100		– 3% (+ 3.0 °C)	– 21% (+ 3.0 °C)
CIE 2021 (median)	2030	Labor prod. RCP 8.5	– 0.04%	-6.6% / -2.6% / 0%
CIE 2021 (median)	2050	Labor prod. RCP 8.5	– 0.11%	– 11.9%/ – 5.4%/0%
CIE 2021 (median)	2070	Labor prod. RCP 8.5	– 0.25%	– 19%/ – 9.1%/0%
CIE 2021 (median)	2100	Labor prod. RCP 8.5	– 0.42%	– 30.5%/ – 15%/0%
Swiss Re (2021)	2050	GDPRCP 2.6	– 0.9%	– 2.6%/ – 0.5%/0%
Swiss Re (2021)	2050	GDPRCP 4.5	– 2.1%	– 4.8%/ – 1.3%/0%
Swiss Re (2021)	2050	GDPRCP 6.0	– 2.3%	– 11.6%/ – 1.7%/0%
Swiss Re (2021)	2050	GDPRCP 8.5	– 3.0%	– 12.2%/ – 2.2%/0%
McKinsey (2020)	2019	Labor productivity	– 0.1% of GDP	– 7.5%/ – 0.8%/ – 0.1%
McKinsey (2020)	2030	Labor productivity	– 0.1% of GDP	– 15.1%/ – 1.2%/ – 0.1%
McKinsey (2020)	2050	Labor productivity	– 0.1% of GDP	– 15.1%/ – 1.6%/ – 0.1%
Cruz and Rossi-Hansberg (2021)	2200	Labor productivity	– 5%	– 40.7%/ – 8.6%/73.4%
Cruz and Rossi-Hansberg (2021)	2200	GDPpc (baseline)	– 1.9%	– 4.6%/ – 2.1%/2.6%

Dasgupta et al. 2021; CIE 2021). However, some regions such as India, Brazil, North and Central Africa, Arabia, and the northern Australia may lose 10% or more of their labor productivity (McKinsey 2020; Dasgupta et al. 2021).

Furthermore, an OECD exercise also shows that Chile could avoid 54% of the potential damages from climate change to GDP through policy mitigation (see the exercise with mitigation policies in Table 8 of OECD 2015), which is primarily related to their model assumptions about how green investments impacts health, energy, and tourism (OECD 2015). Krusell and Smith (2020), however, estimate that Chile would neither gain nor lose much from a global carbon tax: in their study, a common carbon tax implemented across the globe would impose a small loss of0.2% of GDP for Chile, while benefitting 40% of the Chilean population. It is also interesting to note that Cruz and Rossi-Hansberg (2021) expect Chile's losses to be more mitigated by International Trade and Migration rather than from Technological Innovation and Carbon Tax policies. Using a gravity model for migration between countries, Gaska (2021) also finds that climate change under an RCP 8.5 path could increase the number of immigrants in 5% of the Chilean population by 2080. This can have important implications for Chile in the near term since the last few years saw a strong increase of migration to Chile from poorer Latin American countries (Arias and Guerra-Salas 2019).

Therefore, as climate change impacts the neighboring countries in a more negative way, one could expect that migration to Chile may increase even more in years to come.

It is relevant to note that all these studies report high estimates for the costs of climate change for the world and other countries. Therefore, Chile is one of the least affected countries in those studies, even if the same studies forecast high costs of climate change for the globe as a whole, especially for developing countries such as India, Brazil, or Mexico. Past studies show that the world could suffer a loss of GDP much larger than Chile, with the OECD (2015) reporting 1.82% (almost 3 times more than Chile), Roson and Sartori (2016) estimating an average GDP loss of 3.7% for the world (with Chile losing just 0.26%), Krusell and Smith (2020) reporting a loss of2.19% (while Chile benefits in 14%), Cruz and Rossi-Hansberg (2021) find a loss of 2.1% for the world (slightly worse than Chile's 1.9% loss). Finally, Roson and Sartori (2016) estimate negligible costs for Chile in terms of lost labor productivity from climate change, even though the average country will face a loss of 1.3% and the worst countries may lose 8.2% in labor productivity.

