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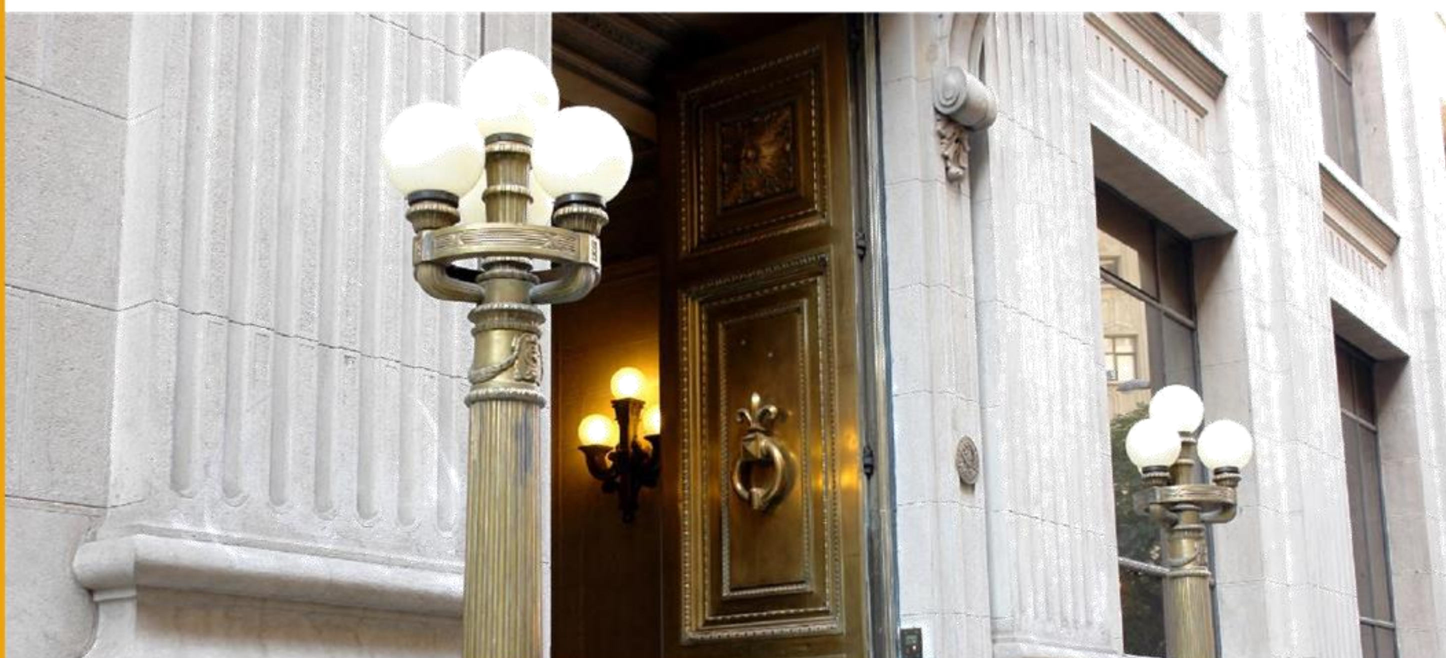

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Exposures to climate change's physical risks in Chile*

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Abstract

We estimate real estate's exposure in Chile to five weather risks, including labor productivity loss due to heat, fires, floods, drought coastal deterioration as measured by the Chilean Climatic Risk Atlas (ARCLIM) and Climate Impact Explorer (CIE) sources. According to our joint ARCLIM-CIE indicator, we measure risk exposure for the appraisal value of all properties of 39% for Chile and 51%, 36%, 36% and 27% for the Central, North, Metropolitan and South macrozones, respectively. flooding is the greatest risk for Chile, followed by drought. We find that the CIE source underestimates the climate exposures in Chile relative to the ARCLIM measures, particularly for the flooding and drought risks.

Resumen

Estimamos la exposición de los bienes raíces en Chile a cinco riesgos climáticos: pérdida de productividad laboral debido al calor, incendios, inundaciones y deterioro costero por sequía. Utilizamos como fuentes el Atlas de Riesgo Climático de Chile (ARCLIM) y Climate Impact Explorer (CIE) de Climate Analytics. Generamos un indicador conjunto ARCLIM-CIE, que indica que la exposición al riesgo para el valor de todos los inmuebles a nivel nacional es de 39% y del 51%, 36%, 36% y 27% para las macrozonas Centro, Norte, Región Metropolitana y Sur, respectivamente. Las inundaciones son el mayor riesgo para Chile, seguidas de las sequías. Encontramos que la fuente CIE subestima las exposiciones climáticas en Chile en relación con las medidas por ARCLIM, particularmente para los riesgos de inundaciones y sequías.

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1 Introduction

It is estimated that the Latin America region will suffer substantially from global warming in the 21st century, with some Caribbean countries being strongly affected due to their oceanic location and dependence on the agriculture and fishing sectors (Bárcena Ibarra et al., 2020). Climate change issues are gaining more relevance in financial markets, as banks and other financial institutions prefer investments with higher environmental, social and governance (ESG) factors (Hoffmann et al., 2020, Schydlowsky, 2020). The macroeconomic implications of climate change for central banks, fiscal policy and financial regulation are also being discussed (Clerc et al., 2021, NGFS, 2021). Climate change has the potential to cause substantial economic disruption in the coming decades, particularly in areas closer to the Equator (Bárcena Ibarra et al., 2020) or with lower possibilities of adaptation to the new weather (Kahn et al., 2021, Kahn, 2021). However, forecasting climate risks is challenging due to the unpredictability of natural weather events, uncertainty about the damages, probability of tail-risks and the long time horizons over which the risks may materialize (Stern, 2013).

In this paper, we study the anticipated exposure of properties in Chile to physical risks from climate change.[1] over the next 30 years (2050 horizon), with real estate properties being measured in terms of the number of properties and their tax appraisal value across various property types and regions. To assess the economic exposure to climate change's physical risks,[2], we use an

[1]Climatic risks are defined as the probability that events of a climatic nature will result in negative impacts on a territory or social system or communities that inhabit it those effects' expected intensity (IPCC 2021). Climate change poses two types of risk to financial institutions, physical risks and transition risks (on Banking Supervision, 2021, NGFS, 2021)) This article is focused on physical risks of climate change.

Physical risks include extreme weather conditions (such as wildfires, droughts, floods and storms) and damage caused by more gradual climate and environmental changes, such as air and water pollution, soil contamination, water shortages, biodiversity loss and deforestation, rising temperatures, rising sea levels, land-use change, destruction of biotopes and resource scarcity.

Transition risks are the risks of direct and indirect loss during the transition to a cleaner economy, which can be caused, for instance, by sudden environmental policies such as new taxation, regulation, technological progress or changes in market sentiment (on Banking Supervision, 2021).

[2]It is important to emphasize that exposure to risk does not necessarily imply a loss equal to the value of the economic property that is being measured (Kahn, 2021). For example, a wildfire can burn a house down, but the land may retain its value. On the other hand, it's difficult to assess the impact of potential mitigators, such as air

administrative register, the Real Estate Registry (hereafter on CBR, according to its acronym in Spanish, *Catastro de Bienes Raíces*) which captures the universe of real estate properties in Chile.

Physical risk is the economic impact stemming from the expected increase in the frequency and magnitude of natural hazards, such as riverside and coastal floods, wildfires, heat and water stress and windstorms. These risks can be measured from various data sources that summarize current scientific measurements of the exposure of each geographical area in Chile (ARCLIM 2021, CIE 2021). These climate physical risk indicators are then matched to the addresses of individual companies and real estate properties to account for heterogeneous climate exposures across geographical regions (Alogoskoufis et al., 2021, NGFS, 2021).

We then use the Climate Risk Atlas database (hereafter ARCLIM data, according to its acronym in Spanish) from the Chilean Ministry of Environment and the Climate Impact Explorer (hereafter, CIE) database published by Climate Analytics to obtain the exposure of each geographical area (municipality or region) to five distinct climate risks: loss of labor productivity in heat waves, fires, floods, drought and coastal deterioration. These data are obtained as measures for risks occurring until the year 2050 or within the next 30 years, assuming a scenario in which current policies are unchanged (as expressed by the global scenario RCP 8.5.[3]) Using these two climate databases, we then build three overall indicators of physical risks: i) the ARCLIM indicator, which is available at the municipality level (Chile has 346 municipalities, known as *comunas* in Spanish), ii) the CIE indicator available at the municipality level and iii) the ARCLIM-CIE indicator, which is expressed as the maximum value between the ARCLIM and CIE indicators for each area.

We then use the CBR dataset to measure the exposure of all the real estate properties (in terms of number and their total appraisal value) in each geographical area (whether a municipality or region) to the climate change physical risks, according to the ARCLIM, CIE and ARCLIM-CIE indicators. We find that the ARCLIM and the CIE datasets show substantially different results.

conditioning in office buildings, homes or schools, the adaptation of crops to global warming, new crop irrigation systems that save water, or night work shifts. Aditionally, the areas exposed to physical climatic risks can have positive externalities in other areas, with migration to safer urban areas potentially increasing economic activity and development in those areas (Kahn, 2021).

[3]Climate studies consider several scenarios given by Representative Concentration Pathways (RCP) published by the IPCC (2021), with RCP 2.6 being denoted as the best possible scenario in which climate change is completely controlled, RCP 4.5 being a scenario in which the global temperature rise is likely to fall below 2.0°C RCP 8.5 being considered the worst scenario in which no country implements policies or mitigators for climate change.

