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A synthetic control approach on Chile's transition to democracy

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Abstract

We use a synthetic control approach for performing a case study of the impact of Economic Reforms and Democracy Openness on Chile's GDP per capita. We use data available at the World Bank Open Data from 1976 to 2014 for different countries in order to build a synthetic "authoritarian Chile" and compare it with the "real Chile". We find a significant positive effect of the process of re-democratization on Chile's long-term GDP per capita. The results are robust to placebo tests and time series methods such as endogenous structural break tests and an analysis of causal impact based on the forecasts of a Bayesian Structural Time Series model.

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A synthetic control exercise on Chile’s transition to democracy

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Abstract

We test the effect of the re-democratization process on Chile’s long run GDP per capita. Using a synthetic control approach, we show that the long-run GDP per capita trajectories of "real Chile" and "authoritarian Chile" are different and that if Chile had remained "authoritarian", income and growth rates would have been lower. All data used in this study came from the World Bank Open data. The results show that the process of re-democratization has positively and significantly affected Chile's long-term growth.

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1. Introduction

With an economic policy strongly based on liberal principles together with liberalizing financial reforms implemented during the mid-1980s, Chile stands out among the Latin American countries as the most developed and economically free. Over the past 30 years, Chile has experienced outstanding economic performance, growing at an annual average rate of 7% during 1985-1997 and 5% during 2000-2007, even though it has undergone a major change in its regime of government: from authoritarian to democratic rule. The transition occurred smoothly, preserving the economic and institutional pillars, but advancing in freedom and democracy. Since then, Chile has been consistently ranking at the top of indicators such as quality of institutions, rule of law, economic freedom, and openness. It was also the first country in the region to create autonomous regulatory agencies, such as a Central Bank and a Public Ministry (Perry and Leipziger, 1999).

As pointed out by Acemoglu *et al.* (2016), democracy may have a significant and robust positive effect on GDP per capita. While this is true for most countries, it is not valid for all countries, since the transition to democracy may present significant difficulties in terms of the implementation of reforms and economic stability. The case of Chile may shed light on the importance of such reforms and economic policies prior to the transition to democratic rule.

Our goal is to test the effect of the re-democratization process on Chile's long run GDP per capita in a simple exercise comparing "real Chile" with a synthetic "authoritarian Chile". For this purpose, we use data available at the World Bank Open Data, from 1976 to 2014, and a synthetic control approach proposed by Abadie and Gardeazabal (2003) and successive works (Abadie *et al.*, 2010, 2011, 2015). Our motivation for using synthetic control is the fact that this relatively recent method in the literature allows for the estimation of causal effects when only one unit (country) is exposed to a treatment (such as Chile's case). The idea of this method is to generate the best comparable unit (synthetic unit) based on the convex combination of data from countries that have not been affected by the intervention. As pointed by Abadie *et al.* (2015), a combination of countries often provides a better comparison for the country exposed to the intervention than any single country alone. We also perform placebo tests and employ time-series methods, such as tests of endogenous structural breaks and a Bayesian structural time series forecast, to check for the robustness of our results.

This paper is organized as follows. Section 2 describes Chile's transition from authoritarian government to democratic rule. Data and empirical strategy are described in Section 3. Section 4 discusses the results. Section 5 discusses the robustness checks. Section 6 presents the final remarks.

2. Transition from Authoritarian to Democratic Rule

The military government begins in 1973, after a coup led by General Augusto Pinochet. At that time, Salvador Allende, from the Socialist Party, was president. The state assumed a dominating role in the economy, controlling prices, interest rates and capital movements, and nationalizing companies (Billmeier and Nannincini, 2013; Keech, 2004). The country had been suffering from high inflation levels and uneven economic growth for a long period and Allende's administration was responsible for worsening the scenario with hyperinflation and economic recession (Keech, 2004). After the coup, the regime set immediately new economic policies largely influenced by the Chicago School of Economics, based on free market, sound fiscal policy, and privatizations, with a focus on macroeconomic stability[1] (Alcalá, 2008;

[1] Many structural reforms were introduced during the period, which included tax reforms and social security reforms. For more information, we recommend reading Calvo and Mendoza (1999) and Schmidt-Hebbel (1999).

Keech, 2004; Calvo and Mendoza, 1999). The military government also promulgated a new constitution which had a "protected democracy view", including restrictions on political parties and labor unions and giving the military a tutelary role of the institutional order (Keech, 2004; Heiss and Navia, 2007). The Constitution was approved in a national plebiscite and took effect in 1981 (Heiss and Navia, 2007; Alcalá, 2008).

The transition from authoritarian to democratic rule starts in 1988. The 1980 constitution set up the necessity of a referendum, after eight years of government, to vote whether Pinochet would continue as president. This new plebiscite occurred under a climate of greater freedom of expression and reconstituted political parties (Alcalá, 2008; Keech, 2004). Augusto Pinochet did not get enough votes to stay in power and the military government was forced to start the transition to a democratic government. After the defeat, the government introduced a series of constitutional reforms that aimed to maintain the economic and constitutional pillars and to prevent broader changes to the constitutional text. According to Fuentes (2011), the most import ones were related to the "reduction of the presidential period; increased senators; balanced appointment of senators between civilians and military; and the acceptance of the Communist Party". The Central Bank was also given full autonomy (Foxley and Sapelli, 1999; Alcalá, 2008). Changes were approved by a new popular referendum in 1989, backed up by the opposition. General elections took place in the same year.