5 Other climate change costs: agriculture, water, mortality, and ecosystem

This section reviews the impact on Chile of climate change in terms of other economic outcomes, distinct from GDP or productivity, which includes the agriculture sector, human mortality and health costs, water scarcity, and ecosystem changes. The literature review is based on a wide range of articles from the literature, as shown in Table 1. I summarize the major findings for Chile in four tables. Table 6 provides a summary of estimates of the climate impact on the Chilean agriculture sector. Table 7 shows the impact in Chile of climate change on water availability, riverine floods, and amenities. Table 8 reviews the impact of climate change on non-economic outcomes in Chile, such as mortality, ecosystem, or land classification, while Table 9 shows climate change's impact on the Chilean population, welfare, and trade.

Table 6 shows the impact estimates of climate change on the Chilean agriculture sector through reduced crop yields and lower land value. The OECD 2015 estimates a positive

Table 6 Review of estimates of the climate change impact for the Agriculture economic sector in Chile (relative to no climate change scenario)

Authors	Time horizon	Outcome	Estimated impact for Chile
OECD (2015)	2060	Agricultural GDP	+ 0.30% of GDP
OECD (2015)	2060	Agricultural GDP	+ 0.25% of GDP (global factors)
OECD (2015)	2060	Agricultural GDP	+ 0.05% of GDP (domestic factors)
OECD (2015)	2060	Agriculture, fisheries, forestry	+ 0.40% of GDP
OECD (2015)	2050	Change in crop yields	+ 31% (rice), + 9% (fruits and vegetables), + 8% (sugarcane and beet), – 7% (other grains), – 13% (wheat), – 15% (plant fibers), – 28% (oil seeds)
IPCC (2014)	2060	Maximum available fish catch	– 6 to – 20%
Roson and Sartori (2016)	2062	Agriculture	+ 0.01% of GDP (RCP 8.5)
Vergara et al. (2013)	2020	Change in crop yields	– 8% (coarse grains), 18% (wheat)
Vergara et al. (2013)	2050	Change in crop yields	– 17% (coarse grains), 19% (wheat)
Gonzalez & Velasco (2008)	2100	Agricultural land value	– 6.2% (+ 2.5 °C, – 10% precipitation)
Barcena et al. (2019)	2080	Agricultural GDP	– 27% (crop method)
Barcena et al. (2019	2080	Agricultural GDP	– 22% (Ricardian method)
Barcena et al. (2019)	2080	Agricultural GDP	– 13% (with fertilization development)
Barcena et al. (2019)	2080	Agricultural GDP	– 24% (without fertilization development)

impact of 0.3% of GDP for Agriculture and 0.4% of GDP for the aggregated agriculture, fisheries, and forestry sector, with the positive impact coming from stronger international demand for the Chilean products and from higher yields in rice, fruits and vegetables, sugarcane, and beet. However, these agricultural impact results are highly model dependent, with Gonzalez and Velasco (2008), Vergara et al. (2013), and Barcena et al. (2019) showing negative estimates of climate change for the Chilean agriculture sector. According to the OECD 2015, tourism expenditure in Chile would also benefit from climate change, although Roson and Sartori (2016) predict no change in tourism flows to Chile from climate change. It is also worth noting that the climate change damage functions estimated by Roson and Sartori (2016) imply a negligible effect of a RCP 8.5 scenario on the agricultural productivity.

