FX Interventions in a Small Open Economy: The Case of Domestic Non-Deliverable Forwards*

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Abstract

We study the effects of domestic non-deliverable forwards (DNDF) on the level and volatility of the USD/MXN nominal exchange rate. We focus on the introduction of the DNDF policy by the Bank of Mexico in 2017 and find that the first announcement of the policy was successful in mitigating both depreciation pressure and volatility of the USD/MXN exchange rate. Our estimates show an appreciation of the Mexican Peso by 32.91 cents after the announcement of the policy and a reduction in the option-implied exchange rate volatility of different maturities by 40 cents on average. We rationalize our findings using a model of a small open economy with collateral constraints and show that the DNDF policy can be used to mitigate the severity of a self-fulfilling currency crisis, thereby counteracting the downward pressure on the domestic currency.

JEL classification: E44, E58, F31, F41, G14, H23

Keywords: FX intervention, Non-deliverable forwards, Self-fulfilling crisis

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1 Introduction

Many countries intervene in the foreign exchange (FX) market when there is downward pressure on the domestic currency. While numerous studies such as Fanelli and Straub (2021) and Hassan et al. (2022) have focused on providing the rationale behind the exchange rate stabilization, not many of them have studied the effects of policy instruments other than foreign reserves and monetary policy. However, in reality, there was a recent advance in terms of the intervention tools, and central banks have started providing FX forwards in the market to stabilize the exchange rate and alleviate exchange rate volatility.

FX forward contract is one of the most widely used instruments to hedge exchange rate risk in the global FX market (Drehmann and Sushko (2022)). It offers market participants a way to insure themselves against unexpected exchange rate fluctuations, but it is usually inaccessible to agents in emerging market economies where markets are shallow. In this context, there are recent examples in Brazil and Mexico where the central bank directly provided private agents with FX forwards to reduce the exchange rate risk they face and stabilize the exchange rate.

A natural question arises here: is FX intervention through FX forward contracts a useful means to mitigate domestic currency depreciation and reduce the exchange rate volatility? To address this question, we focus on the adoption of domestic non-deliverable forwards (DNDFs) by the Bank of Mexico in 2017. Early 2017, the Bank of Mexico announced that it will provide DNDF contracts to local financial intermediaries for the first time. The policy was adopted to provide domestic agents with a hedging tool against the large depreciation of the Mexican Peso due to the 2016 US Presidential Election outcome and President Trump's "America First" approach in foreign policy. We find that the first announcement of the DNDF policy was successful in mitigating both the downward pressure on the Mexican Peso and the heightened volatility of the USD/MXN exchange rate. In particular, using linear models and high-frequency data, we find an appreciation of the Mexican peso by 32.91 cents and a reduction in volatility by approximately 40 cents after the policy was announced by the central bank authority.

Subsequent announcements about increases in the amount of forwards provided by the Bank of Mexico had smaller effects on both the level and volatility of the peso, but still appreciated the exchange rate. However, we do not find a meaningful effect associated with the actual provision of the DNDF contracts in a form of auctions, which we refer to as the implementation of the policy henceforth. This indicates that introducing the DNDF policy mainly affected private agents' expectations about future USD/MXN exchange rates by decreasing the probability of severe depreciations, and its effect diminished as the FX market quickly reflected those expectations.

This is consistent with what we find with the effects of the announcement and implementation of the policy on option-implied volatilities of USD/MXN exchange rate options for different maturities. In particular, we find that the policy announcement was successful in reducing the exchange rate volatility for very short maturities. The effect tends to dissipate as the maturity of the financial instrument increases, and it took more than 3 months for such an effect to disappear. In other words, we find that option-implied volatilities fall after the release of the policy announcement leading to a resolution of uncertainty regarding the underlying asset, and that this effect is stronger for shorter maturities. Our empirical findings are robust to different sensitivity checks.

Finally, by looking at the results of the survey conducted by the Central Bank among specialists in the private sector, we find evidence indicative of a change in the trend of the private sector's expectations regarding both the level of the exchange rate and the business climate of the Mexican economy, coinciding with the month of the announcement of the policy. Given the low frequency of the reported responses, it is not possible to argue for a causal effect on such variables; however, the timing of the trend reversal and the introduction of the policy is thought-provoking.

To better understand the impact of DNDF on the exchange rate and its volatility, we introduce the central bank's insurance provision into a model that features multiple equilibria even in a deterministic environment. The model consists of a small open economy subject to a borrowing constraint on external debt. Even when there is no fundamental risk associated with income, this class of models features multiple equilibria including self-fulfilling financial crises that occur when the private agents collectively become pessimistic. In such a self-fulfilling crisis, the borrowing constraint binds and the exchange rate depreciates.

We analyze that the DNDF policy can be used to mitigate the severity of the worst possible crisis with the maximum amount of deleveraging and exchange rate depreciation. Moreover, the DNDF policy requires private agents to become much more pessimistic than in an environment without the policy for a crisis to happen. In this sense, our result echoes the finding of Jeanne and Rose (2002) that showed that a credible exchange rate stabilization policy can reduce the exchange rate volatility by reducing the fraction of irrational investors and noise trading in the FX market. We also provide a rationale for the central bank to utilize the DNDF policy when it cannot announce a state-contingent rule for the capital control tax, which is a common prescription to avert the self-fulfilling crisis as studied by Schmitt-Grohé and Uribe (2021).