According to the ARCLIM, CIE and ARCLIM-CIE indicators, around 31%, 16% and 39% of the total appraisal values of all the real estate properties in Chile are exposed to climate change risks, respectively. In terms of the number of properties affected, the ARCLIM, CIE and ARCLIM-CIE indicate that around 28%, 17% and 37% of all the real estate properties in Chile are exposed to climate risks, respectively. Therefore, the CIE indicator underestimates exposure to climate risks relative to the ARCLIM data. It is important to emphasize that whenever we talk about under or over estimation, we refer to the value of one index relative to the other, not relative to the "true value". Since the "true value" for the risks of climate change is unknown and it is dependent on the modeling approach and data sources, it is relevant for studies to use a variety of measures to analyze the influence of physical risks. As we will mention in section 3.2, both indices can be used with different scopes and purposes, so it will depend on the context which is more correct to use. In this case, we generate a new one from both indices to collect and publicize both tools, in addition to highlighting their differences.

This underestimation of climate risks in the CIE source relative to the ARCLIM measures is particularly strong for flooding risks, with the ARCLIM reporting 20% exposure, while the CIE indicator reports just 1%. The CIE indicator also underestimates the risk of drought, with 5% of the properties in the ARCLIM dataset being exposed relative to 3% in the CIE source. According to the joint ARCLIM-CIE indicator, the appraisal value of all real estate properties is subject to exposures of 20.2%, 6.7%, 6.1%, 5.4% and 0.1%, for the risks of flooding, drought, wildfire, coastal deterioration, and labor productivity loss due to heat, respectively. Therefore, flooding represents the strongest exposure to the real estate, followed by the risks of drought, wildfire and coastal deterioration, while the labor productivity loss due to heat has almost no implications for properties' risk.

The exposure values are similar whether one counts the number or the appraisal of all properties or just the residential properties. Residential real estate properties are slightly less exposed to risk, which makes sense if urban planners are careful to exclude residential construction from areas at a higher risk of wildfire or flooding (Kahn, 2021). Furthermore, we show that the North and Central macro-regions have the highest economic exposure to climate change's physical risks, whether in terms of appraisal value or in the fraction of properties exposed, according to any of the ARCLIM, CIE and ARCLIM-CIE indicators. The appraisal value of the North macrozones has exposures of

36%, 12% and 36%, according to, the ARCLIM, CIE and ARCLIM-CIE indicators, respectively. The Central macrozone is the most exposed area, according to the joint ARCLIM-CIE indicator, with its appraisal showing exposures of 35%, 38% and 51%, according to the ARCLIM, CIE and ARCLIM-CIE indicators, respectively. Therefore, while the North macrozone is the most exposed area, according to the ARCLIM indicator, the exposure of the Central macrozone is much higher according to the CIE and ARCLIM-CIE indicators. The South macrozone is the least exposed area, according to the ARCLIM and the ARCLIM-CIE indicators, with its appraisal showing exposures of 15%, 14% and 27%, according to the ARCLIM, CIE and ARCLIM-CIE indicators, respectively. The Metropolitan macrozone is the least exposed area according to the CIE indicator, with its appraisal showing exposures of 31%, 8% and 36%, according to, the ARCLIM, CIE and ARCLIM-CIE indicators, respectively Again, there are considerable disparities if one considers the ARCLIM and the CIE sources. Relative to the ARCLIM database, the CIE underestimates climate exposures at the national level and in the North and Metropolitan macrozones. The ARCLIM and CIE datasources, however, appear to provide similar exposure values for the Central and South macrozones.

This work is related to research on economic exposure to the physical risks of climate change (Stern, 2013, Alogoskoufis et al., 2021) and its heterogeneity across regions (Alogoskoufis et al., 2021). Previous research on Chile shows that electricity generation and manufacturing are the sectors with the highest carbon emissions in Chile, but using an input-output framework shows that manufacturing and mining sectors (in particular, their exports) are the highest indirect sources of carbon emissions (Avilés-Lucero et al., 2021). A study of climate change's effects on the GDP growth across industries and regions in Chile shows that agriculture-silviculture, fishing and energy (electricity, gas and water) are the most negatively affected economic sectors, while construction, manufacturing and retail also show minor effects (Hernandez and Madeira, 2022). Other works also deal with the transition risks (Clerc et al., 2021, on Banking Supervision, 2021) and with other costs, such as biodiversity loss and ecosystem damages (Martínez-Jaramillo and Montanez-Enriquez 2021, NGFS 2022), which are not analyzed in this paper.

Finally, several studies of the effects of climate change on GDP have been developed based on both reduced-form regressions and structural models, with a range of estimates for Chile going from a large positive impact to a large negative impact (Madeira, 2022). However, reduced-form regressions of the effects of climate change in the literature are often limited to two weather variables given by temperature and precipitation (Madeira, 2022). We advance such studies by including a wide range of climate risks, such as labor productivity loss due to heat, fires, floods, drought, and coastal deterioration. Furthermore, we provide a more conservative approach toward measuring the effects of climate change in Chile. Because GDP estimates for the effects of climate change (Madeira, 2022) range widely, with results dependent on some assumptions such as allowing positive (Hernandez and Madeira, 2022), then our approach is limited to simply measuring the fraction of real estate properties and the appraisal value that is exposed to weather risks. This approach provides a reliable upper bound for the effects of future adverse weather on Chilean real estate properties.

This article is structured as follows. Section 2 summarizes the literature on physical climate exposures in Chile and shows some data on the evolution of temperature and precipitation across Chilean regions since 1950. Section 3 summarizes the data and methodology employed to establish the physical risk indicators. Section 4 shows the results of the indicators at the national level, four macrozones and across property types. Section 5 summarizes the results across regions. Section 6 summarizes the main results and policy implications.

2 A review of climate change in Chile

This section presents a brief literature review of the climate change implications for the risks of fires, drought, heatwaves, water availability and flood hazards in Chile.

Climate change is expected to change the magnitude of, frequency of, intensity of, and exposure to physical risks in Chile, especially due to changes in temperature and precipitation. Temperatures are expected to rise 1.4°C-1.7°C by mid-century and 3°C-3.5°C by the end of the century across all emission scenarios. The annual probability of heat waves in Chile could also increase by 8% by the 2040s and 20% by the 2090s. Precipitation is projected to decrease by 1.5 mm to 9.3 mm per month by the 2050s and 5.5 mm to 11 mm by the 2090s (wor, 2021).

Table 1 presents data from 1950 to 2017 for the mean yearly temperature (Celsius degrees) for Chile and its 15 regions (defined according to the 2007 administrative reform), while Table 2 shows the mean precipitation (cm per month). These series are obtained from raw daily weather data for each square grid of 0.5 latitude-longitude degrees from the University of Delaware Air Temperature and Precipitation data set, as in Hernandez and Madeira (2022). The data shows that Chile has already experienced a substantial weather change. Table 1 shows that Chile overall experienced a warming of 0.5°C between 1950 and 1980, a higher temperature level that has persisted in recent years. Furthermore, all regions in Chile have experienced some degree of warming between 1950 and 2017, with regions XI, XIII and XIV showing the highest warming: an average yearly temperature growth above 0.7 Celsius degrees during this period. In terms of temperature, the country benefits from having its regions with higher population and GDP activity located in colder areas (Hernandez and Madeira, 2022).

Average national precipitation has deteriorated by 0.9 cm per month at the national level between 1950 and 2017, with the 1980s and the 2010s being marked by severe droughts. Many of Chile's wealthiest regions are located in areas exposed to drought, especially in the Central region (wor, 2021, Vicuña et al., 2011). According to Table 2, ten regions (regions V, VI, VII, VIII, IX, X, XI, XII, XIII and XIV) experienced a decline in precipitation between 1950 and 2017. Five regions have been particularly affected, with average precipitation in the regions VII, VIII, IX, X and XIV declining by more than 2 cms per month. The regions VII and VIII (which also includes the region XVI, which was only created in 2018) are in the Central macrozone of Chile, while regions IX, X and XIV are in the northern part of the South macrozone. Therefore, an extensive area of Chile is now exposed to drought in the case of the Central macrozone (regions VII and VIII) or to a severe decline in precipitation in the case of the South macrozone (regions IX, X and XIV).

A lot of evidence has been recorded regarding the relationship between materialized physical risks and climate change. Urrutia-Jalabert et al. (2018) study the relationship between large wildfires and climatic variability in Chile in the 1976-2013 period. They find that the fires in the central macrozone were associated with high precipitation during the winter months of the previous year and with very dry conditions during the spring and summer seasons. Abarzúa and Moreno (2008) study the changing wildfire regimes in the rainforest region of southern Chile, and they also associate the increase in wildfire activity in Chiloé (the island) to negative anomalies in on the effects of inter-annual climatic variation on wildfire occurrence in south-central Chile finds that low moisture availability is the main factor in fire occurrence and that these fires are associated with longer and drier summers (González and Veblen, 2006)

Table 1: **Mean yearly temperature (C°) by decade for each region**

Macrozone	Region	1950-59	1960-69	1970-79	1980-89	1990-99	2000-09	2010-17
Chile	Chile	7.4	7.3	7.3	7.9	7.7	7.7	7.8
North	XV	3.9	4.1	4.2	4.5	4.1	4.0	4.2
North	I	6.8	7.0	7.0	7.5	7.2	7.0	7.0
North	II	9.1	9.3	9.2	9.9	9.8	9.8	9.2
North	III	5.9	5.5	5.5	7.1	6.2	6.2	6.2
North	IV	4.1	3.8	3.9	4.4	4.1	4.1	4.3
RM	XIII	8.0	7.9	7.8	8.1	8.1	8.4	8.8
Center	V	9.8	9.6	9.6	9.8	9.6	10.0	10.2
Center	VI	10.3	9.7	9.9	10.2	10.2	10.7	10.9
Center	VII	9.3	8.6	9.1	9.2	9.3	9.6	9.8
Center	VIII	11.0	10.8	10.8	11.1	11.2	11.1	11.5
South	IX	8.9	8.5	8.4	8.7	8.9	8.8	9.1
South	X	8.3	8.1	8.0	8.2	8.2	8.5	8.6
South	XI	7.9	8.1	8.0	8.4	8.0	8.2	8.8
South	XII	5.0	5.0	5.0	5.3	5.3	5.2	5.5
South	XIV	8.8	8.6	8.4	8.7	9.0	9.5	9.5

Note: Chile's territory is divided into regions, which are geographically grouped one above the other from north to south. Over time, some regions have been split in two, which explains why some numbers are out of order. For example, region XV is the northernmost, since it was a division of region 1. At the time of data collection, according to the 2007 administrative reform, there were 15 regions (in the table, in geographical order). As of 2018, there are 16 regions. The metropolitan region has the number XIII because it is generally named "RM" (Región Metropolitana, in Spanish) and its number is not used. Temperature is expressed in Celsius.