The review in Table 7 shows that Chile may suffer damages from extreme precipitation, flood damages, higher water stress, and lower water availability (Gerten et al. 2011; World Bank 2013; Burek et al. 2016; McKinsey 2020). Chile's central area (Metropolitan and Valparaiso Regions) is in the top 30 to 18% of the globe land area associated with higher exposure to drought mortality risk during the period 1981–2000 (Dilley et al. 2005). The entire territory also shows a high risk of fire hazards and forest fires (World Bank 2021). However, McKinsey (2020) estimates only a slight increase in the drought risk for Chile in 2050, even though it estimates a much higher level of water stress. The University of Notre Dame's ND-GAIN index for 181 countries in 2018 also estimates that

Table 7 Review of estimates of the climate change impact for water availability, riverine floods, and amenities in Chile (relative to no climate change scenario)

Authors	Time horizon	Outcome	Estimated impact for Chile
Gerten et al. (2011)	2080	Water availability	– 10% in blue, green, and total water
Gerten et al. (2011)	2080	Water scarcity	0 to 10% of the population (minor effect)
OECD (2015)	2060	Extreme precipitation	– 0.10% of GDP
OECD (2015)	2030	Flood damages	0 to 0.3 billions of USD
OECD (2015)	2080	Flood damages	2 billions of USD
Burek et al. (2016)	2050	Water demand	+ 10% to + 25%
World Bank (2013)	2069–2099	Blue-water per capita	– 0 to – 10% (RCP 2.6) – 10 to – 20% (RCP 8.5)
McKinsey (2020)	2050	Water stress (demand/supply ratio)	High-risk increase: > 7%
McKinsey (2020)	2050	Time spent in drought	Slight risk increase: 0 to 3%
McKinsey (2020)	2050	Capital stock at risk of riverine floods	Risk decrease: < 0%
Cruz and Rossi-Hansberg (2021)	2200	Amenities	+ 5%
Cruz and Rossi-Hansberg (2021)	2200	Innovation	– 2%
U. Notre Dame's (ND-GAIN 2018) ranking of 181 countries' scores in climate change readiness for 2040–2070 (lower value means lower vulnerability)			
ND-GAIN (2018)		Overall ND-Gain rank: 29	
ND-GAIN (2018)		Vulnerability rank: 22	
ND-GAIN (2018)		Readiness rank: 36	
ND-GAIN (2018)		Economic rank: 37	
ND-GAIN (2018)		Governance rank: 26	
ND-GAIN (2018)		Social readiness rank: 52	

Chile is one of the countries that is least vulnerable to climate change, but it is worse in terms of Social readiness. Finally, the general equilibrium model of Cruz and Rossi-Hansberg (2021) finds that, over the long term (with a horizon of 2200), Chile would improve its amenities to deal with the transition implied by climate change, but its innovation rate would suffer moderately.

Table 8 provides a summary of the results for Chile from a wide range of studies with projections of other non-economic costs of climate change at a multinational level. The studies of OECD (2015), McKinsey (2020), and Roson and Sartori (2016) expect that mortality risks from heat distress in Chile should increase slightly, with the latter predicting just 0.27% of GDP costs from health in an RCP 8.5 scenario. Carleton et al. (2020)

Table 8 Review of estimates of the climate change impact for mortality and ecosystem damages in Chile (relative to a scenario without climate change)

Authors	Time horizon	Outcome	Estimated costs impact for Chile
OECD (2015)	2015	Mortality risk	0 persons
OECD (2015)	2030–2050	Mortality risk	1000 persons per year
OECD (2015)	2080	Mortality risk	3000 persons per year
OECD (2015)	2060	Health costs	0.90% of GDP
OECD (2015)	2015	Mortality damages	0.3 billions of USD
OECD (2015)	2030	Mortality damages	1.5 billions of USD
OECD (2015)	2050	Mortality damages	3.5 billions of USD
OECD (2015)	2080	Mortality damages	7.5 billions of USD
OECD (2015)	2060	Ecosystem damages	0.3% of GDP (RCP 6.0)
OECD (2015)	2060	Ecosystem damages	0.6% of GDP (RCP 8.5)
Roson & Sartori (2016)	2062	Human health	0.27% of GDP (RCP 8.5)
Carleton et al. (2020)	2100	Mortality risk	− 50 to − 100 deaths (per 100,000 people)
Carleton et al. (2020)	2100	Mortality damages	− 2 to − 4% (GDP)
McKinsey (2020)	2050	Population with heat waves	Slight risk increase: 0.5 to 5.0%
McKinsey (2020)	2050	Land changing climate classification	High-risk increase: > 10%
Vergara et al. (2013)	2050	Land changing climate classification	Very high risk