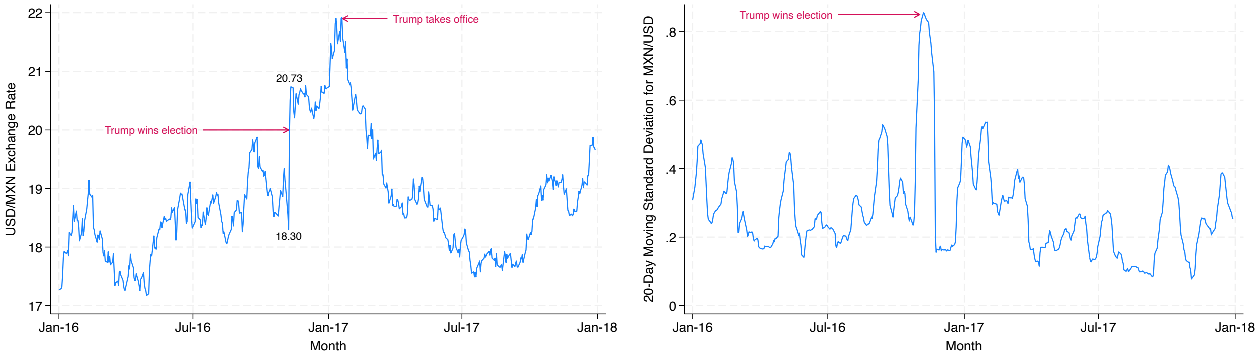
Related Literature. This paper contributes to two main strands of literature. First, we provide empirical evidence of the effect of the DNDF policy on the nominal exchange rate and option-implied volatilities. To the best of our knowledge, this is the first paper to explore the impact of the announcement and implementation of such a policy on the nominal exchange rate during the period of increased FX uncertainty in Mexico. Second, we provide a theoretical justification for how this type of policy announcement helps prevent a self-fulfilling financial crisis in which households collectively deleverage under pessimistic beliefs leading to exchange rate depreciation.

Regarding the empirical literature on FX interventions and, in particular, the DNDF program, Chamon et al. (2017) are among the first to assess the impact of such a policy on the level and volatility of the nominal exchange rate. They show that the DNDF policy effectively reduced the volatility of the exchange rate in Brazil, and we complement their analysis by distinguishing the effects of the announcement and implementation of the DNDF intervention by using intraday data, thereby highlighting that the policy took effect mainly by affecting the beliefs of market participants. Gonzalez et al. (2021) also provide that this intervention in the derivatives market in Brazil was successful in attenuating the exposure of local banks to global shocks, leading to a partial reversion of the downward trend in credit supply and employment. Macalós (2023) argues that the DNDF program in Brazil was effective in mitigating the volatility of the exchange rate, but it cannot perfectly substitute the FX intervention using foreign reserves because frequent interventions through the DNDF policy can lead to speculative attacks against the domestic currency. Similarly, Garcia and Volpon (2014) show that the DNDF program is useful in preventing the central bank from depleting its foreign reserves, but it increases the rollover risk for the banking sector. While we abstain from comparing the effects of the DNDF policy to FX intervention through foreign reserves, we provide that the DNDF policy reduces exchange rate volatility mainly through its effect on the market's belief on future exchange rates. We find robust evidence that the main announcement of intervention and subsequent announcements of extensions to the original program were effective in mitigating the downward pressure over the Mexican peso and its volatility, but we do not find a meaningful effect of the policy implementation. Once the Bank of Mexico announced that it will provide an insurance against the exchange rate depreciation, this potentially reduced the likelihood of a nonfundamental shock on the FX market by preventing a coordination failure of private agents' beliefs.

In relation to the literature on multiple equilbria in small open economy models subject to borrowing constraints, Schmitt-Grohé and Uribe (2021) show that there exist self-fulfilling financial crises that materialize under pessimistic views of the economy that induce households to deleverage, leading to a current account reversal and a contraction in domestic absorption. In a similar framework, Davis et al. (2023) show that the crisis equilibria can be eliminated through FX interventions. In particular, the central bank can use foreign reserves to reduce or even eliminate the risk of a self-fulfilling financial crisis. Bianchi and Coulibaly (2024) develop a theory that explains why flexible exchange rates can exacerbate the risk of the self-fulfilling crisis and argue that a commitment to keep the nominal exchange rate within a crawling band or fixed can help reduce this exposure. Our paper uses a model framework similar to these studies to show that the central bank can use DNDF policy to avoid a self-fulfilling crisis or reduce the severity of the crisis when it occurs.

Outline. This paper is organized as follows. Section 2 provides a general description of the DNDF program implemented by the Bank of Mexico and presents empirical evidence on the effect of the announcement and implementation of the policy. We construct a model to rationalize our empirical findings in Section 3 and analyze how the DNDF policy can be used to mitigate a self-fulfilling financial crisis in Section 4. Section 5 provides concluding remarks.

2 DNDF Program and Empirical Evidence



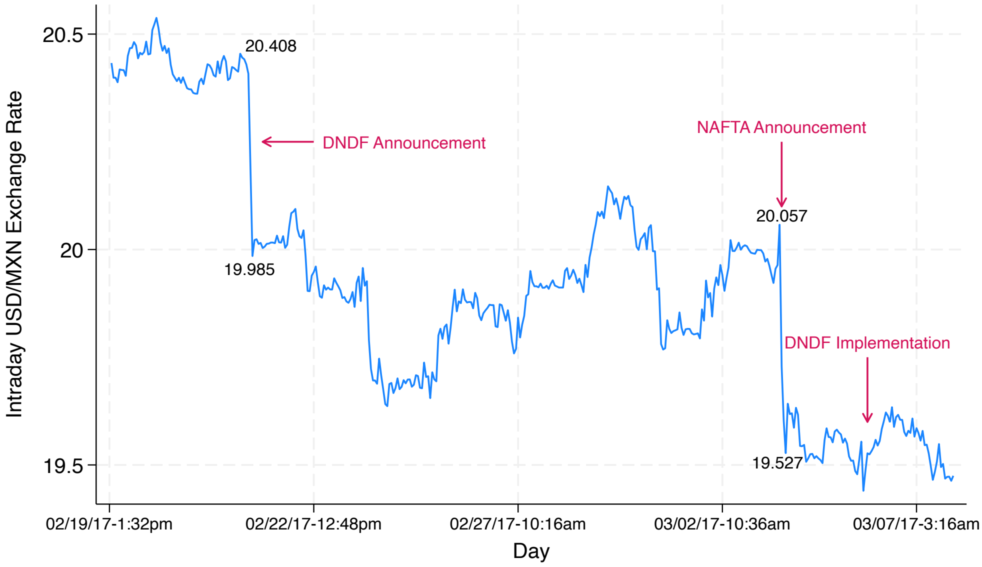
(A) Level

(B) Volatility

Note: Own elaboration with Bloomberg and the WSJ data. An increase represents a depreciation of the peso. The volatility is computed as a 20-day rolling standard deviation.