Table 2: **Mean yearly precipitation by decade for each region**

Macrozone	Region	1950-59	1960-69	1970-79	1980-89	1990-99	2000-09	2010-17
Chile	Chile	6.5	6.4	6.2	5.7	6.1	6.4	5.6
North	XV	1.5	1.4	1.9	1.5	1.4	1.6	1.6
North	I	0.5	0.4	0.7	0.6	0.5	0.5	0.5
North	II	0.4	0.3	0.4	0.4	0.4	0.4	0.4
North	III	0.4	0.4	0.3	0.5	0.5	0.5	0.5
North	IV	1.3	1.2	1.2	1.4	1.5	1.5	1.3
RM	XIII	4.1	3.4	4.4	4.2	3.8	4.2	3.2
Center	V	2.8	2.4	2.5	2.9	2.8	2.9	2.0
Center	VI	5.9	5.4	6.4	6.1	5.9	6.5	4.9
Center	VII	7.7	7.2	8.1	7.3	7.3	7.8	5.7
Center	VIII	12.1	11.6	11.2	10.8	11.1	11.6	8.8
South	IX	14.6	14.1	13.7	12.6	12.9	14.0	11.4
South	X	16.8	16.5	15.1	13.9	14.8	15.7	13.9
South	XI	10.6	11.2	10.4	8.4	9.5	10.2	9.7
South	XII	8.7	8.3	8.0	7.9	9.1	9.2	8.2
South	XIV	16.5	16.4	15.1	13.3	13.5	15.2	12.9

Note: Chile's territory is divided into regions, which are geographically grouped one above the other from north to south. Over time, some regions have been split in two, which explains why some numbers are out of order. For example, region XV is the northernmost, since it was a division of region 1. At the time of data collection, according to the 2007 administrative reform, there were 15 regions (in the table, in geographical order). As of 2018, there are 16 regions. The metropolitan region has the number XIII because it is generally named "RM" (Región Metropolitana, in Spanish) and its number is not used. Precipitation is expressed in cms/month.

The Central Chile Megadrought (2010-2021) was one of the longest drought events recorded over the last millennia, with a mean rainfall deficit of 20-40% (Garreaud et al., 2020). A very emblematic case that has caused terrible water scarcity problems is the Petorca basin drought, displaying the driest period over the last 700 years of streamflow reconstruction, where consumptive withdrawals reach up to 18% of the mean annual precipitation (Muñoz et al., 2020). The Biobio basin in central south Chile has also suffered from drought periods that have affected agriculture in the area over the past two decades (Zambrano et al., 2016).

During the Megadrought in Central Chile, the number, area, simultaneity and duration of large fires increased significantly compared with the previous 10-year period (González et al., 2018). The fires of the 2016-2017 summer burned an area measuring 14 times the mean for the period 1985-2016, the highest on record to date (Bowman et al., 2019). This megafire was one of the most severe ever recorded, burning an area close to 350,000 hectares in south-central Chile in three weeks (CONAF, 2017), and it was also associated with prolonged drought and increased heatwaves (González et al., 2018, Miranda et al., 2020, Castillo et al., 2020). According to Pliscoff et al. (2020), it is considered the second largest wildfire in the Chilean history, with 518,174 hectares affected.

There has also been a significant increase of heatwaves in the Central macrozone (Piticar, 2018) and an extreme sea level rise of 15-20 cm in Chile (Campos-Caba, 2016, Martínez et al., 2018). Rainfall has decreased and rapid glacier melting increased, which has caused changes in environmental and biological properties of the central-southern and Andes lakes (Pizarro et al., 2016). Furthermore, droughts in the Central Chilean Andes increase the freezing resistance of high-Andean plant species, implying that warmer growing seasons due to climate change may threaten plant survival (Sierra-Almeida et al., 2016).

Water availability could change dramatically in some regions in Chile due to these changes in temperature and precipitation, which leaves the water system particularly vulnerable (Bonelli et al., 2014, Vicuña et al., 2011). Adaptation studies for the city of Santiago show that water supply performance without climate change adaptations is worse under climate scenarios with lower water availability, which are likely to be associated with higher GHG emissions scenarios such as RCP 8.5 (Ricalde et al., 2022).

Krellenberg et al. (2013) analyze heat and flood hazards in the Metropolitan region, showing that the loss of green spaces leads to higher hazard rates, as well as exposing populations to risks in terms of housing conditions. They find that poorer households are more affected by heat hazards, whereas richer households are more likely to be exposed to flood hazards, the physical housing characteristics a beign proxy for families' economic conditions.

There is also a significant effect on regional agriculture and crop failure, small-scale farmers being the most vulnerable group because of their adaptation capacity (Fernández et al., 2019). Education and access to meteorological information can improve awareness of climate change and help farmers adapt technologies to current and future weather changes (Roco et al., 2015). Finally, Kjellstrom et al. (2009) estimate the impact of two climate scenarios on future labor productivity. They find that climate change will decrease labor productivity under the assumption that there is no specific adaptation.

Finally, a literature review by Madeira (2022) concludes that there is a substantial degree of uncertainty regarding the potential effects of climate change on the GDP of Chile and other countries. A review of reduced-form regression estimates from international studies of GDP growth and weather (Madeira, 2022) shows that the estimated impact of climate change on the GDP of Chile in 2100 under an RCP 8.5 scenario ranges from i) a positive effect of +32% (Burke et al., 2015), ii) almost no effect of -0.3% (Roson and Sartori, 2016), iii) a moderate effect of -4.8% or -6.1% (Kalkuhl and Wenz, 2020) and iv) a strong effect of -11.1% (Kahn et al., 2021). Using just the GDP data for the Chilean regions and industries, Hernandez and Madeira (2022) show that evaluating the influence of climate change in Chile depends crucially on whether the model allows for potentially positive effects of climate change on the individual industries. If one ignores possible positive effects of warmer temperatures in Chile ("positive economic effects" of climate change are allowed in several studies, such as Burke et al. (2015), OECD (2015), Krusell and Smith (2022), Cruz and Rossi-Hansberg (2021)), then Hernandez and Madeira (2022) conclude that climate change would have a negative effect of -29.6% on the Chilean GDP by 2100 under an RCP 8.5 scenario.

More complex structural models of climate change also give a wide range of estimates for the GDP impact of climate change in Chile (Madeira, 2022), with estimates ranging from i) a positive effect of 14% (Krusell and Smith, 2022), ii) a minor effect of -0.6% (OECD, 2015) or iii) a moderate effect of -3% of the GDP (Guo et al., 2021). The structural model of Cruz and Rossi-Hansberg

(2021) finds that climate change could have a minor positive effect on the Chilean GDP if one allows for international migration and adaptation measures, while climate change could have a minor negative effect on the Chilean economy if no adaptation measures are implemented.

3 Data and methodology

3.1 Data on real estate properties

To measure the economic impact of climate change physical hazards on real estate properties, we use the Chilean Real Estate Properties Registry (in Spanish, *Catastro de Bienes Raíces*, hereafter CBR). The CBR dataset is from the most recently available year, the tax reports of April of 2021 (which corresponds to the economic activities performed during the calendar year of 2020). The CBR dataset has the location (municipality) of each real estate property. To summarize the geographical distribution of risks, we also show the results across macrozones by defining four large macrozones, with macrozone 1 "North Chile" corresponding to regions I, II, III, IV and XV; macrozone 2 "Central Chile"" corresponding to regions V, VI, VII, VIII and XVI; macrozone 3 "South Chile" corresponding to regions IX, X, XI, XII and XIV; and macrozone 4 "Metropolitan Region" corresponding to region XIII (which comprises around 45% of the population and GDP of the nation). Figure 1 in section 5 shows the population density, as well as the ARCLIM-CIE indicator that we built, across the Chilean regions.

This administrative dataset from the Chilean tax authorities includes all the real estate properties in Chile, whether for the purposes of Agriculture, retail/commerce, offices, residential, storage/cellar, parking space or empty site/undeveloped terrain. For the purposes of our climate change analysis, we focus only on agriculture and residential properties. The CBR dataset contains the following information on each property in Chile: address, municipality, date (day, month, year), price in real monetary units of the transaction[4], taxable value in real monetary units[5], year and quality of the

[4]UF is a real monetary unit applied in Chile, which is updated according to the official consumer price inflation (CPI) index. This real monetary unit is widely used for long-term contracts such as mortgages and real estate transactions.