estimate a cost of 3.2% of GDP in mortality damages for the world,[8] while Chile could receive health benefits between 2 and 4% of GDP. However, Chile has the highest air pollution rates among OECD countries, which causes around 4000 premature deaths per year (Baum and Hurn 2021; Basso et al. 2021). Mortality from climate change, however, may increase substantially in India, North Africa, and the Middle East (OECD 2015; Roson and Sartori 2016; McKinsey 2020; Carleton et al. 2020).

One risk that Chile faces is ecosystem damages, between 0.3 and 0.6% of GDP (OECD 2015). It may also experience changes to land surface changing climate classification according to the Koppen Climate Classification System (McKinsey 2020) and the Holdridge Life Zone Classification (Vergara et al. 2013), which indicates that Chile suffers a strong risk of reduction in the biodiversity of fauna and flora, especially with the reduction of the polar areas in the south and the desertification of the north (Vergara et al. 2013). Patterson et al. (2020) estimate that Chile is in the group of countries with a middle level of risk arising from climate change, biodiversity loss, and other changes in natural capital,

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[8] Carleton et al. (2020) estimate a U-shaped impact of the weather on mortality for all ages, with extreme cold and hot temperatures causing higher damages. This function is allowed to change with adaptation to the local climate and the economic development of each country.

Table 9 Review of estimates of the climate change impact on the population, immigration, welfare, and trade in Chile (relative to a scenario without climate change)

Authors	Time horizon	Ooutcome	Estimated impact for Chile
Gaska (2021)	2080	Fraction of immigrants due to climate change	+5% (in % of the Chilean population)
Cruz and Rossi-Hansberg (2021)	2200	Population growth due to migration	+5%
Cruz and Rossi-Hansberg (2021)	2200	Welfare (no tax changes)	−5%
Cruz and Rossi-Hansberg (2021)	2200	Welfare (with carbon tax)	−6.5%
Cruz and Rossi-Hansberg (2021)	2200	International Trade	+0.4%
Patterson et al. (2020)	2020	Climate and Nature Sovereign Index: Middle level of risk	
U. Notre Dame's (ND-GAIN 2018) ranking of 181 countries' scores in climate change readiness for 2040–2070 (lower value means lower vulnerability)			
ND-GAIN (2018)		Ecosystem services: 54	
ND-GAIN (2018)		Food: 4	
ND-GAIN (2018)		Health: 54	
ND-GAIN (2018)		Human habitat: 108	
ND-GAIN (2018)		Infrastructure: 37	
ND-GAIN (2018)		Water: 41	
ND-GAIN (2018)		Adaptive capacity: 37	
ND-GAIN (2018)		Exposure: 52	
ND-GAIN (2018)		Sensitivity: 14	

according to their Climate and Nature Sovereign Index. Dasgupta (2021) shows that Chile may suffer from a reduction of 4 to 10% in Mean Species Abundance (MSA) until 2100 under a stressed SSP 8.5 scenario, which adds to a decline in local species richness around 5 to 10% between since the colonial times until now. Chile also presents natural assets similar to most of the world's regions and an ecological deficit of 0 to 50%, showing an ecological footprint larger than its biocapacity (Dasgupta 2021).

Finally, Table 9 shows that Chile may experience increased immigration in the future due to climate change (Cruz and Rossi-Hansberg 2021; Gaska 2021) since it is the country in the Latin America region that is better prepared to face the economic costs of climate change. The University of Notre Dame's ND-Gain index for 181 countries estimates that Chile will suffer from climate change in terms of human habitat, health, and ecosystem, but it does well in terms of food security and in terms of sensitivity (the fraction of people susceptible to a climate change hazard). The Climate Action Tracker[9] country ratings also show that Chile is still in the middle of the table for the climate change efforts across a wide range of aspects.