FIGURE 1. USD/MXN Exchange Rate and Volatility

The Mexican peso experienced a period of downward pressure and high volatility due to the process and outcome of the 2016 US Presidential Election and further political pressure exerted by President Trump. In Figure 1A we display daily dynamics of the USD/MXN exchange rate from January 1, 2016, to January 31, 2018. Once Trump was announced as the winner of the presidential election, the peso experienced a depreciation of 13.28% in one single day and it reached a maximum of almost 22 pesos per US dollar when Trump took office. Figure 1B displays the volatility of the exchange rate computed as a 20-day moving standard deviation, where we can see a large increase in volatility after the announcement of Trump's victory and another spike once he took office in late January 2017. To provide a point of reference, the peso only experienced a similar increase in volatility during the 2008-2009 Global Financial Crisis; however, one key difference is that volatility was more persistent during Trump's mandate given the uncertainty generated by the trade war against China and the rounds of renegotiation of NAFTA. Due to such pressures on the peso, the Bank of Mexico announced around 2:14 pm on February 21, 2017, the introduction of domestic non-deliverable forwards (DNDF) to provide insurance to domestic private agents against future currency depreciations. The announcement included a detailed description of the program and the date on which the first auction would occur which was Tuesday, March 6, 2017. A translation of the official press release is available in Appendix A.



Note: Own elaboration with data from the Bloomberg. An increase represents a depreciation of the MXN. The Central Bank of Mexico announced the FX intervention at 2:14 pm on February 21, 2017. The first auction occurred at 10:00 am on March 6, 2017.

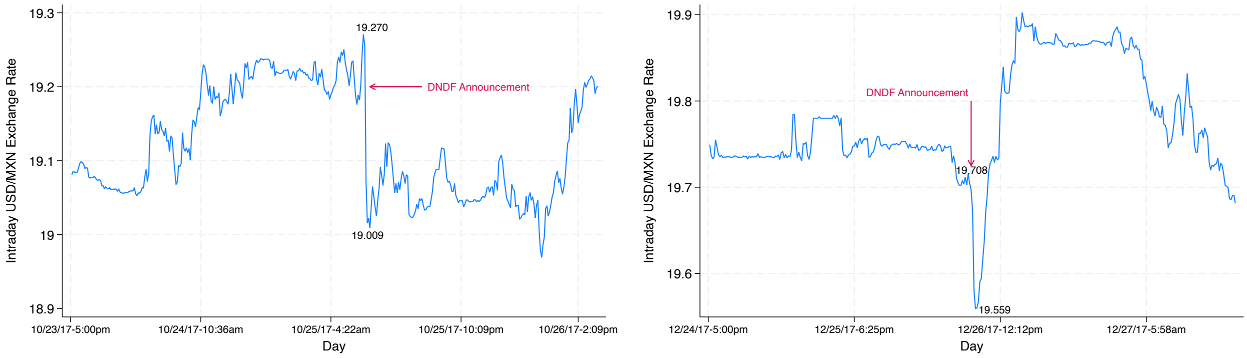
FIGURE 2. Intraday Exchange Rate: First Announcement and Implementation

Then what is a DNDF? It is "domestic" in that it is settled in the domestic currency and "non-deliverable" in that it involves remittances of the differential between the forward rate and the spot rate when settled. A typical DNDF works as follows. Let f_t be the forward rate determined by the central bank authority in period t denominated in domestic currency per US dollar, e_{t+h} be the exchange rate of domestic currency per US dollar in period $t+h$ where h is a pre-specified period by the central bank and the insured agent, and let q_t represent the amount of insurance purchased by the agent from the central at the auction. After h periods, the transfer that the agent will receive from the central bank can be written as

$$\text{Payment}_{t+h} = (e_{t+h} - f_t) \times q_t. \tag{1}$$

If the forward rate f_t is below the observed nominal exchange rate at period $t+h$, the agent will receive a transfer in *domestic currency* from the central bank. If the forward rate is above the observed exchange rate at time $t+h$, the agent has to pay in *domestic currency* to the central bank. For example, let $f_t = 18$ pesos per US dollar and $q_t = 1,000,000$ US dollars. After h periods (e.g., 30 days) the nominal exchange rate is given by $e_{t+h} = 19$ pesos per dollar. In this case, the central bank will transfer 1,000,000 pesos to the insured agent.

In Figure 2 we display the intraday (i.e., tick-by-tick) evolution of the USD/MXN exchange rate from February 19, 2017, to March 7, 2017. At the moment of the announcement of the policy, the peso appreciated approximately 40 cents and began a downward trajectory.