[5]Taxable value is evaluated using the characteristics of the property plus the transaction price of similar properties

construction (with 7 categories for quality), property surface of the land area (in square meters) and property surface of the construction (in square meters). From the CBR, we get information on over 4 million real estate properties in Chile, which are classified as residential, retail or commercial, office, agriculture, storage, parking lot, undeveloped land and unclassified-other.

Table 3 summarizes the fraction of each type of property in the register, their share of the national real estate appraisal value and the mean and percentiles of the appraisal value of each property type. Residential homes represent 73.6% of the number of all properties, but homes have a small mean value (only 1,095 UF) and, therefore, represent just 50.8% of the overall appraisal value. Next to residential homes, the most significant properties in terms of number are parking lots, storage and wasteland, which represent 8.8%, 6.5% and 6% of all properties, respectively. In terms of the appraisal value, next to residential homes, the highest shares of the total appraisal value represent agriculture-silviculture, retail and wasteland, which represent, 10.5%, 8.8% and 7.5% of the total appraisal, respectively. The most valuable properties, according to the mean appraisal, are public administration (106,810 UF) and mining (96,848 UF) properties, while the lowest valued are parking lots (215 UF), storage (478 UF) and residential homes (1,095 UF).

Figure 1 presents the ARCLIM-CIE climate risk exposition indicator that we estimated in this article across regions, next to the population density.

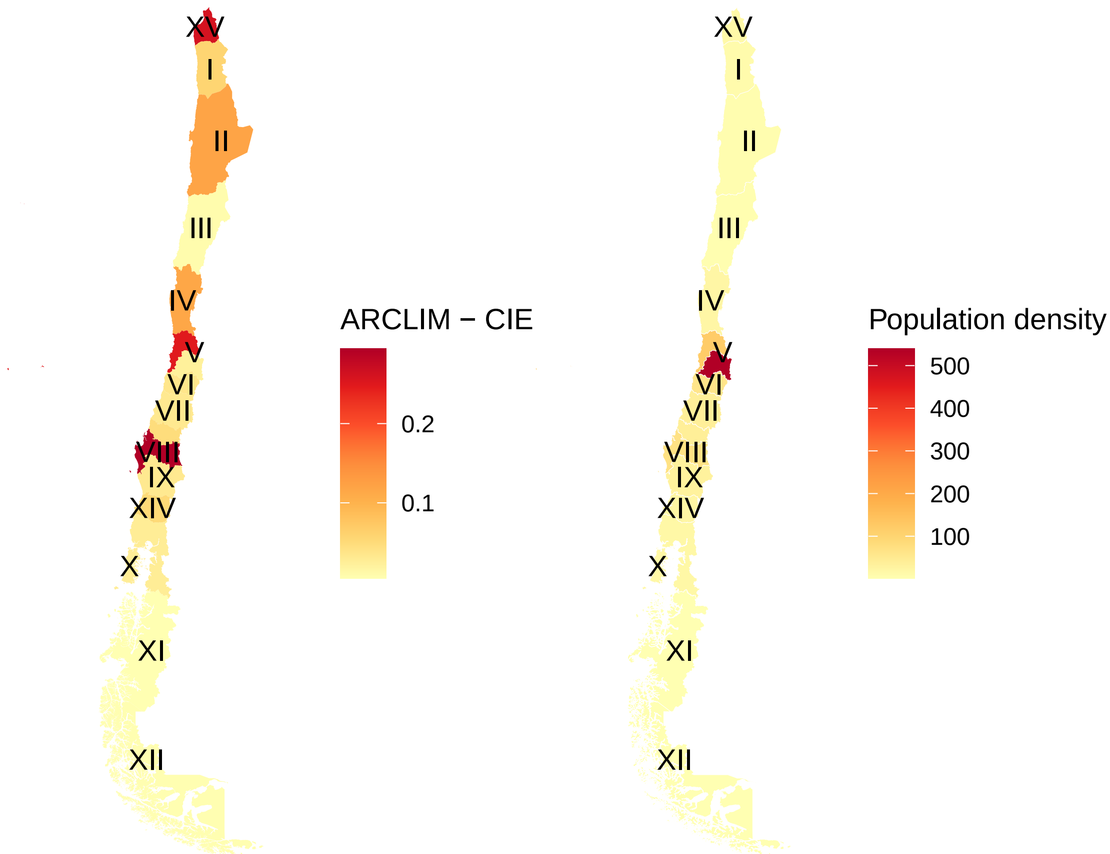
3.2 Data on climate hazards in Chile

We use two data sources to measure climate hazards in Chile: i) ARCLIM dataset from the Chilean Ministry of Environment and ii) CIE data from the science-based climate policy organization Climate Analytics.

ARCLIM is a project of the Ministry of Environment of the Government of Chile, developed by the Climate and Resilience Research Center (CR2) and the Global Change Center (CCG – Catholic University of Chile) with the collaboration of other national and international institutions. The methodology for the climate risk indicators in ARCLIM is extensively documented in Meza et al.

in the same county area in recent years. Taxable values are updated every three years. This method is implemented by tax authorities to prevent owners from under-reporting the properties' true transaction values. In Chile, there are few known home or land transactions outside of the legal registry.

Figure 1: **ARCLIM-CIE indicator and population density by region**



Note: The left panel shows the ARCLIM-CIE indicator across regions and the right panel shows the population density in each municipality. The more red (dark) the region, the higher the index, and the more yellow (light), the lower the index. Given this, the darker the color of the region/municipality, the higher its exposure to physical risks from climate change (left) and the more population density (right) there is. Both figures reference the country's geography, which, as mentioned in the text, is long and narrow, giving it climatic diversity. Population density is expressed in number of people per km^2.

Table 3: **Shares, mean and percentile statistics for the appraisal value of properties**

Property type	Number of properties		Fraction of total	Appraisal Value of the properties (in UF)				
	Number	% of total	appraisal (in %)	Mean	p25	p50	p75	p90
Retail	151,088	2.1	8.2	6,298	672	1,456	3,471	8,445
Sports & recreation	4,278	0.1	1.2	32,059	1,238	3,459	11,830	43,684
Education and culture	18,526	0.3	3.9	24,374	2,119	5,793	17,822	49,099
Hotels and motels	9,597	0.1	0.8	9,756	1,242	2,197	4,746	13,160
Residential	5,378,993	73.6	50.8	1,095	386	654	1,195	2,187
Industrial	18,445	0.3	3.8	23,606	2,473	5,970	17,450	50,185
Agriculture-silviculture	33,463	0.5	10.5	36,399	3,580	11,529	41,036	99,207
Storage	471,348	6.5	1.9	478	30	44	70	136
Mining	333	0.0	0.3	96,848	1,478	7,549	55,174	285,395
Office	94,647	1.3	3.9	4,808	967	1,734	4,061	10,207
Public administration	2,109	0.0	1.9	106,810	1,699	5,284	19,486	69,193
Religious	11,312	0.2	0.5	5,180	612	1,431	3,607	9,858
Health	4,403	0.1	1.1	28,880	864	2,636	9,846	34,132
Transport and communications	2,287	0.0	0.5	25,568	984	3,218	11,456	43,532
Other - non classified	24,889	0.3	2.0	9,438	572	1,514	4,206	13,108
Wasteland	439,688	6.0	7.5	1,991	142	275	688	1,868
Parking lots	641,262	8.8	1.2	215	134	161	202	273

Note: Shares are % in terms of the number and appraisal of all properties in Chile. Mean and percentile statistics are for the appraisal values of the individual properties.

(2020) and (Urquiza et al., 2020). ARCLIM was supported by the Global Risk Assessment and Management Program for Adaptation to Climate Change (Loss and Damage) commissioned by the German Federal Ministry for Economic Cooperation and Development (BMZ). We collected data describing various physical climate risks affecting Chile, such as heat waves, wildfires, hydrological droughts and floods (urban areas, river overflow and coastal settlements). [6]

The project has been prepared following the guide of the Fifth Report (AR5) from working group II of the Intergovernmental Panel on Climate Change. Its objective is to develop a set of risk maps related to climate change for Chile using a common conceptual framework and a

[6] Access to the ARCLIM data and Climatic Risk Atlas here.

consistent database, which makes it an important tool for the design of public policies. The tool was developed by 93 local experts organized into 15 specialized working groups, distributed in 31 research centers throughout Chile. In addition, it is developed from 25 GCM models [7] (among others) of the IPCC corrected for Chile in high resolution, with permanent coordination with the Ministry of the Environment. With all this, we consider this tool more appropriate when it comes to local studies, since it has a higher level of dis-aggregation. Aditionally, being developed by local experts, research centers and universities, it considers more idiosyncratic elements of the country and its geographical territory than our other source might include.