Foxley and Sapelli (1999) point out that the first presidential government (Aylwin, 1990 – 1994) had to balance different expectations regarding economic, political and social issues. The new democratic government, based on a strong political coalition called *Concertación*[2], was politically inclusive and maintained economic stability, providing, therefore, a smooth transition from authoritarian to democratic rule. The Aylwin administration was a "national reconciliation" government that adopted an "agreement policy", contrasting with the military authoritarian rule. The objective was to create a climate of social peace and economic growth (Foxley and Sapelli, 1999). According to Foxley and Sapelli (1999), economic policy was based on four pillars: market allocation of resources; macroeconomic stability; open trade economy; and an increase in social spending with new social programs. The following administrations, all supported by *Concertación*, continued this trend, seeking to pacify the country, and giving greater power to regional and municipal governments (Alcalá, 2008)[3]. They gave more attention to income distribution but also continued with the economic policies implemented during the military regime (Keech, 2004).

3. Method and Data

We follow the formal method proposed by Abadie and Gardeazabal (2003) and Abadie *et al.* (2011) to test the effect of the transition from authoritarian to democratic rule in Chile.

Due to the falling copper prices and strong financial crises in 1982-83, Chile only started growing again in 1987 (Schmidt-Hebbel, 1999).

[2] The *Concertación* was a strong political coalition formed by 17 different political parties that became victorious in the 1989 elections. The *Concertación* also had an important role in the 1989 constitutional reforms, drafting most of the alterations, and in the 1988 referendum that defeated Pinochet (Alcalá, 2008; Fox and Sapelli, 1999). The coalition also made two important signalizations to the market: first, the acceptance of the 1980's Constitution; and second, the willingness to conduct the economy in a nonpartisan way (Foxley and Sapelli, 1999). The later one, according to Foxley and Sapelli (1999), was important for the "democratic legitimization of the free market economy" in Chile.

[3] See Alcalá (2008) and Fuentes (2011) for a political and legal analysis on following governments and other constitutional reforms. Both authors point out that, after 1990, Chile made small yet continuous reforms, culminating with the great constitutional reform of 2005. All reforms aimed to expand civil rights, social justice, and democracy, replacing authoritarian features, and ending the "protected democracy" cycle. Foxley and Sapelli (1999) stress the importance of the creation of autonomous agencies to democracy, such as an independent judiciary, Central Bank, and other regulatory agencies.

Suppose that we observe J+1 countries and only the first country is exposed to the intervention of interest (Chile) so that we have J remaining countries as potential controls, which we refer as "donor pools". Let Y_{it}^N be the annual GDP per capita for country *i* at time *t* in the absence of intervention, for units $i = 1, \cdots, J + 1$, and time periods $t = 1, \cdots, T$. Consider T_0 the number of pre-intervention periods, with $1 \leq T_0 < T$. Let Y_{it}^I be the GDP per capita that would be observed for country *i* at time *t* if unit *i* was exposed to the intervention in periods $T_0 + 1$ to T. We assume that the transition to democracy in Chile had no anticipated effect on the outcome before the implementation. We aim to estimate $\alpha_{1t} = Y_{1t}^I - Y_{1t}^N = Y_{1t} - Y_{1t}^N$, which is the effect of the re-democratization process in Chile. Since Y_{1t}^I is observed, we only need to estimate Y_{1t}^N by using a vector of covariates that were not affected by the intervention.

Considering a $(J + 1)$ vector of weights $W = (w_2, \dots, w_{J+1})'$ such that $w_j \geq 0$ for $j = 2, \cdots, J + 1$ and $\sum_{j=2}^{J+1} w_j = 1$, the estimated intervention effect, for $t \in \{T_0 + 1, \dots, T\}$, would be $\widehat{\alpha_{1t}} = Y_{1t} - \sum_{j=2}^{J+1} w_j^* Y_{jt}$, where Y_{jt} represents the observed GDP per capita for other countries ("donor pools") after the period of re-democratization in Chile . The idea is to estimate the GDP per capita of Chile in the absence of the intervention, Y_{1t}^N, through a weighted average of the GDP per capita of countries similar to Chile pre intervention in terms of a $(k \times J + 1)$ matrix of covariates X. The synthetic control provides weights for an unbiased estimator of Y_{1t}^N. Abadie *et al.* (2010) showed that the synthetic control estimator is unbiased even if data for only a single pretreatment period are available. Each value of W represents a weighted average of the available control country. If we define X_1 as a vector of pre-intervention characteristics for Chile, and X_0 a $(k \times J)$ matrix that contains the same variables for the unaffected countries, the vector of optimal weights, W^*, is chosen to minimize the root mean square prediction error (RMSPE), given by $\|X_1 - X_0 W\|$, subject to $w_2 \geq 0, \dots, w_{J+1} \geq 0$ and $w_2 + \cdots + w_{J+1} = 1$. Abadie *et al.* (2010) present all the steps to perform this minimization and a complete description and derivations of the synthetic control method. The idea behind this approach is that a combination of units often provides a better comparison for the unit exposed to the intervention than a single unit alone.

Our outcome variable, Y_{jt}, is the annual GDP per capita at the country level (constant 2010 US$). The covariates for Chile, X_1, and for the other countries, X_0, are related to past economic growth and labor force (population). These are the variables available from the World Bank Open Data for many countries during the period of 1976 to 2014. More specifically, we used GDP per capita levels of 1976, 1979, 1982 and 1988; an average between 1982 to 1988; the populational levels for 1976 (between 0 and 14 years and between 15 and 64 years); and an average of the population between 15 and 64 years for the entire period. We selected those variables in order to match the characteristics of the evolution of Chile's GDP per capita during 1976 and 1988, specially in moments of uncertainty such as the 1979 energy crisis and the 1982 debt crisis. An average of the GDP per capita in the period post crisis also helps to match the characteristics of the economic policies implemented in Chile as a response to the crisis. The initial population levels of 1976 and the average of the economically active population level during our sample may help to correctly match the labor force characteristic of Chile during the period of analysis.