(A) Second Announcement

(B) Third Announcement

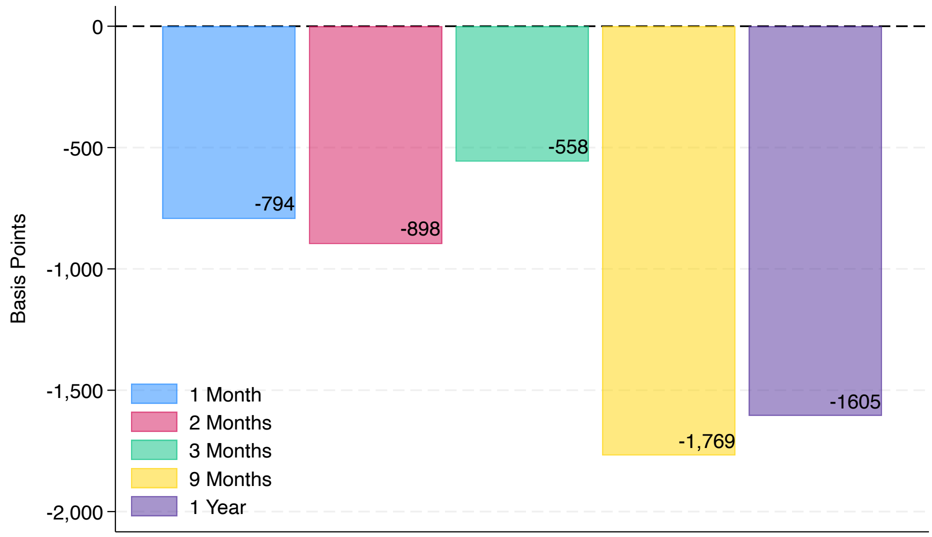
Note: The second announcement was made by the central bank authority on October 25, 2017, at 9:00 am, while the third announcement occurred on December 26, 2017, at 7:45 am.

FIGURE 3. Intraday Exchange Rate: Subsequent Announcements

Early in the morning of Friday the week before the first auction, the Secretary of Commerce, Wilbur Ross, made some public statements about the renegotiation of NAFTA which favorably impacted the peso which appreciated 59 cents; however, there is no sizeable impact on the peso associated with the implementation of the policy that occurred at 10:00 am on March 6, 2017.

Months after the announcement and implementation of the initial program and due to the process of monetary policy normalization in the US, higher uncertainty related to the renegotiation of the Free Trade Agreement, and the approval of the fiscal reform by the US Senate, the Bank of Mexico made two subsequent announcements where they increased the supply of these forwards in 4 billion and 500 million US dollars, respectively. The second announcement was made on October 25, 2017, at 9:00 am, while the third one occurred at 7:45 am on December 26, 2017. Figure 3 displays the intraday evolution of the peso vis-à-vis the US dollar in a short window around those days. After the second announcement (see 3A), the peso appreciated by approximately 20 cents, and for the third one (see 3B), the peso increased its value by 13 cents on impact.

During these episodes of depreciation of the domestic currency and sharp increases in its volatility, local agents struggle to find hedging instruments or find them at a very high price (see Gonzalez et al. (2021)). By intervening in the FX derivative market, the central bank provides "affordable" insurance for domestic agents against exchange rate risk. In Figure 4, we display the average difference between the forward points from the nine auctions held by the Bank of Mexico during 2017 and the forward points observed in the market for the same days and comparable maturities. From the auctions, domestic agents only demanded maturities of 1 month, 2 months, 3 months, 9 months, and 1 year. On average and for each maturity, the central bank offered insurance at lower rates (i.e., forward points closer to the spot rate of that day).



Note: Bars display, for a given maturity/horizon, the average difference between the forward rate observed in the market and the one from the auctions.