The CIE is an initiative by Climate Analytics in collaboration with the Network for Greening the Financial System (NGFS), the Postdam Institute for Climate Impact and ETH Zürich. According to the CIE's web page, this tool shows how the severity of climate change impacts will increase over time in continents, countries, and provinces at various levels of global warming and future years. The data includes RCP scenarios (IPCC 2014), ant those for the current policy commitments and the NGFS's most likely policy paths.[8] CIE has three main sources of information. Impact projections are are assesed in the global open access databases produced by ISIMIP (The Inter-sectoral Impact Model Intercomparison Project) (Frieler et al., 2017) and CLIMADA (Aznar-Siguan and Bresch, 2019). [9] These datasets are averaged from the simulation results of many scenario experiments conducted with several climate and climate impact models. Finally, the last source is MAGICC (Model for the Assessment of Greenhouse Gas Induced Climate Change), which provide simpler climate models used to capture the full Global Mean Temperature (GMT) uncertainty for various emissions scenarios (Meinshausen et al., 2011). [10]

One of the main contributions of this paper is to publicize these open-access tools that are

[7] According to the IPCC, General Circulation Models (GMCs) are numerical models representing physical processes in the atmosphere, ocean, cryosphere and land surface, are the most advanced tools currently available for simulating the response of the global climate system to increasing greenhouse gas concentrations. Find a broader explanation here: https://www.ipcc-data.org/guidelines/pages/gcm_guide.html

[8] Climate Analytics, 2022. Climate Impact Explorer. Available at: https://climate-impact-explorer.climateanalytics.org/

[9] Access to more information on these sources in their websites: https://www.isimip.org/ and https://github.com/CLIMADA-project/climada_python, respectively.

[10] Climate Analytics, 2022. Climate Impact Explorer. Available at: https://climate-impact-explorer.climateanalytics.org/. More information on methodological details of the Climate Impact Explorer and its sources can be found in the methodology section.

friendly to researchers who are not dedicated to climate models. The idea is to show that it is not necessary to know in detail or understand all the climate models used to generate these indices. We want to show that the information is available to be incorporated as a control variable in all types of models, considering that the physical risks attributed to climate change cannot be ignored.

For Chile, the geographic level of aggregation of the data are the 15 regions in which the country was divided for administration purposes until 2017 (Hernandez and Madeira, 2022).

We use five indicators of climate risks: Crop failure, wildfires, river flood depth, coastal deterioration and labor productivity lost due to extreme heat. The first four indicators represent the change in the fraction of population annually exposed to that specific hazard (expressed in percent) at various global warming levels compared to the reference period 1986-2006, based on the RCP85 scenario. The last indicator refers to the change in labor productivity due to heat stress (expressed in percent) at various global warming levels compared to the reference period 1986-2006, based on the RCP85 scenario.

3.2.1 ARCLIM climate risk indicators

We use four indicators from ARCLIM for each municipality i: i) $ARCLIM - wildfire_i$, ii) $ARCLIM - flood_i$, iii) $ARCLIM - drought_i$ and iv) $ARCLIM - Coast_i$.

The ARCLIM wildfire indicator is obtained as follows

1) $ARCLIM - wildfire_i = \frac{1/D_i}{\max_c 1/D_c} \times (\frac{SNF_i \times ANF_i \times \max(NF-P_i, NF-F_i)}{100} + \frac{SPF_i \times APF_i \times \max(PF-P_i, PF-F_i)}{100})$,

with D_i (which is variable *b_road_dist_buffer* in the raw ARCLIM data) denoting the average distance of the municipality's residential areas to the forest paths, information retrieved by ARCLIM from the Ministry of Public Works (in Chile, this government unit's name is translated as Ministry of Public Works, but it is the ministry responsible for building and maintaining infrastructures, and it is equivalent to the Ministry of Public Infrastructure in other countries).

The term $\frac{SNF_i \times ANF_i \times \max(NF-P_i, NF-F_i)}{100}$ represents the climate exposure of the native forests in municipality i, with SNF_i (given by the raw variable *b_inc_bnativ6* in ARCLIM) denoting the sensitivity of the native forests in municipality i to fires, ANF_i (*b_expos_bn_p* in ARCLIM) denoting the percentage of surface area in the municipality i that is occupied by native forests (in hectares, see Zhao et al. (2016), CONAF (2017), Hansen et al. (2013): and it represents the exposure of native forests to wildfires), $NF-P_i$ (*b_inc_bnativ4* in ARCLIM) denoting the present risk of native forest fires in municipality i and $NF-F_i$ (*b_inc_bnativ5* in ARCLIM) denoting the future risk of native forest fires in municipality i. The term $\frac{SPF_i \times APF_i \times \max(PF-P_i, PF-F_i)}{100}$ represents the climate exposure of the plantation forests in municipality i with SPF_i (*b_inc_plant8* in ARCLIM) denoting the sensitivity of the plantation forests in municipality i to fires (calculated as the sensitivity to native forest wildfires) APF_i (*b_expos_pf_p* in ARCLIM) denoting the percentage of surface area in the municipality i that is occupied by plantation forests (in hectares, see Zhao et al. (2016), CONAF (2017), Hansen et al. (2013), and it represents the exposure of plantation forests to wildfires.), $PF-P_i$ (*b_inc_plant5* in ARCLIM) denoting the present risk of plantation forest fires in municipality i and $PF-F_i$ (*b_inc_plant6* in ARCLIM) denoting the future risk of plantation forest fires in municipality i. Note that using the maximum between current and future risks does not imply a significant difference in our results, because future risks are significantly larger than current risks for almost all the municipalities. We opted for using the maximum between current and future risks as a robustness measure, because future risk is likely to be more dependent on uncertain assumptions about the future weather; therefore, using the maximum level of risk provides a worst-case measure.

The information for the variable SPF_i (*b_inc_plant8* in ARCLIM) comes from the CONAF (National Forestry Corporation; acronym based on its Spanish name). This database contains information on 19,413 wildfires. Sensitivity to wildfires depends on the probability of occurrence, which was determined by selecting a set of variables that can operate as underlying factors of the early stages of forest fires (Ganteaume and Syphard, 2018). For this analysis, a database was used that includes only fires between January 2013 and December 2015, considering that the most complete land-cover map made for the country is from 2014 (Zhao et al., 2016).

To evaluate the fire risk, we look at native forests and plantation forests, and the evaluation covers four stages, i) exposure evaluation, that is, mapping the national geographic distribution, ii) evaluation of the socio-environmental (internal or external) conditions for the sensitivity analysis, iii) determination of variables that may affect native forests and plantation forests directly or indirectly through decreased productivity or forest fires and finally iv) determination of the geographic area where each system may be under a higher climatic risk.

Therefore, the present or future risk is the conclusion of the general workflow of ARCLIM, and is defined as follows: Risk = Exposure × Threat × Sensibility. The exposure index is the exposed area of native forests and native plantations in Chile. Then, sensibility describes the socio-economic conditions that make either system more prone to suffer any consequence of climate change. Finally, the threat index has two parts: first, the effect of high temperatures and decreased precipitation on the photosynthetic productivity of forests (greenness), and second, the effect of heat waves as a driver of the spread of wildfires.

The ARCLIM flood indicator is obtained as follows

2) $ARCLIM - flood_i = \min(flood - risk - 10years_i, flood - risk - 20years_i)$,

with $flood - risk - 10years_i$ (*ind_riesgo8* in the ARCLIM raw dataset) denoting the index of flood risk within 10 years into the future of municipality i. As explained earlier for the wildfires, the risk flood index is not the probability of occurrence, but the susceptibility of counties a greater or lesser consequences from the flood. This risk indicator is presented for a return period of 10 years, and as before, is constructed as a product between the exposure, threat and sensibility indices. In this case, exposure is related to population density, educational density and available services for the community. The threat index shows the communities with greatest adverse effects because of floods generated in the urban area.The quality of housing and public services is evaluated to indicate the susceptibility to flooding due to extreme rainfall in the area.

We opted for the minimum of the 10-year and 20-year flood risks of each municipality, because it has a high correlation (98.7% correlation) with the average of the 5-year, 10-year and 20-year flood risk, and therefore appears to be robust to possible measurement errors in the prediction of flood risks in the long term. This option also provides a conservative value for the flood risks, which are shown to be substantial in the ARCLIM datasource.

The ARCLIM drought indicator is obtained as follows

3) $ARCLIM - drought_i = Future - yearly - drought - days_i/365$,

with $Future - yearly - drought - days_i$ (*dias_seq3* in the ARCLIM raw dataset) denoting the expected yearly days of drought in the future for municipality i. A day of drought is defined as having lower river flows than historically observed, defining a flow rate with a 85% probability of exceeding the historical observation.

The ARCLIM coastal deterioration indicator is obtained as follows

4) $ARCLIM - Coast_i = coastal - threat_i$,

with $coastal - threat_i$ (*cost_amenaza* in the ARCLIM raw dataset) denoting the climate threat index by the mid-21st century for the coastal settlements of municipality i. This is the change in flood elevation (due to a combination of sea level rise and tidal surge intensity), expressed in terms of probability (increase in flood elevation) and with a zero value for settlements with reduced flood elevation. The indices in the ARCLIM data are applied to their respective municipalities and then applied to the total appraisal value or number of properties in each municipality to obtain aggregate values for each region or macrozone, as explained in equations 8) and 9).

3.2.2 CIE climate risk indicators

We use data from the CIE for each region r to obtain their values for the year 2050 relative to four indicators under an RCP 8.5 scenario (which is the same scenario used in the ARCLIM data): $CIE - heat_r$, $CIE - wildfire_r$, $CIE - flood_r$ and $CIE - drought_r$. All the CIE indicators have 1986-2006 as a reference period. More details about the methodology of these variables are available from the Climate Analytics website (CIE 2021).

$CIE - heat_r$ denotes the fraction of labor productivity lost due to extreme heat. heat stress influences labour productivity indicates the percentage decrease in efficiency during regular working hours under hot and humid climate conditions, due to the reduced capacity of the human body to perform physical labour. Projections weighted by population or GDP were calculated assuming that both the size and the partition of these two parameters would stay constant as of 2005. This indicator quantifies heat stress by looking at wet-bulb global temperature, using a combination of five exposure response functions to translate projected variations in wet-bulb global temperature into changes in labor productivity. However, these functions have been derived from field studies focusing on the effects of heat stress on the conduction of tasks specific to a work field (e.g., in agriculture) or a location; hence there is substantial uncertainty around their applicability at global scale.