All data used in this study came from the World Bank Open Data. We only considered countries that had complete information for the 1976-2014 period (balanced panel) because the synthetic control method does not allow for missing data. We choose 1988 as our intervention year because that was the year that Augusto Pinochet lost the "stay in power referendum" and was forced to start a transition to a new democratic government, as described in section 2. We have twelve years prior to the intervention and twenty-five years after it.

In order to enhance the robustness of our results, we employ four groups of countries as candidates for controls, so that we obtain four different donor pools and four different synthetic Chiles. The for groups are: (i) Occidental World, composed by countries from Europe, Central Asia, North America, Latin America, and the Caribbean; (ii) Americas, a subgroup removing countries from Europe and Central Asia; (iii) Americas without the US[4]; and (iv) Latin America and the Caribbean, a subgroup removing countries from Europe, Central Asia, and North America. From 111 occidental countries available at the dataset, we ended up with 46 potential candidates for the donor pool Occidental World that had no missing information. For American countries, only 26 had complete information for the whole period (originally 44 in the dataset). Finally, for the Latin America and the Caribbean, 24 countries had no missing information from a total of 41.

In section 5 we perform placebo tests and apply two methods of time-series to check for the robustness of the results. The placebo tests apply the synthetic control approach to all countries in the control groups (donors) as if they had undergone the same treatment as Chile. The time series approach employs an endogenous structural break test and a Bayesian structural time-series model to detect and estimate the effect of the democracy openness in Chile considering the dynamics of the GDP per capita. While the placebo tests are the synthetic control approach to check statistical significance of the results, the time-series model measures a plausible range for the treatment effect based on credible intervals.

4. Estimating the Effects of Re-democratization in Chile

After applying the algorithm proposed by Abadie and Gardeazabal (2003) and Abadie *et al.* (2011) for the selection of donors, we ended up with four different synthetic Chiles that are combinations of the following: Bahamas, Bolivia, Costa Rica, Cyprus, Georgia, Paraguay, St. Vincent and the Grenadines, United States of America, and Uruguay. The weights can be seen at Table I. It's important to stress that the countries weights are the result of the optimization process performed by the synthetic control algorithm, reflecting the optimal W* for each donor pool. For example, as Table I shows, synthetic Chile for the Latin America & Caribbean donor pool is composed by the Bahamas (4.5%), Paraguay (33.6%), St. Vincent and Grenadines (25.7%), and Uruguay (36.3%).

Table I - Countries weights by group of donor pool

Country	Occidental World	Americas	Americas without US	Latin America & Caribbean
Bahamas	0	0.031	0.048	0.045
Bolivia	0.021	0	0	0
Costa Rica	0.424	0	0	0
Cyprus	0.069	0	0	0
Georgia	0.358	0	0	0
Paraguay	0	0.658	0.376	0.336
St. Vicent and Grenadines	0.127	0	0.223	0.257
United States	0	0.023	0	0
Uruguay	0	0.287	0.354	0.363

Note: For space considerations, we omit the countries with weights equal to zero in all donor pools. The computation of weights used a total of 46 countries for the Occidental World, 26 for Americas, 25 for Americas without US and 24 for Latin America and Caribbean.

[4] Abadie *et al.* (2010) suggest dropping candidates that is believed not to have the same characteristics of the treated unit (for instance, geographic, socio-economic or cultural factors).

Table II shows the pre-democracy values (prior 1988) of the indicator variables for real Chile (treated) and for the synthetic Chile by donor pool. We can see how similar the synthetic versions are from real Chile before the transition to democracy. This indicates the adequacy of the construction of the synthetic Chile as a control group to evaluate the effect of the treatment.

Table II – Predictor balance by donor pool

		Synthetic Chile			
	Real Chile	**Occidental World**	**Americas**	**Americas without US**	**Latin America & Caribbean**
GDP pc_1976	3814.54	3830.95	3941.30	3921.20	3931.68
GDP pc_1979	4630.03	4577.98	4733.34	4769.78	4763.08
GDP pc_1982	4500.29	4506.11	4747.33	4747.02	4737.2
Aver. GDP pc_1982_1988	4825.40	4858.49	4782.05	4802.53	4795.842
GDP per capita_1988	5503.27	5255.64	5155.05	5231.34	5237.07
Aver. Pop_1564	61.43	60.62	56.72	56.72	56.71
Pop_1564_1976	58.64	58.31	55.86	55.29	55.19
Pop_0014_1976	35.58	35.44	38.41	38.52	38.49

We estimate the effect of the intervention (the transition to democracy starting in 1988) by comparing the evolution of real Chile's GDP per capita (treated) with the evolution of the same variable for each synthetic Chile or, as we call it, “authoritarian Chile” (control).

The Figure 1(A) shows the difference between “real Chile” and “authoritarian Chile” in terms of GDP per capita using the Occidental World donor pool. The difference between them is close to zero prior to the intervention in 1988 (marked by a vertical line) and increases sharply after that. Figure 1 (B) shows the long-run GDP per capita trajectories of "real Chile" (upper) and “authoritarian Chile” (lower). We can see in the counterfactual of the re-democratization process, that is, if Chile had remained “authoritarian”, income and growth rates would have been lower. The same analysis is valid for the other three donor pools in Figures 2, 3 and 4.