FIGURE 4. Comparison of Forward Points: Auction vs. Market

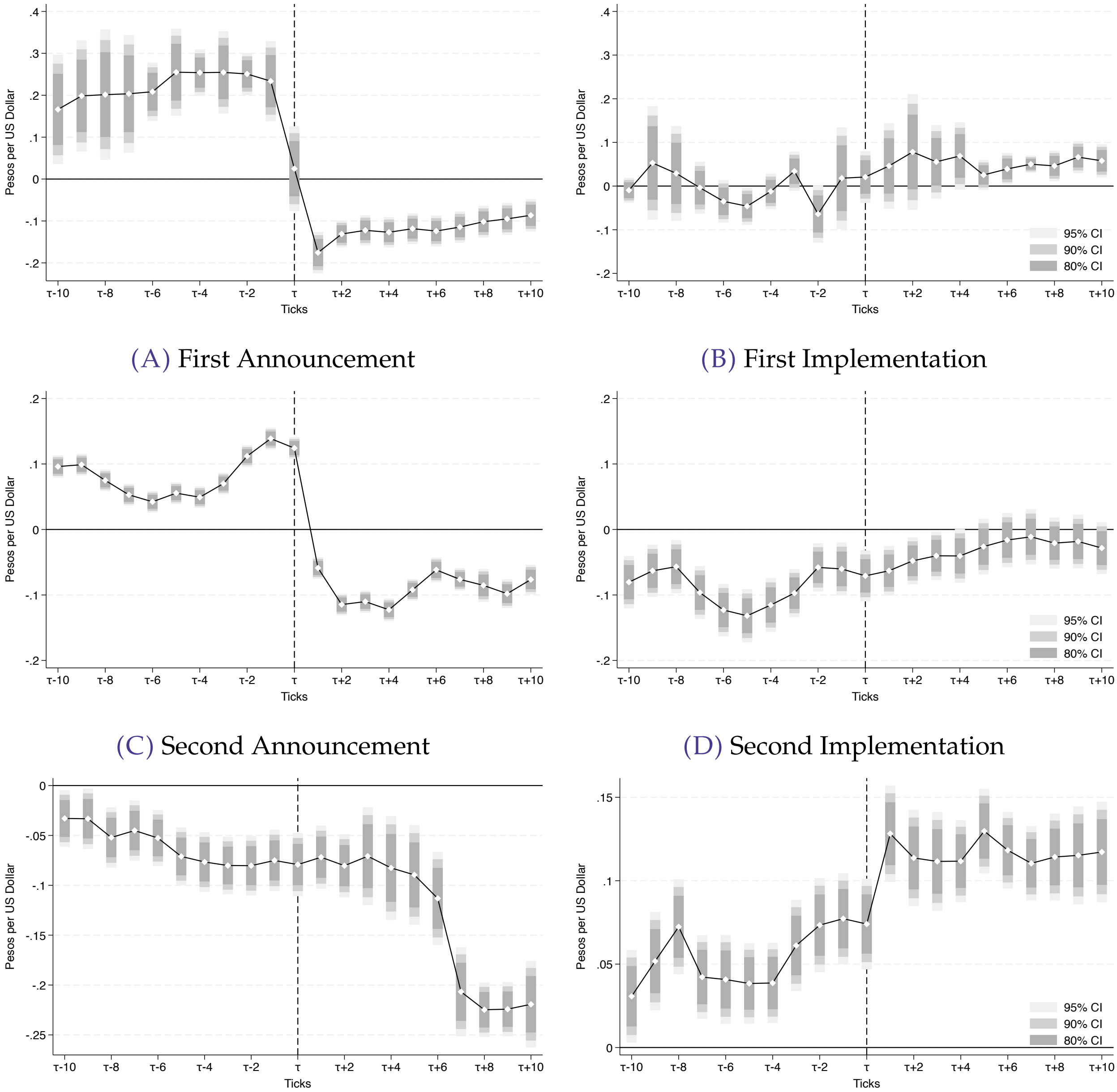
2.1 USD/MXN Exchange Rate

To further explore the effect that the first announcement and implementation of the policy had on the Mexican peso, we estimate the following linear model:

$$y_t = \alpha + \rho t + \sum_{s=-\tau}^{\tau} \beta_s \mathbb{1}\{t = T_0 + s\} + \theta VIX_t + \varepsilon_t, \tag{2}$$

where y_t represents the intraday peso-dollar exchange rate, t accounts for a linear trend, $\mathbb{1}\{x\}$ is an indicator function that takes the value of 1 if condition x is satisfied (i.e., s-ticks before and after the announcement/implementation T_0), VIX_t controls for global volatility, and ε_t represents the error term. For the baseline estimation, we choose $\tau = 10$ meaning that we are looking at 10 ticks before and after the announcement/implementation of the policy and only use data on the two days before and after the announcement/implementation. For some observations, there is a mismatch between the timing of the peso-dollar observation and the VIX index. In those cases, we select the value of the VIX index that corresponds to the timestamp closest to the one of the USD/MXN exchange rate.

Figure 5 displays the point estimates of β_s for the announcement and implementation of the policy, respectively. In panel 5A, we observe an average treatment effect of 32.91 cents associated with the announcement of the policy on the Mexican peso. These results are robust to the selection of the number of ticks before and after the treatment (i.e., τ) and adding extra controls such as the price of commodities (i.e., gold) and the volatility index



(A) First Announcement

(B) First Implementation

(C) Second Announcement

(D) Second Implementation

(E) Third Announcement

(F) Third Implementation

Note: The diamond-shape marker corresponds to the point estimates of β_s, while the shaded areas correspond to the 80%, 90%, and 95% confidence intervals, respectively, constructed using heteroskedastic and autocorrelation robust standard errors.

FIGURE 5. Effect of DNDF on USD/MXN: Announcement and Implementation

for Europe (i.e., Euro Stoxx 50).[1] In panel 5B, we display the results for the first auction of this type of forwards. We do not find evidence of an effect on the peso after the implementation of the policy. In Figure 5C to Figure 5F, we display the estimates for the other events where we also get similar results for the announcements related to extensions of the program; however, no statistically significant effects associated with the auctions of the financial instruments. These results are consistent with the theoretical and empirical studies

[1] Due to the lack of tick-level data for oil prices during that period, we use the price of gold in US dollars as an additional control.

on FX interventions where the domestic authority announces an intervention in the currency spot market in advance. Those announcements affect agents' expectations leading to important effects on the domestic currency on impact and virtually no effect once the authority executes the program.

2.2 USD/MXN Option-Implied Volatility

Option-implied volatilities are forward-looking measures that proxy for uncertainty regarding the future value of the underlying asset at different horizons or maturities. While they are not directly observable in the data, we can back them out by inverting the pricing formula of a financial derivative such as call and put options (e.g., Dumas et al. (1998)). The higher the implied volatility, the wider the range of potential values for the underlying asset, leading to a lower valuation (see Kim and Kim (2003)).

To assess the impact that the policy had - both announcements and implementations - on the uncertainty regarding the future values of the peso vis-à-vis the US dollar at different horizons/maturities, we estimate the following linear model using daily data from January 2016 to December 2017 on option-implied volatilities for the USD/MXN exchange rate at different maturities ranging from 1 week to 1 year:

$$y_{i,t} = \alpha_i + \gamma t + \rho y_{i,t-1} + \omega_1 \mathbb{A}\{t = T_0\} + \omega_2 \mathbb{I}\{t = T_1\} + \boldsymbol{x}_t \boldsymbol{\beta} + \eta z_{t-1} + \varepsilon_{i,t}, \tag{3}$$