$CIE-wildfire_r$ denotes the fraction of the regional surface area exposed to fires. Land fraction annually exposed to wildfires describes the land area fraction, within a grid cell of 0.5° resolution, burnt at least once a year on average by wildfires. Land-use and irrigation patterns, as well as fire management practices, are assumed to be constant as of 2005.

$CIE-flood_r$ denotes the fraction of the regional surface area exposed to floods. Land fraction annually exposed to river floods is defined as the land area fraction which is flooded on average during the most severe flood of the year. A flood is considered to occur in a specific location if the annual maximum river discharge exceeds the local protection standard from the FLOPROS database. Land-use and irrigation patterns, as well as water use for human activities and flood protection standards, are assumed to be constant as of 2005.

$CIE-drought_r$ denotes the fraction of the regional surface area exposed to crop losses from climate events. We could also call this indicator $CIE-Crop_r$, but we prefer the drought denomination to compare the indicators of various databases. The $CIE-drought_r$ indicator refers to the land fraction annually exposed to crop failures, defined as the fraction of a grid cell of 0.5° resolution, in which one of the four considered crops (maize, wheat, soybean and rice) is grown, and where its average annual yield falls short of the 2.5th percentile of the pre-industrial reference distribution (i.e., an exceptionally low yield that would occur on average only 2-3 years per century in the absence of climate change). All crop-specific land area fractions exposed are added together. Land-use and irrigation patterns, as well as agricultural management practices, are assumed to be constant as of 2005.

3.2.3 Overall ARCLIM, CIE and ARCLIM-CIE indicators

We construct indices from the indicators of the ARCLIM and CIE for various geographic levels: municipality, region and macrozone (northern, central, south and the Metropolitan region, where the capital city Santiago is located, which represents around 45% of national GDP and population). These overall indexes sum up the separate indicators for heat, wildfire, flood, drought and Coastal risks:

5) $ARCLIM_i = \sum_{risk \in \{heat, wildfire, flood, drought, Coast\}} ARCLIM-risk_i,$

6) $CIE_r = \sum_{risk \in \{heat, wildfire, flood, drought, Coast\}} CIE - risk_r$,

7) $ARCLIM - CIE_i = \sum_{risk \in \{heat, wildfire, flood, drought, Coast\}} ARCLIM - CIE - risk_i$,

with $ARCLIM - heat_i = CIE - heat_{r(i)}$ (in the absence of this information in the ARCLIM data), $CIE - Coast_r = \frac{1}{n_r} \sum_p 1(p \in r) ARCLIM - Coast_{i(p)}$ (with $n_r = \sum_p 1(p \in r)$ denoting the number of real estate properties in region r and $i(p)$ denoting the municipality of property p, this indicator is obtained in the absence of such information in the CIE data), $ARCLIM - CIE - risk_i = \max(ARCLIM - risk_i, CIE - risk_{r(i)})$, r denoting one of the 15 administrative Chilean regions, i denoting the municipality, and $r(i)$ denoting the region of municipality i. Note that all the risks $(ARCLIM - risk_i, CIE - risk_{r(i)} and ARCLIM - CIE - risk_i,)$ are bounded between 0 and 1.

To obtain the economic exposition measures to climate risk, we use the CBR and SII data by municipality or region to obtain:

8) $M_i^{Source} = \frac{\sum_{p \in i} M_p \times Source_{i(p)}}{\sum_{p \in i} M_p}$,

with p denoting a real estate property or a firm; $i(p)$ denoting the municipality of firm or property p; M denoting the type of economic measure ($M \in \{Appraisal, Assets, Debt, Net - worth, Sales\}$), with M_p being the appraisal value of real estate p from the CBR dataset or the total assets, debt, net worth or annual sales of firm p from the SII data; and $Source \in \{ARCLIM, CIE, ARCLIM - CIE\}$ denoting the database of the indicator. Note that real estate properties can also be divided according to their property classification type (residential, industrial, mining, retail or commercial, office, public administration, agriculture-silviculture, Storage, parking lots, undeveloped wasteland, sports & recreation, education and culture, hotels and motels, religious, health, transport and communications and unclassified-other) and firms can be classified by industry. We can also compute compute various economic measure exposures M for each physical risk type:

9) $M_i^{Source-risk} = \frac{\sum_{p \in i} M_p \times Source{-}risk_{i(p)}}{\sum_{p \in i} M_p}$.

All the exposures presented in this article take place in an RCP 8.5 scenario, in which countries do not adopt climate change mitigation policies and the greenhouse gas emissions maintain their current evolution. The reason is that most of the ARCLIM measures are available only under an

RCP 8.5 scenario, although the CIE variables are available under several scenarios. Therefore, for reasons of data compatibility, we only present the results under the worst-case RCP 8.5 scenario. Note that all exposures, whether the ARCLIM, CIE or the joint ARCLIM-CIE measures, are presented in terms of annual risk of exposures (this does not imply that all regions will be experience a climate disaster in every year, only that the region is exposed to an estimated probability to such risks). The results are discussed in terms of absolute exposures in each future year, not as changes to the levels of a predetermined year (such as 2023 or some past year).

4 Results

4.1 Real estate properties

We start by summarizing the exposure of real estate properties to each physical risk. This makes sense, because real estate cannot be moved to safer areas (although the loss in appraisal value in some areas can be attenuated by the increase in appraisal value in safer areas due to the movement of economic activity). This section is focused on the indicators measures obtained using the RCP 8.5 scenarios from the ARCLIM and CIE datasources.[11]

Table 4 summarizes the exposure of the real estate properties in Chile to different types of risk, according to the source (ARCLIM, CIE or ARCLIM-CIE). Using the ARCLIM-CIE overall indicator, the population of all the properties in Chile faces an exposure of 38.6% to climate change, while residential properties face a slightly lower exposure of 38.2%, this difference being explained by the lower flood and coastal deterioration risks of residential areas. This result makes sense, because urban plans should be designed to limit the exposure of residential areas to climate risks.

There are some substantial differences between the ARCLIM and CIE climate risk measures. The appraisal exposure of the ARCLIM, CIE and ARCLIM-CIE indicators is 31.1%, 15.9% and 38.6% for all real estate properties, respectively, and slightly lower (30.6%, 15.6% and 38.2%) for the residential homes. The CIE data gives a much lower exposure risk than the ARCLIM source, especially for flood and drought risks, although the CIE source reports a higher risk of wildfire

[11] Both the RCP 8.5 and the current policies, scenarios in the CIE data source provide qualitatively similar results for Chile and its regions, although with differences in the numeric values.

than the ARCLIM dataset. Furthermore, the CIE source gives a higher risk for drought in some areas, since the joint $ARCLIM - CIE - drought_i$ indicator is bigger than the ARCLIM and CIE indicators.

Finally, the results show that the ARCLIM and ARCLIM-CIE indicators measured in terms of the total risk exposure for appraisal values are larger than in terms of the number of properties exposed, particularly for the flood and coastal deterioration risks. This result is due to the higher value of the properties in the most exposed areas. The CIE risks, however, are larger in terms of the number of properties affected than in terms of their appraisal value.

Table 4: **Exposure of the real estate properties to the climate change physical risks**

Physical risks	All real estate properties			Residential properties		
	ARCLIM	CIE	ARCLIM-CIE	ARCLIM	CIE	ARCLIM-CIE
	Exposure in % of the appraisal value					
Overall	31.1	15.9	38.6	30.6	15.6	38.2
heat		0.1	0.1		0.1	0.1
wildfire	0.7	6.1	6.1	0.8	6.2	6.2
flood	20.1	1.2	20.2	19.6	1.2	19.7
drought	5.0	3.1	6.7	5.5	3.2	7.1
Coast	5.4		5.4	4.8		4.8
	Exposure in % of the number of properties					
Overall	27.9	16.8	36.9	27.9	16.9	37.3
heat		0.2	0.1		0.2	0.1
wildfire	1.1	8.3	8.3	1.2	8.9	8.9
flood	16.8	1.0	16.9	16.4	1.0	16.5
drought	5.4	2.7	6.8	6.0	2.6	7.3
Coast	4.7		4.7	4.4		4.4

Note: Estimates are under the NGFS RCP 8.5 scenario, according to its source (ARCLIM, CIE and ARCLIM-CIE).

Table 5 summarizes the overall risk indicators across macrozones. The North and Central macro-regions are the most exposed areas in terms of appraisal value or in the fraction of properties exposed, according to any of the ARCLIM, CIE and ARCLIM-CIE indicators. According to the ARCLIM-CIE indicator, the North and Central zones have 36.1% and 51% exposure of their appraisal values for all real estate properties, respectively, while showing a risk of 38.1% and 49.2% for residential homes. The Central macrozone is by far the area with the highest exposure according to the CIE and ARCLIM-CIE indicator, although the risk of the North macrozone is slightly higher under the ARCLIM indicator. The appraisal value of the North macrozones has exposures of 36%, 12% and 36%, according to the ARCLIM, CIE and ARCLIM-CIE indicators, respectively. The Central macrozone is the most exposed area, according to the CIE and ARCLIM-CIE indicators, its appraisal showing exposures of 35%, 38% and 51%, according to the ARCLIM, CIE and ARCLIM-CIE indicators, respectively. The reason for the overall higher risk of the Central macrozone according to the CIE and ARCLIM-CIE indicators is due to its wildfire risks, which are more reported in the CIE data.