Figure 1 – GDP per capita for Chile and ‘Occidental World’ Synthetic Chile

(A) Difference **(B) Trajectories**

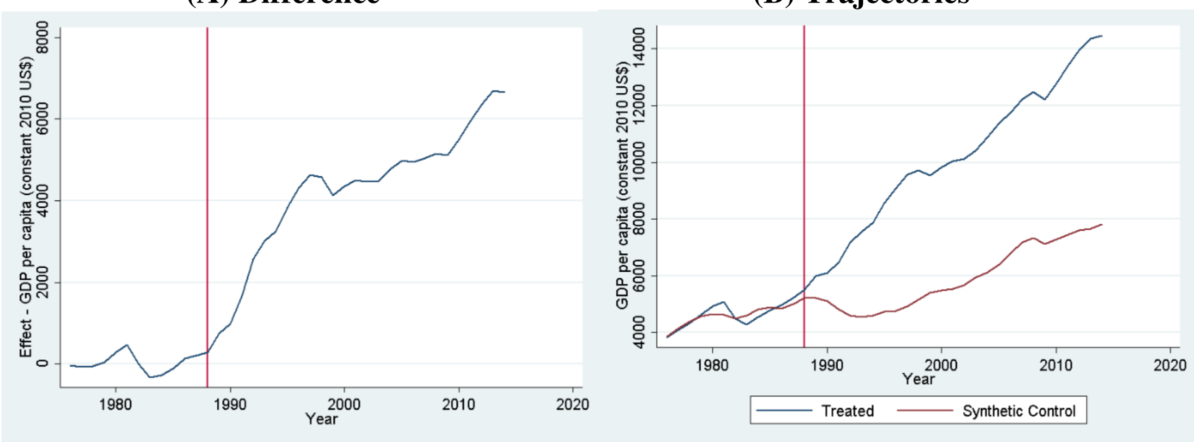


Figure 2 – GDP per capita for Chile and 'Americas' Synthetic Chile

(A) Difference **(B) Trajectories**

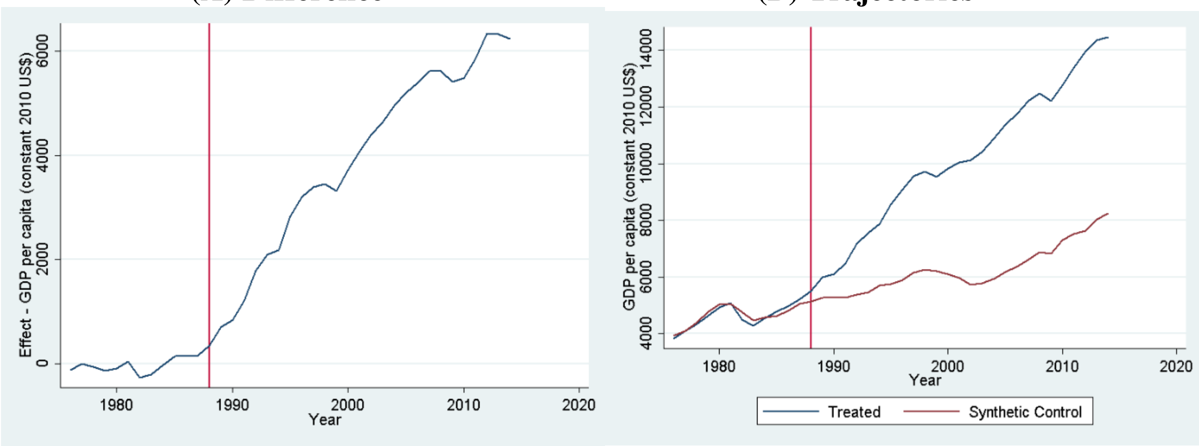


Figure 3 – GDP per capita for Chile and 'Americas without US' Synthetic Chile

(A) Difference **(B) Trajectories**

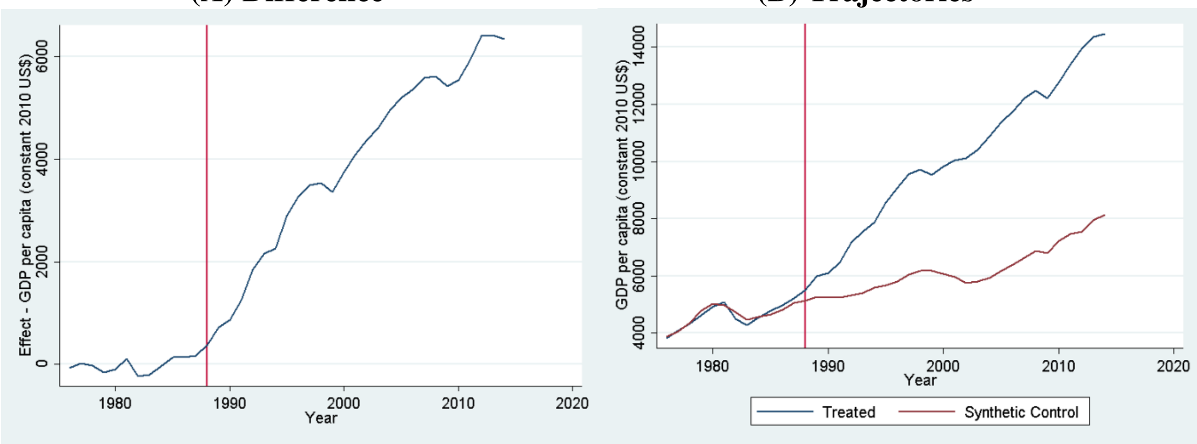
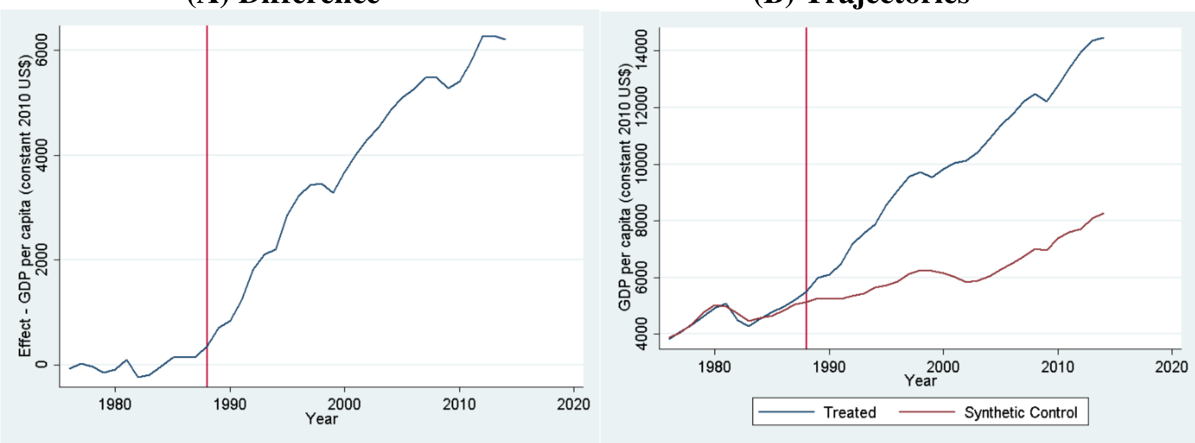