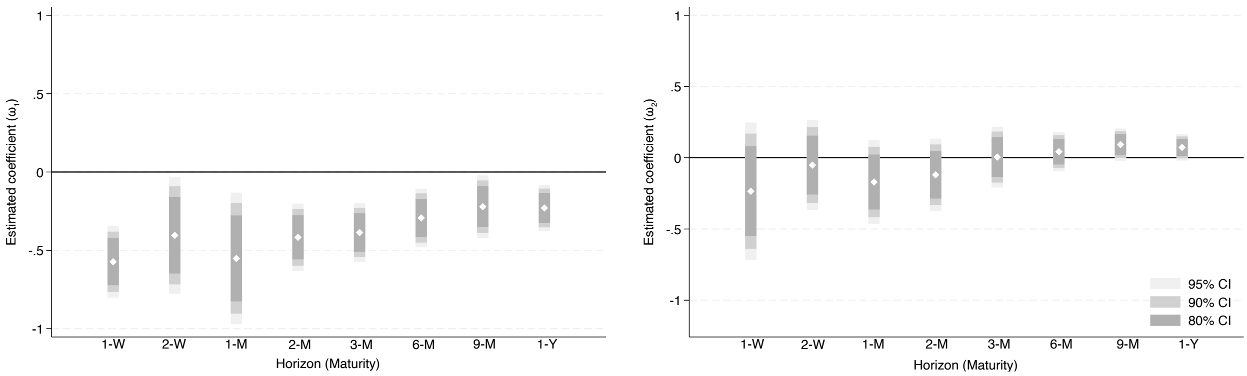
where $y_{i,t}$ represents the implied volatility at horizon i and time t, α_i corresponds to a maturity fixed effect, t accounts for a linear trend, $\mathbb{A}\{t = T_0\}$ is an indicator function that takes the value of 1 if in period t there was an announcement, $\mathbb{I}\{t = T_1\}$ is an indicator function that takes the value of 1 if in period t there was an implementation, $\boldsymbol{x}_t$ is a vector of contemporaneous global controls such as the VIX index, oil prices, and the daily change in Fed Funds rate in basis points, z_{t-1} corresponds to the lagged daily change in the monetary policy rate in basis points in Mexico, and $\varepsilon_{i,t}$ represents the error term.[2]

First, we estimate (3) separately for each i and report the estimates of $\hat{\omega}_1$ and $\hat{\omega}_2$ in panel 6A and 6B, respectively. For each maturity/horizon, the option-implied volatility falls after the announcement from the Bank of Mexico regarding the introduction or extension of non-deliverable forwards.[3] Moreover, we find that shorter maturities fall more relative to longer maturities; however, the results are non-monotonic since we observe a larger contraction for 1 month relative to 2 weeks. Regarding the response to the implementation of the policy, we

[2] To prevent small-sample issues, the indicator functions will account for all of the announcements and implementations observed in the sample. In other words, we do not estimate the linear model using separate indicators for each event since it will imply dichotomous variables that only take the value of 1 once.

[3] This result is consistent with the findings from Ederington and Lee (1996) and Kim and Kim (2003) that show that option-implied volatilities fall after the release of macroeconomic announcements leading to a resolution of uncertainty. The first one focuses on interest rate options while the second one analyzes currency options.

find no statistically significant effect for any maturity.



(A) Announcement ($\hat{\omega}_1$) (B) Implementation ($\hat{\omega}_2$)

Note: The diamond-shape marker corresponds to the point estimates of ω_i with $i = 1, 2$, while the shaded areas correspond to the 80%, 90%, and 95% confidence intervals, respectively, constructed using heteroskedastic and autocorrelation robust standard errors.

FIGURE 6. Effect of DNDF on Option-Implied Volatility for USD/MXN

Variable	Pooled			Panel		
	(1)	(2)	(3)	(4)	(5)	(6)
Lagged volatility	0.942***	0.929***		0.942***	0.929***	
	(0.020)	(0.021)		(0.032)	(0.032)	
Linear time trend	-0.0004***	-0.0001		-0.0004*	-0.0001	
	(0.0001)	(0.0002)		(0.0002)	(0.0003)	
Announcement	-0.325***	-0.373***	-0.380***	-0.324***	-0.372***	-0.380***
	(0.059)	(0.061)	(0.051)	(0.108)	(0.111)	(0.089)
Implementation	0.062	-0.043	0.018	0.062	-0.043	0.018
	(0.051)	(0.053)	(0.052)	(0.114)	(0.111)	(0.114)
Lagged Change Mon. Pol.		-0.005***	-0.007***		-0.005**	-0.007***
		(0.001)	(0.001)		(0.002)	(0.002)
VIX Index		0.050***	0.028***		0.050***	0.028**
		(0.008)	(0.007)		(0.013)	(0.013)
Oil Prices (WTI)		0.019***	0.010***		0.019***	0.010*
		(0.004)	(0.003)		(0.006)	(0.006)
Daily Change in Fed Funds Rate		0.003**	0.005***		0.003	0.005
		(0.002)	(0.002)		(0.003)	(0.003)
Constant	✓	✓	✓	✓	✓	✓
Fixed Effects				✓	✓	✓
Obs.	4,160	4,160	4,160	4,160	4,160	4,160
R^2	0.903	0.906	0.013	0.902	0.905	0.013

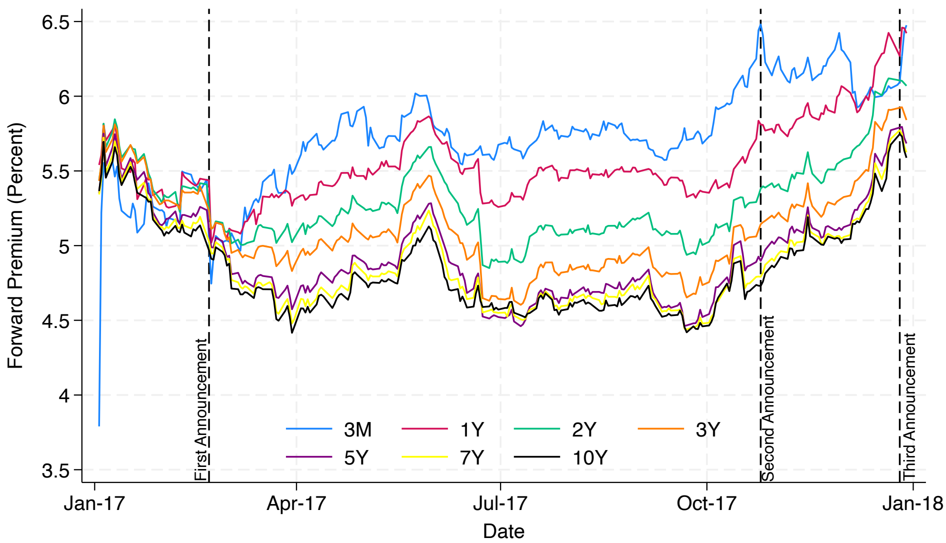
Note: The R^2 associated with the panel data exercises corresponds to the within goodness-of-fit measure. ***, **, *, denote statistical significance at 1%, 5%, and 10%, respectively. When we use pooled data, we compute HAC robust standard errors and, when the model is estimated exploiting the panel structure, we compute Driscoll and Kraay (1998) standard errors to account for potential cross-sectional correlation.