The South macrozone is the least exposed area according to the ARCLIM and the ARCLIM-CIE indicators, with its appraisal showing exposures of 15%, 14% and 27%, according to the ARCLIM, CIE and ARCLIM-CIE indicators, respectively. The Metropolitan macrozone is the least exposed area according to the CIE indicator, with its appraisal showing exposures of 31%, 8% and 36%, according to the ARCLIM, CIE and ARCLIM-CIE indicators, respectively. The results also show that the residential properties have a lower risk in appraisal value than the population of all properties for Chile as a whole, particularly for the Central and Santiago Metropolitan macrozones. This is a sign that urban plans reduce the risk in residential areas. The data, however, shows that results are reversed in terms of the number of properties, with a higher exposure of residential homes relative to the population of all properties, which is due to high climate exposure among residential homes of lower value and could be a sign that poorer neighborhoods in Chile face higher climate risks.

Again, there are considerable disparities if one considers the ARCLIM and the CIE sources. Relative to the ARCLIM database, CIE underestimates climate exposures at the national level and in the North and Metropolitan macrozones. The ARCLIM and CIE datasources, however, appear to provide similar exposure values for the Central and South macrozones.

Finally, Table 6 shows the exposure (given by the ARCLIM-CIE joint source) across all the various property types of the CBR database. The results show that transport and communications are the property types most exposed to risks, showing an overall exposure of 44.1%, with its wildfire risk exposure being the highest among all property types. Office properties also face a high overall

Table 5: **Overall exposure of the real estate properties across macrozone regions**

Macro zone	All real estate properties ARCLIM	CIE	ARCLIM-CIE	Residential properties ARCLIM	CIE	ARCLIM-CIE
	Exposures in % of the appraisal value					
Chile	31.1	15.9	38.6	30.6	15.6	38.2
North	35.6	11.5	36.1	37.5	10.7	38.1
Central	35.0	37.7	51.0	33.8	35.0	49.2
South	14.5	14.4	26.7	14.7	14.4	26.8
Metro	30.8	7.5	35.5	30.1	7.5	34.8
	Exposures in % of the number of properties					
Chile	27.9	16.8	36.9	27.9	16.9	37.3
North	33.8	9.4	34.5	34.1	9.3	34.8
Central	29.9	32.6	46.4	29.3	31.5	46.3
South	12.8	14.9	25.6	13.5	14.9	26.1
Metro	28.7	7.5	33.6	29.0	7.5	33.7

Note: Estimates are under the RCP 8.5 scenario. Regions are divided as follows, North: XV, I, II, III, IV; Center: V, VI, VII, VIII; South: XIX, X, XII, XII XIV; Metro: XIII (Metropolitan region).

exposure of 40.5%, particularly due to their flood exposure risk of 27.1%, the highest among all property types.

Mining properties show the lowest climate exposures of all property types. Mining areas have an overall exposure of 24%, much lower than the 38.6% risk for all properties. In particular, mining properties have the lowest wildfire exposure (just 0.4% relative to the 6.1% of all properties) and the lowest flood risk (just 9.7% relative to the 20.2% of all properties). However, the drought exposure of Mining areas is the highest among all properties, with a value of 9.8%. This lack of access to water may increase mining exploration costs in the future.

Public administration properties show the highest risk of coastal deterioration, because large stretches of the coastal area and natural parks are owned by the state. Wastelands owned by private companies also show high exposure to coastal deterioration, with a value of 7.7% (which is still much lower than the 12.2% of public administration properties), while industrial and office properties show the lowest risks of coastal deterioration, with 3% and 3.5% risk exposures. Public administration properties, on the other hand, have a low drought exposure, at just 3.1%, the lowest value among all property types.

5 Results by region

According to the ARCLIM-CIE indicator, the fraction of properties and the appraisal value of real estate are most affected in regions VIII and XVI, whether in all properties or residential homes. Region VIII and XVI belong to the Central macrozone. Table 7 shows that in regions VIII and XVI, around 82% of the appraisal value of all properties and residential homes is exposed to climate risks. In terms of the fraction of properties, regions VIII and XVI display exposure levels of 75.2% and 74.4% for all properties, with similar numbers for the residential homes, being again the most affected regions. Regions VIII and XVI are also the most impacted regions according to the CIE indicator reporting exposure of 69.9% and 45.5%, respectively, for the appraisal of all properties. Again, for the CIE indicator, regions VIII and XVI are the most impacted for the appraisal of residential homes or the fraction of the properties affected, either in all properties or residential homes.

Table 6: **Exposures in % of the appraisal value by property type.**

Property type	Overall	heat	wildfire	flood	drought	Coastal
All properties	38.6	0.1	6.1	20.2	6.7	5.4
Retail	40.5	0.1	5.7	20.4	7.2	5.8
Sports & recreation	36.9	0.1	3.7	20.5	5.8	4.9
Education and culture	40.5	0.1	6.0	19.8	7.3	6.3
Hotels and motels	37.1	0.1	4.7	18.1	6.5	6.4
Residential	38.2	0.1	6.2	19.7	7.1	4.8
Industrial	36.4	0.1	6.0	17.5	7.1	3.0
Agriculture-silviculture	39.6	0.1	2.7	24.4	5.7	5.6
Storage	40.4	0.1	3.7	25.8	5.5	3.5
Mining	24.1	0.0	0.4	9.7	9.8	3.9
Office	40.5	0.1	3.0	27.1	5.1	4.2
Public administration	37.3	0.1	2.9	18.1	3.1	12.2
Religious	39.2	0.1	5.7	20.0	7.2	4.6
Health	37.4	0.1	5.4	18.1	6.3	6.0
Transport and communications	44.1	0.1	9.6	18.1	6.3	6.5
Other - non classified	39.4	0.1	7.1	16.7	7.1	5.9
Wasteland	36.9	0.1	5.0	16.0	6.4	7.7
Parking lot	38.9	0.1	2.8	24.6	4.7	5.9

Note: Exposures of ARCLIM-CIE indicators, according to RCP 8.5 scenarios.

Table 7: **Overall exposure of the real estate properties across regions**

Region	All real estate properties			Residential properties		
	ARCLIM	CIE	ARCLIM-CIE	ARCLIM	CIE	ARCLIM-CIE
	Exposures in % of the appraisal value					
Chile	31.1	15.9	38.6	30.6	15.6	38.2
I	21.3	6.0	22.0	21.0	6.0	21.6
II	31.0	12.0	31.0	32.9	10.2	32.9
III	33.5	0.2	33.5	35.1	0.2	35.1
IV	42.1	12.1	43.4	41.8	12.0	43.1
V	34.1	36.3	46.2	33.6	34.3	45.6
VI	15.4	12.3	24.2	15.8	12.3	24.6
VII	19.9	3.9	22.3	19.2	3.9	21.7
VIII	53.2	69.9	82.2	52.7	68.5	82.1
IX	15.4	18.0	29.8	15.4	18.0	29.7
X	15.2	19.1	33.6	15.9	19.1	34.3
XI	1.8	4.5	5.9	1.8	4.5	5.9
XII	8.9	1.1	9.6	9.2	1.1	9.9
XIII	30.8	7.5	35.5	30.1	7.5	34.8
XIV	19.1	8.4	23.6	18.9	8.4	23.3
XV	63.5	25.9	63.5	64.0	26.2	64.1
XVI	43.7	45.4	81.8	43.6	45.4	82.0
	Exposures in % of the number of properties					
Chile	27.9	16.8	36.9	27.9	16.9	37.3
I	18.5	5.4	19.4	16.6	5.1	17.7
II	30.4	10.3	30.4	30.4	9.7	30.4
III	30.9	0.2	31.0	30.8	0.2	30.8
IV	36.7	9.8	37.9	36.5	9.7	37.8
V	33.0	32.0	44.9	32.9	29.6	44.7
VI	12.1	12.3	21.1	12.9	12.3	21.7
VII	17.3	3.9	19.6	17.6	3.9	19.9
VIII	43.3	62.9	75.2	40.3	61.2	73.9
IX	13.7	18.0	28.1	13.7	18.0	28.0
X	12.8	19.1	31.2	14.4	19.1	32.8
XI	1.7	4.5	5.8	1.7	4.5	5.8
XII	8.1	1.1	8.8	8.4	1.1	9.0
XIII	28.7	7.5	33.6	29.0	7.5	33.7
XIV	16.7	7.8	21.4	17.4	7.9	22.1
XV	62.6	25.5	62.6	63.2	25.8	63.3
XVI	36.1	45.4	74.4	37.9	45.4	76.0

Note: Estimates under the RCP 8.5 scenario.

According to the ARCLIM indicator, the most impacted region is region XV, which belongs to the North macrozone, while regions VIII and XVI are the second and third most affected. In particular, the appraisal value of all properties in regions XV, VIII and XVI has an exposure of 63.5%, 53.2% and 42.7%, respectively. A similar pattern appears for the residential properties and for the number of properties affected (whether all properties or residential homes), with region XV being the most exposed to the ARCLIM-measured risks, while regions VIII and XVI are the second and third most exposed.

The two regions with least exposure, according to the ARCLIM and the ARCLIM-CIE indicators, are regions XI and XII, which belong to the South macrozone. Region XI is the least affected by climate risks, with just 1.8% and 5.9% exposure for the appraisal of all properties, according to the ARCLIM and ARCLIM-CIE indicators, respectively. Region XII's exposure is 8.9% and 9.6% for the appraisal of all properties, according to the ARCLIM and ARCLIM-CIE indicators, respectively. The conclusions are similar if we look at the ARCLIM and ARCLIM-CIE indicators of regions XI and XII for the appraisal of the residential homes and the number of properties affected, whether in all properties or residential homes.