Figure 4 – GDP per capita for Chile and 'Latin America & Caribbean' Synthetic Chile

(A) Difference **(B) Trajectories**



The results show a significant deviation of the actual GDP per capita trajectory after 1988 compared with the synthetic Chile, supporting the conclusion that the transition to a democratic rule had a positive impact on Chile's GDP. To discard the possibility of these results being random, in the next section we proceed with inference checks using a placebo test (Abadie, 2011; Abadie *et al.*, 2010; Bertrand *et al.*, 2004). Additionally, in a time-series approach, we test for endogenous breaks (Bai and Perron, 2003) and present an analysis of causal impact based on the forecasts of a Bayesian structural time-series model (Brodersen *et al.*, 2015).

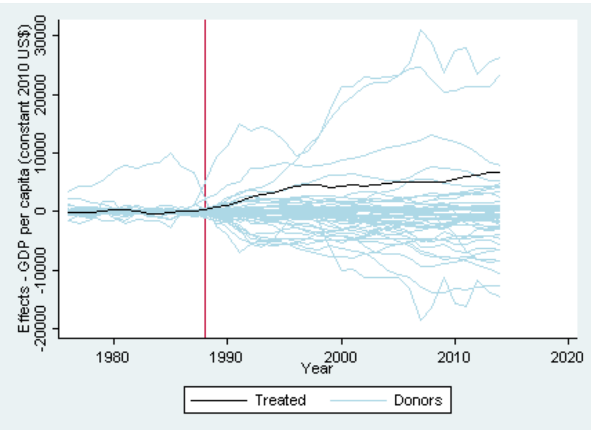
5. Robustness Checks

5.1 Placebo test

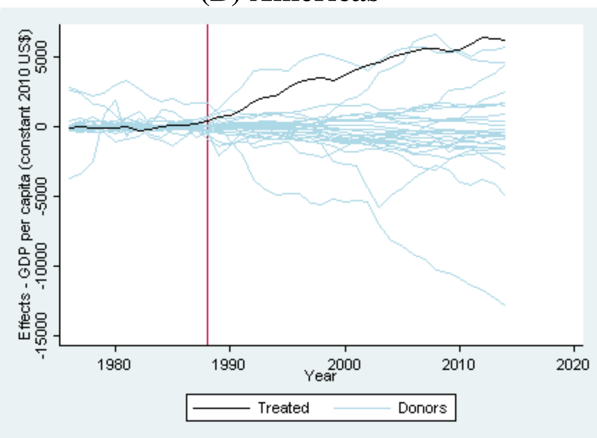
As usual in the synthetic control approach, we check the statistical significance of our results by running placebo tests. We first estimate the same model for each country in the donor pool, as if they had undergone the same treatment of Chile in 1988. Then we calculate the differences between the real GDP per capita of those countries and the synthetic one. To exclude the possibility that the positive effect of the re-democratization in Chile was obtained by chance, we would expect this difference to be close to zero for other countries. In this case, only Chile have a positive difference between the real GDP per capita and the synthetic (counterfactual) one. Figure 5 (A to D) shows the results of the placebo tests.