TABLE 1: Estimates from Linear Model

Second, we estimate the linear model (3) using pooled and panel data. The results are presented in Table 1. In the first three columns, we display the estimates using pooled OLS for the level and first difference of the outcome variable. In particular, columns (1) and (2) correspond to the outcome variable in levels while column (3) corresponds to the estimates of the the linear model where the outcome variable is in first differences. The same applies to columns (4)-(6) with the difference that the model is estimated using panel data. Consistently with the USD/MXN exchange rate level results, we find that the policy announcement had a negative and statistically significant impact on the outcome variable. In terms of the implementation of the policy, we consistently find no statistically significant effects. These results are robust even when we account for unobserved fixed characteristics in the panel setting.

2.3 Forward Premium

What was the response of the implied forward premium in cross-currency swaps to the announcements made and auctions held by the central bank? We use Du and Schreger (2016) data on the forward premium for all available maturities: 3 months, 1 year, 2 years, 3 years, 5 years, 7 years, and 10 years. Given our previous results on the exchange rate and the option-implied volatilities, we would expect the forward premium to drop after the announcements of the interventions as there is less pressures on the Mexican peso.



Note: Own elaboration with data from Du and Schreger (2016). The first announcement of Banxico's intervention using DNDFs is February 21st, 2017. The second and third announcements correspond to October 25th, 2017, and December 26th, 2017, respectively.

FIGURE 7. Forward Premium by Maturity

In Figure 7, we display the daily dynamics of the forward premium for each tenor. First, we observe a larger contraction in the forward premium the shorter the maturity. For example, after the first announcement, the 3-month premium fell approximately by 80 bps, while the 10-year premium dropped by 17 bps. Second, the forward premium was more sensitive to the first announcement relative to the other announcement. This could be potentially driven by the fact that markets were expecting the subsequent interventions by the Central Bank of Mexico given the pressures over the Mexican peso.[4]

Variable	Pooled			Panel		
	(1)	(2)	(3)	(4)	(5)	(6)
Lagged premium	0.985***	0.983***		0.984***	0.982***	
	(0.003)	(0.003)		(0.002)	(0.003)	
Linear time trend	0.0001***	0.0001***		0.0001**	0.0001	
	(0.0000)	(0.0000)		(0.0000)	(0.0000)	
Announcement	-0.064*	-0.065*	-0.064	-0.064**	-0.066**	-0.065*
	(0.038)	(0.038)	(0.039)	(0.024)	(0.024)	(0.026)
Implementation	0.020***	0.015**	0.022***	0.014**	0.014**	0.022***
	(0.006)	(0.006)	(0.052)	(0.004)	(0.004)	(0.004)
Lagged Change Mon. Pol.		0.001***	0.001***		0.001**	0.001***
		(0.0002)	(0.0002)		(0.0002)	(0.0001)
VIX Index		0.002***	0.002***		0.002***	0.002***
		(0.0005)	(0.0005)		(0.0005)	(0.0003)
Oil Prices (WTI)		0.001**	0.0007**		0.001***	0.0007***
		(0.0004)	(0.0003)		(0.0002)	(0.0001)
Daily Change in Fed Funds Rate		0.001**	0.0007**		0.0007***	0.0007***
		(0.0003)	(0.0003)		(0.0000)	(0.0000)
Constant	✓	✓	✓	✓	✓	✓
Fixed Effects				✓	✓	✓
Obs.	2,708	2,708	2,708	2,708	2,708	2,708
R^2	0.993	0.993	0.029	0.999	0.999	0.061

Note: The R^2 associated with the panel data exercises corresponds to the within goodness-of-fit measure. ***, **, *, denote statistical significance at 1%, 5%, and 10%, respectively. Robust standard errors are reported in parentheses.

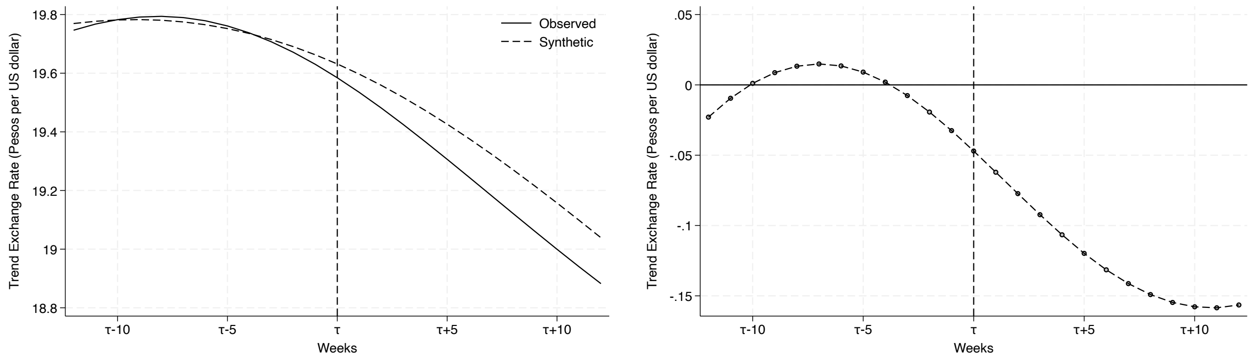
TABLE 2: Estimates for Forward Premium

To test if the announcements and auctions had an effect on the forward premium, we estimate (3) by changing the dependent variable. The results are displayed in Table 2. We find that both the announcements made and the auctions held by the Bank of Mexico had a statistically significant effect on the forward premium. In particular, the announcement decreased the premium by 6 bps while the implementation increased the premium by 2 bps, approximately.