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[9] https://climateactiontracker.org/countries/chile/

6 Conclusions

This study reviews in depth the literature on the impact of climate change for Chile. Summarizing the results from four major reduced form studies (Burke et al. 2015; Kalkuhl and Wenz 2020; Roson and Sartori 2016; Kahn et al. 2021), I find that Chile has a low or moderate forecast for the GDP loss from climate change by 2100, with the exception of the study of Kahn et al. (2021). There is a high correlation between the GDP loss forecasts across different countries for the Burke et al. (2015), Roson and Sartori (2016), and the panel estimates of Kalkuhl and Wenz (2020). These studies predict a GDP impact for Chile in 2100 between a loss of 6.1% and a gain of 32% in the RCP 8.5 scenario. Kahn et al. (2021) differ from the other studies because it does not account for quadratic trends in countries' growth rates, while using instead lagged values of temperature changes and growth rates to account for potential negative effects of climate change when the new temperatures are outside of the national historical norm. Although Chile has low temperatures for a significant part of its regions, their model finds that it may take costs to adapt to an unusual climate. For this reason, Kahn et al. (2021) make a GDP loss forecast for Chile of 11.1% by 2100 in the RCP 8.5 scenario. Finally, a review of the labor productivity and GDP loss forecasts for Chile from structural models also shows that Chile is expected to suffer a small impact from climate change relative to other countries, with losses below 3% until 2100 and below 5% until 2200. Again, some structural models even predict that Chile may have a GDP gain from climate change. This shows that there is substantial uncertainty around GDP loss forecasts from climate change, including for Chile.

A review of the impact of climate change on other outcomes shows that Chile may experience a significant loss in Agricultural GDP and fish catch, although health costs, mortality risk, and tourism revenues may experience a small change or can even benefit from climate change. However, according to several studies, Chile may experience a significant degree of water stress and scarcity due to low precipitation, fire hazards, air pollution, ecosystem damages, a high risk of land changing climate classification, a moderate reduction in biodiversity loss, and a significant reduction in species abundance. Some studies also predict a significant increase in migration towards Chile from poorer neighboring countries that may be strongly affected by climate change.

Finally, according to several indexes, Chile is still only in the middle of the table in terms of policy, infrastructure, and climate readiness. Chile could extend and increase its carbon tax (Espinosa and Fornero 2014; Harris et al. 2017). According to the IMF's climate data,[10] Chile in 2019 was gaining less than 1% of the GDP through environmental tax revenues, which is much lower than the 3% of GDP in taxes of many European countries. The IMF also shows that in 2020 Chile was dedicating just 0.11% of the GDP in terms of Government Expenditure on Environmental Protection, much lower than the 1% of GDP dedicated by several developed countries. At the same time in 2020, Chile spent more than 4% of the GDP on fossil fuel subsidies,[11] while many developed countries spend less than 1.5% of the GDP on this category. Therefore, there is a substantial space for Chile to implement stronger climate policies, such as higher carbon prices and gas taxes, higher expenditures on environmental protection, and lower expenses on fossil fuel subsidies.

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[10] https://climatedata.imf.org/

[11] In 2017 the gasoline prices per gallon were around 4.1 USD in Chile, but for the European Union countries the prices ranged between 6.3 and 9.8 USD (Harris et al. 2017). Furthermore, in 2017 Chile imposed a price of 5 USD per ton of carbon dioxide and with a coverage of 42% at the national level (Barcena et al. 2019), which is a much lower value than the carbon costs above 50 USD imposed across several developed nations.

Data availability All the data used in this article is publicly available. The final dataset in the analysis and all its codes are available through the Mendeley Data repository, https://data.mendeley.com/datasets/nm9ckg6kgv/1.

Declarations

Conflict of interest The author has no conflicts of interest to declare that are relevant to the content of this article.

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