Figure 5 – Placebo Test

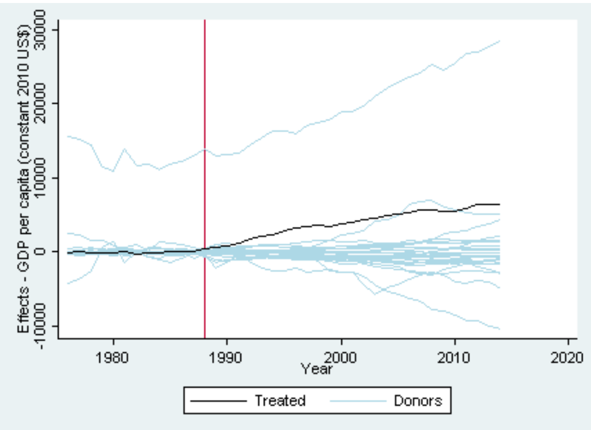
(A) Occidental World



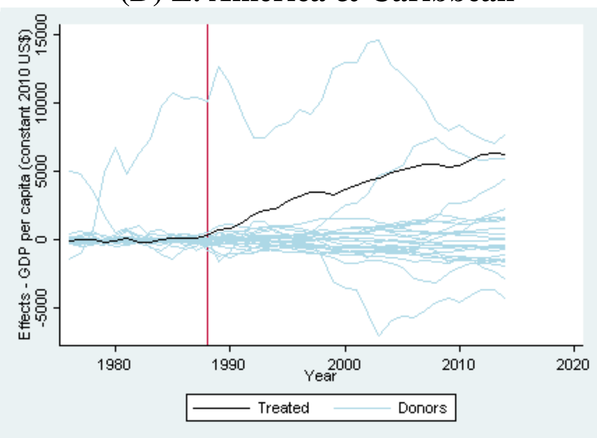
(B) Americas



(C) Americas without US



(D) L. America & Caribbean



The darker line in Figure 5 shows the difference between "real Chile" and "authoritarian Chile" for each of the four donor pools, which can be interpreted as the treatment effect. The red line specifies the year of the re-democratization in Chile. In the years before 1988, the synthetic method provides an excellent fit for Chile's GDP per capita, since the difference between "real Chile" and "authoritarian Chile" is close to zero. After the treatment period, while this difference becomes positive for Chile, we can see that the other countries in the donor pools have differences close to zero, which means that the positive effect obtained in the case of Chile is unlikely due to chance.

5.2 Time Series

We also apply two time-series methods: endogenous break tests based on Bai and Perron (2003) and an analysis of causal impact based on the forecasts of a Bayesian structural time-series model (Brodersen *et al.*, 2015).

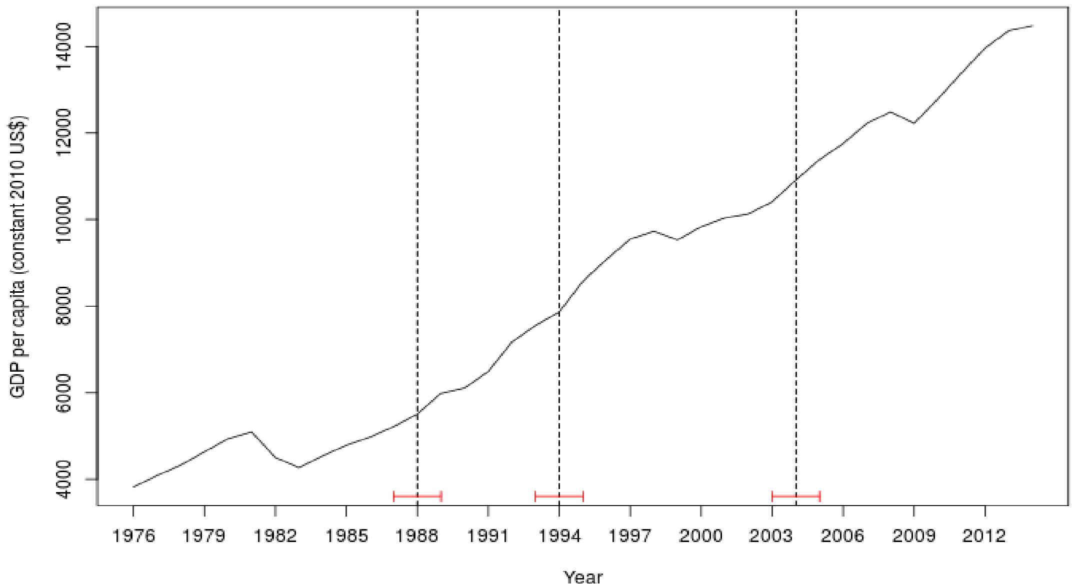
The procedure of Bai and Perron (2003) is able to detect multiple structural breaks on a time series through the minimization of the sum of square residuals for each m-partition $(T_1, T_2, \dots, T_m)$, with the partitions detected by solving the following problem:

$$\left(\hat{T}_1, \hat{T}_2, \dots, \hat{T}_m\right) = argmin_{T_1, T_2, \dots, T_m} RSS_T(T_1, T_2, \dots, T_m), \quad (1)$$

where RSS_T is the residual sum of squares of the model using m structural breaks. Given the maximum number of breaks m, the algorithm endogenously defines the optimum number and position of the breaks within the time series to minimize the residual sum of squares.

Figure 6 shows the GDP per capita of Chile and the endogenous structural breaks from Bai and Perron's algorithm. The years marked in red are the 2.5% and 97.5% confidence intervals for the structural breaks. We can see that the algorithm detected three structural breaks: the first one comprises the period of 1987 to 1989, the second one is from 1993 to 1995, and the last one refers to the period of 2003 to 2005. The first structural break in 1988 adds to the evidence of an effect of the transition from authoritarian to democratic rule on Chile's GDP per capita.