In terms of the CIE indicator, region III (in the North macrozone) is the least affected, with just 0.2% of its appraisal of all properties exposed to climate change. The other regions with a low exposure according to the CIE indicator are region VII (Central macrozone), XI (South macrozone) and XII (South macrozone), which have between 1.1% and 4.5% exposure in terms of the appraisal value of all properties. The CIE values for these regions are also similar for the appraisal of the residential homes and the number of properties affected, whether all properties or residential homes.

Note that in some regions, the ARCLIM and CIE overall measures of exposure risk present similar values, but this is mostly a coincidence. For instance, Table 5 shows that the South macrozone has an exposure of appraisal value of 14.5% and 14.4% for the ARCLIM and CIE measures, respectively. However, the ARCLIM and CIE overall measures are different in terms of the nature of the risks (wildfire, flood, drought) behind these numbers and therefore, the joint ARCLIM-CIE measure is 27%, quite higher than the individual ARCLIM and CIE measures. Table 7 also shows that the ARCLIM and CIE overall exposure measures in terms of appraisal value are similar for regions V, VI, IX, X, XI and XVI, but again, this similarity hides large differences between both measures in terms of the nature of the risks; therefore, the joint ARCLIM-CIE measure is much larger than the individual ARCLIM and CIE exposures.

Again, the conclusions differ markedly between the ARCLIM and CIE indicators, not just in terms of the values, but also in qualitative conclusions. According to the CIE indicator, region III in the North macrozone has a very low climate exposure, but its exposure in terms of the ARCLIM indicator is slightly above the national level.

Finally, Table 8 shows the risks faced by each region and macrozone as a percentage of the appraisal value of all the real estate properties. Region XV faces the highest exposure to labor productivity loss from heat, while all the other regions face a somewhat small impact. The South macrozone, despite having cooler temperatures relative to the rest of the country, is the most exposed to the labor productivity loss from heat due to its high humidity levels. Regions VIII and XVI face a high exposure to wildfire risks, with 34.6% of their properties exposed. Regions V, IX and X also face a significant wildfire exposure, with risks of 9.7%, 14.1% and 12.1%, respectively. Overall, the Central macrozone, due to its dry weather, has the highest risk of wildfire, with an exposure of 15.4%, followed by the South macrozone with a wildfire exposure of 9.9%. The Santiago Metropolitan area (region XIII) has highest exposure to flooding, presenting a risk of 27.9%. The north macrozone, particularly regions III and XV, is the second area with the highest risk of flooding, with an exposure of 15%. drought has a risk above 20% in regions IV and XV, with exposures of 20.6% and 24.2%, respectively. Regions III, VI, XIV and XVI also face significant drought risks, with exposures of 18.4%, 10%, 9.4% and 14.4%, respectively. The North macrozone shows the highest risk of drought, with an exposure of 10.6%, and the Central and Metropolitan macrozones also show high exposures of 6.6% and 6%, respectively. Finally, regions V, VIII and XV show the highest risk of coastal deterioration, with respective exposures of 23.3%, 25.3% and 22.1%. Regions II and IV also face significant coastal deterioration risks, with exposures of 11.9% and 8.9%, respectively. Overall, almost all the coastal deterioration risk is experienced by the North and Central macrozones, with respective exposures of 10% and 16.4%.

6 Conclusions

We use an administrative real estate register for all properties in Chile to measure the exposure of the real estate properties across regions and property types to climate change's physical risks.

Table 8: **Exposures of all the real estate properties across regions**

Region	Overall	heat	wildfire	flood	drought	Coast	Number of properties
Chile	38.6	0.1	6.1	20.2	6.7	5.4	7,306,668
I	22.0	0.1	0.0	17.1	1.2	3.4	131,165
II	31.0	0.0	0.0	15.8	3.3	11.9	234,062
III	33.5	0.0	0.0	15.0	18.4	0.1	108,983
IV	43.4	0.0	0.0	12.7	20.6	8.9	354,203
V	46.2	0.5	9.7	6.7	3.2	23.3	885,851
VI	24.2	0.0	4.3	3.7	10.0	0.1	357,430
VII	22.3	0.0	1.5	11.4	7.6	0.1	397,299
VIII	82.2	0.1	34.6	17.8	8.7	25.3	566,303
IX	29.8	0.2	14.1	8.7	3.2	0.0	334,093
X	33.6	0.4	12.1	8.0	6.7	0.0	292,780
XI	5.9	0.2	3.2	1.2	0.4	0.0	43,581
XII	9.6	0.0	0.5	9.1	0.0	0.0	65,567
XIII	35.5	0.0	0.0	27.9	6.0	0.0	3,171,698
XIV	23.6	0.4	3.9	5.8	9.4	2.5	122,404
XV	63.5	1.4	0.1	15.3	24.2	22.1	74,084
XVI	81.8	0.1	34.6	22.0	14.4	0.0	167,165
Macrozone	Overall	heat	wildfire	flood	drought	Coast	Number of properties
North	36.1	0.1	0.0	15.0	10.6	10.0	902,497
Central	51.0	0.2	15.4	10.5	6.6	16.4	2,374,048
South	26.7	0.3	9.9	7.7	4.7	0.3	858,425
Metro	35.5	0.0	0.0	27.9	6.0	0.0	3,171,698

Note: Estimates are % of the appraisal value of all real estate properties, using the RCP 8.5 scenario, to each climate risk under the ARCLIM-CIE indicator.

Physical risks are obtained as a composite measure of five indicators from the ARCLIM and CIE datasets, including loss of labor productivity in heat waves, fires, floods, drought and coastal deterioration. We also present the results of a joint ARCLIM-CIE indicator, which applies the maximum exposure obtained from either the ARCLIM or CIE sources for each type of risk. ARCLIM is a compilation of climate exposure risks coordinated by the Ministry of Environment in Chile with several academic partners, while the CIE is an international database for several countries published by Climate Analytics.

According to the joint ARCLIM-CIE indicator, around 39% of the appraisal value and 37% of properties are exposed to the five climate risks included in our study. The exposure values are similar whether one counts the number or the appraisal of all properties or just the residential properties, which show slightly lower exposure as a consequence of urban planning protecting living areas from the worst weather risks. The results show that flooding represents the strongest exposure to the real estate, followed by the risks of drought, wildfire and coastal deterioration, while the labor productivity Loss due to heat has almost no implications for properties' risk. In particular, the joint ARCLIM-CIE indicator shows that the appraisal value of all properties has exposures of 20.2%, 6.7%, 6.1%, 5.4% and 0.1%, respectively, for the risks of flooding, drought, wildfire, coastal deterioration and labor productivity Loss due to heat. In terms of property types, transport and communications properties present the highest exposures, while mining areas are the least exposed.

The North and Central macro-regions are the areas with highest economic exposure to climate change's physical risks, whether in terms of appraisal value or in the fraction of properties exposed, according to the ARCLIM, CIE and ARCLIM-CIE indicators. Using the joint ARCLIM-CIE indicator, the North and Central macrozones show an exposure of their total appraisal value of 36% and 51%, while the South macrozone is the least affected with an appraisal exposure of just 27%. The largest region in Chile, the Santiago Metropolitan macrozone, has a 36% appraisal exposure according to the ARCLIM-CIE indicator, only slightly lower than the North macrozone.

Finally, our study reveals very significant differences between the ARCLIM and CIE climate exposure measures, with the CIE source underestimating the climate exposures relative to the ARCLIM measure. According to the ARCLIM and CIE indicators around 31% and 16% of the total appraisal value and 28% and 17% of the number of properties in Chile are exposed to climate change risks, respectively. This underestimation of climate risks in the CIE source is particularly strong for flooding risks, with the ARCLIM reporting a 20% exposure, while the CIE indicator reports just 1%. The CIE indicator also underestimates the risk of drought, with 5% of the properties in the ARCLIM dataset being exposed relative to the 3% in the CIE source. However, the CIE indicator reveals a higher value of wildfire risks with an appraisal exposure for Chile of 6.1%, much higher than the 0.7% obtained from the ARCLIM data. Relative to the ARCLIM database, the CIE underestimates climate exposures at the national level and in the North and Metropolitan macrozones. The CIE is an international datasource that is widely used as an input for stress tests and economic studies from institutions such as the NGFS. Therefore, our result showing a lower value of risks from the CIE source for Chile could be a warning that several economic and financial studies may be underestimating the risks of climate change. Future researchers could study whether this happens for other countries besides Chile.

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Government Purchases, the Labor Earnings Gap, and Consumption Dynamics

Mario Giarda

DTBC – 971

Spatial Production Networks

Costas Arkolakis, Federico Huneeus, Yuhei Miyauchi

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From Dominant to Producer Currency Pricing: Dynamics of Chilean Exports

José De Gregorio, Pablo García, Emiliano Luttini, Marco Rojas

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Gent Bajraj, Guillermo Carlomagno, Juan M. Wlasiuk

DTBC – 968

From Patriarchy to Partnership: Gender Equality and Household Finance

Luigi Guiso, Luana Zaccaria

DTBC – 967

The COVID-19 Shock and Firm Financing: Government or Market? Or Both?

Miguel Acosta-Henao, Andrés Fernández, Patricia Gomez-Gonzalez, Sebnem Kalemli-Ozcan

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Monetary Policy in Small Open Economies and the International Zero Lower Bound

Marco Rojas

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Jorge Miranda-Pinto, Alvaro Silva, Eric R. Young

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