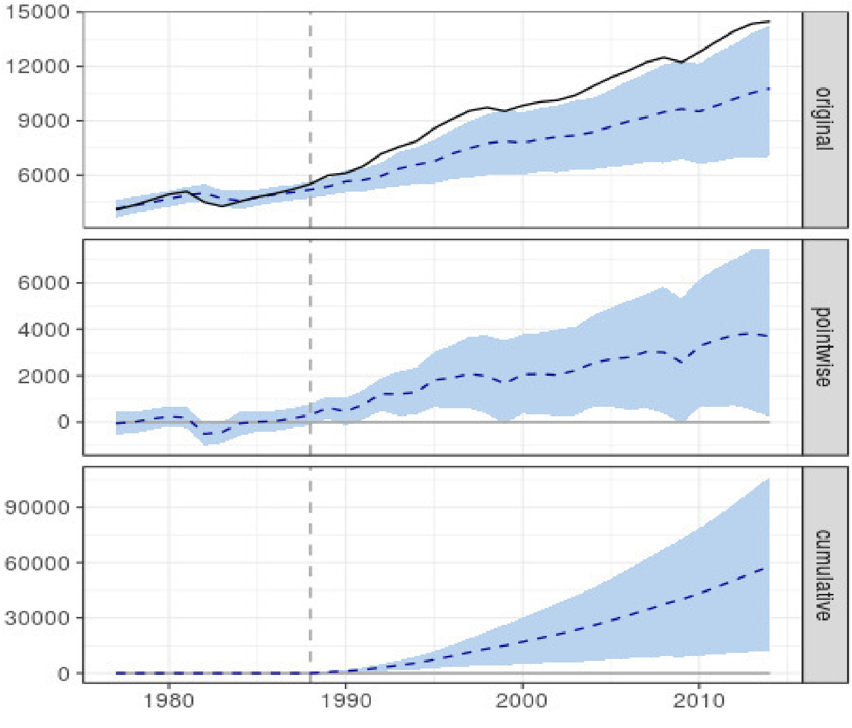
Figure 6 – Endogenous structural breaks



Since we identified a structural break in 1988, we used a Bayesian Structural Time Series Model implemented by Brodersen *et al.* (2015) to estimate the causal effect of the re-democratization on Chile's GDP. This model is based on a state-space structure for time series data. It contains a local level component to model the trend of the GDP and a regression component that includes the percentages of the young and adult population of Chile, variables described in section 3. The estimation of the model uses Markov Chain Monte Carlo methods to sample from the posterior distribution. Once we estimate the model using data from before the democracy openness, we forecast the future values of Chile's GDP to use as a counterfactual, while the gap between the actual and predicted GDP measures the causal effect of interest. A more detailed explanation of the estimation method of Brodersen *et al.* (2015) can be found in Appendix A.

In Figure 7, the first graph shows the actual GDP per capita in the solid line and its forecast in the dashed line. The shaded area also shows the 95% credible interval of the predictions based on the posterior density distribution. The intervention in 1988 represents the vertical dashed line. We can see that before the intervention, the actual GDP per capita is within the limits of the credible interval of the predictions, while after the intervention it starts to exceed its superior limit. We can understand the gap between the actual and predicted GDP, shown in the second graph of Figure 7, as the pointwise effect of the re-democratization on Chile's GDP. The third graph also shows the cumulative effect, which is the sum of the pointwise effect across time.

Figure 7 – Forecast versus Actual Chile's GDP per capita



In Table III we present the estimates of the causal effect based on the forecasts of the Bayesian Structural Time Series Model shown in Figure 7. The first column shows values of the average effect, while the second column refers to the cumulative effect.

Table III – Causal effect based on forecasts of Chile's GDP per capita

	Average	Cumulative
Actual	10308	267995
Prediction	8072	209866
	(942)	(24486)
95% Credible Interval	[6206, 9866]	[161345, 256515]
Absolute effect	2236	58129
	(942)	(24486)
95% Credible Interval	[442, 4102]	[11480, 106651]
Relative effect	28%	28%
	(12%)	(12%)
95% Credible Interval	[5.5%, 51%]	[5.5%, 51%]
Posterior tail-area probability	0.01026	-
Posterior probability of a causal effect	98.974%	-

Note: Values in parenthesis are standard deviations, while values in brackets are 95% credible intervals.

During the post intervention period (democratic government), Chile's GDP per capita had an average value of US$10308. Based on the forecast, in the absence of an intervention, we would have expected an average GDP per capita of US$8072. This means that the average causal effect of the re-democratization is US$2236. In Table III there is also 95% credible intervals for the average prediction, the absolute effect of the intervention and the relative effect, which is 28%. Note that the actual average value of the Chile's GDP per capita exceeds the superior limit of the 95% credible interval of the predictions, indicating a significant positive effect of the transition to democracy. This means that the positive effect observed during the intervention period is statistically significant and unlikely to be due to random fluctuations. The probability of obtaining this effect by chance is very small and equal to 0.01026. This means that the causal effect can be considered statistically significant.

The second column of Table III shows the cumulative effect. If we sum up the individual data points of the GDP per capita during the post re-democratization period we get an overall value of US$267995, while the sum of the predicted values, had the intervention not taken place, is US$209866. That means an absolute cumulative effect of US$58129. The standard errors and the credible intervals for this cumulative estimation are also reported in the second column of Table III.

Both time series methods support the evidence of the synthetic control approach, which signals to a positive impact of the transition from authoritarian to democratic rule on Chile's GDP. The financial and liberal reforms that preceded the transition to democracy may also have played an important role in generating long-term economic growth.

6. Final Remarks

Our goal was to test the effect of the re-democratization process on long-run GDP per capita. The democracy openness, starting in 1988, was a smooth process that advanced in freedom, civil rights, and social justice, but, at the same time, maintained the economic pillars introduced during the military government. We used data from the World Bank Open Data and a synthetic control approach to verify if the transition to democratic rule changed the long run growth trajectory of Chile's GDP per capita. The results show that the process of re-democratization has positively and significantly affected Chile's long-term growth. These pieces of evidence may also shed light on the importance of liberal economic reforms prior the transition. Future research could expand the analysis to different dimensions and explore the effects of democracy transition in education, labor market, quality of institutions, and other variables.

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Appendix A

We estimate a Bayesian structural time series (BSTS) model based on Brodersen *et al.* (2015). Their model allows us to flexibly choose appropriate components for trend, seasonality, and either static or dynamic regression for the controls. Usually BSTS models are based on three main parts: a kalman filter, a spike-and-slab method, and a Bayesian model averaging. The state-space representation of the time series data can be defined in a pair of equations:

$$y_t = Z_t' \propto_t + \varepsilon_t, \tag{A.1}$$
$$\propto_{t+1} = T_t \propto_t + R_t\eta_t. \tag{A.2}$$

Equation (A.1) is the observation equation, that links the time series data y_t – Chile's GDP per capita in our case – to the d-dimensional state vector $\propto_t$ and a matrix of covariates Z_t. Equation (A.2) is the state equation, which governs the evolution of the state vector through time, while T_t is a transition matrix $d \times d$. The residuals $\varepsilon_t \sim N(0, \sigma_t^2)$ and $\eta_t \sim N(0, Q_t)$ are independent of all other unknows. The matrix R_t allows us to incorporate state components of less than full rank, such as a model for seasonality.

In our application we used two sub-models that are assembled together in order to capture specific features of the data. The first sub-model is a local linear trend defined by the following equations:

$$\mu_{t+1} = \mu_t + \delta_t + \eta_{\mu,t}, \tag{A.3}$$
$$\delta_{t+1} = \delta_t + \eta_{\delta,t}, \tag{A.4}$$

where $\eta_{\mu,t} \sim N(0, \sigma_\mu^2)$ and $\eta_{\delta,t} \sim N(0, \sigma_\delta^2)$; the μ_t component is the value of the trend at time t; and the δ_t component is the expected increase in μ between times t and $t+1$. This sub-model quickly adapts to local variation and it is a popular choice for modelling trends. We applied this sub-model to Chile's GDP per capita in order to identify its trend behavior.

The second sub-model includes contemporaneous covariates with dynamic coefficients, which account for time-varying relationships of the data. If we have J covariates, this sub-model can be written in the following equations:

$$\boldsymbol{X}_t'\beta_t = \sum_{j=1}^{J} \boldsymbol{x}_{j,t}\beta_{j,t}, \tag{A.5}$$
$$\beta_{j,t+1} = \beta_{j,t} + \eta_{\beta,j,t}, \tag{A.6}$$

where $\eta_{\beta,j,t} \sim N(0, \sigma_{\beta_j}^2)$. This sub-model can be written in the state-space form by setting $Z_t = \boldsymbol{X}_t$, $\propto_t = \beta_t$, $T_t = I_{J\times J}$ and $Q_t = diag(\sigma_{\beta_j}^2)$, where $\boldsymbol{X}_t$ is the matrix of covariates, which in our case includes the percentages of the young and adult population of Chile, variables described in section 3. Both state-components (sub-models 1 and 2) are assembled independently, with each component providing an additive contribution to y_t.

Using the Bayesian approach, the algorithm first specifies a prior distribution $p(\theta)$ on the model parameters and a distribution $p(\propto_0 | \theta)$ on the initial state values, and then it samples from $p(\propto, \theta | \boldsymbol{y})$ through Markov Chain Monte Carlo (MCMC). Since the models specified above depends only on variance parameters that governs the diffusion of the individual state components, such as σ_μ^2, σ_δ^2 and $\sigma_{\beta_j}^2$, a typical prior distribution for such variances is given by:

$$\frac{1}{\sigma^2} \sim \mathcal{G}\left(\frac{v}{2}, \frac{s}{2}\right), \tag{A.7}$$

where $\mathcal{G}(a, b)$ is a Gamma distribution with expectation a/b. The prior parameters can be interpreted as a prior sum of squares s, so that s/v is a prior estimate of the variance σ^2, and v is the weight, in units of prior sample size, assigned to the prior estimate. The default prior is $1/\sigma^2 \sim \mathcal{G}(10^{-2}, 10^{-2} s_y^2)$, where $s_y^2 = \sum_t (y_t - \bar{y})^2/(n-1)$ is the sample variance of the Chile's GDP per capita. The idea is to choose small values of v and s/v such that the incremental errors in the state process are small, and scale them by the sample variance as an effective means of choosing a reasonable scale for the prior.

The posterior inference in the model can be broken down into three pieces. It first simulates draws of the model parameters θ and the state vector $\propto$ given the observed data $\boldsymbol{y}_{1:n}$ in the period pre intervention through MCMC methods based on Durbin and Koopman (2002). Then it uses the posterior simulations to simulate from the posterior predictive distribution $p(\tilde{\boldsymbol{y}}_{n+1:m} | \boldsymbol{y}_{1:n})$ over the counterfactual time series $\tilde{\boldsymbol{y}}_{n+1:m}$ given the observed pre-intervention activity $\boldsymbol{y}_{1:n}$. Finally, it uses the posterior predictive samples to compute the posterior distribution of the pointwise impact $y_t - \tilde{y}_t$ for each $t = 1, \dots, m$. The same samples are used to obtain the posterior distribution of cumulative impact.

The samples from the posterior predictive distribution over the counterfactual activity can be used to obtain samples from the posterior causal effect which we are interested in. For each draw τ of the simulation described above, and for each time point $t = n+1, \dots, m$, we set

$$\phi_t^{(\tau)} \coloneqq y_t - \tilde{y}_t^{(\tau)}, \tag{A.8}$$

which we refer as the pointwise impact for draw τ, and

$$\sum_{t'=n+1}^{t} \phi_{t'}^{(\tau)} \quad \forall t = n+1, \dots, m, \tag{A.9}$$

which is the cumulative sum of causal increments for draw τ. The Bayesian averaging of measures (A.8) and (A.9) represents the pointwise and cumulative causal impacts of the intervention. In our empirical analysis we also used 95% credible intervals which are constructed from these simulations.