[4]During the second semester of 2017, several rounds of the NAFTA renegotiations were held, there were hikes in the Fed funds rate, and the U.S. fiscal reform was approved.

2.4 Synthetic Control Estimation

As an alternative to the previous estimation procedure and in a similar fashion to Chamon et al. (2017), we use the method of synthetic controls developed by Abadie and Gardeazabal (2003) to study the causal impact of the DNDF program over the Mexican peso. In this particular setting, we focus on the first announcement by the Bank of Mexico on February 21, 2017. To construct the synthetic counterfactual for the level and volatility of the USD/MXN exchange rate, we use weekly data on exchange rates, at-the-money option-implied volatilities for different maturities ranging from 1 week to 1 year, the risk-reversal measure, bond and equity flows for Mexico and other 19 economies.[5] The outcome variables are the exchange rate and the option-implied volatilities, while the predictors of those outcome variables correspond to the risk-reversal measure, bond, and capital flows. Price data comes from Bloomberg and Markit while bond and capital flows are obtained from the Emerging Portfolio Fund Research (EPFR) database. Given the volatile nature of the outcome variables and following Abadie (2021), we filter them using the HP filter with a smoothing parameter $\lambda = 14,400$.[6] In that sense, we apply the synthetic control to the trend component of the outcome variables. In terms of the level of the Mexican peso relative to the US dollar, we find that the Mexican peso appreciated around 15 cents per US dollar after three months of



(A) Observed and Synthetic

(B) Estimated Treatment Effect

Note: The solid and dashed lines correspond to the observed outcome variable and the synthetic control, respectively. t denotes the week in which the policy was announced by the Bank of Mexico. Countries with strictly positive weights are Czech Republic ($w_2^\star = 78.30\%$), Poland ($w_3^\star = 8.40\%$), and South Africa ($w_4^\star = 13.30\%$).

FIGURE 8. Mexican Peso per US Dollar Exchange Rate

[5]Our donor pool consists of Brazil, Chile, China, Colombia, Czech Republic, Hungary, India, Indonesia, Korea, Malaysia, Peru, Philippines, Poland, Qatar, Saudi Arabia, South Africa, Thailand, Turkey, and Abu Dhabi, chosen based on data availability and comparable macroeconomic and financial fundamentals to those of Mexico. Most of the countries in the donor pool had S&P credit ratings between B and BBB range before 2017. The only exceptions are Chile (AA-), China (AA-), Czech Republic (AA-), Korea (AA), Malaysia (A-), Qatar (AA), and Saudi Arabia (A-). Even though these countries have stronger macroeconomic fundamentals than Mexico, we include them in the donor pool given comparable liquidity in terms of their currency markets.

[6]Alternative filtering methods such as the Hamilton (2018) or the Kalman filter applied to a local-level model as in Harvey (1990) yield trend components that are almost as volatile as the original variable. Other options that we considered were moving averages to smooth the exchange or the implied volatilities. The results are comparable to those of the baseline estimation.

the policy announcement.

Variables	Observed	Synthetic	Average
3 month option-implied volatility	15.14	11.70	9.47
Stock returns	-1.20	3.71	3.84
Risk-reversal	2.02	1.88	1.83
Equity flows by mutual funds and ETFs	18.42	8.06	-0.80
Equity flows by II.	26.54	9.98	12.19
Bond flows by mutual funds and ETFs	49.32	8.30	10.22
Bond flows by II.	48.21	7.39	16.75
Outcome variable at $t = 1$	19.75	19.78	32.99
Outcome variable at $t = T_0/2$	19.78	19.78	33.05
Outcome variable at $t = T_0 - 1$	19.63	19.67	33.04

Note: This table displays the pre-treatment mean of the predictors of trend exchange rate. The pre-treatment sample goes from December 1, 2016, to February 16, 2017. ETF stands for exchange-traded funds. T_0 corresponds to the week of the announcement.

TABLE 3: Trend Exchange Rate Predictor Means

In the first panel of Figure 8, we display the observed and synthetic USD/MXN nominal exchange rate, while in the second panel, we present the estimated treatment effect up to 12 weeks after the policy announcement. From both figures, we see what seems to be an anticipation effect since the observed trend exchange rate and the synthetic control started to separate a few weeks before the announcement of the policy by the Bank of Mexico; however, this is entirely driven by the filtering method used to "smooth" the exchange rate. In Appendix B, we present the results from estimating the synthetic control method using the three-month percentage change in the exchange rate instead of the trend exchange rate as the outcome variable. We can see that the synthetic control starts to separate from the observed outcome variable after the announcement of the DNDF program. Also, in terms of matching pre-treatment characteristics, the synthetic control does a better job than the simple average. The main difference between these results from those of the baseline is the set of countries that receive strictly positive weights for replicating the pre-treatment dynamics of the outcome variable: Brazil ($w_2^\star = 43.0\%$), Turkey ($w_3^\star = 48.10\%$), and India ($w_4^\star = 8.90\%$).

Table 3 displays the comparison of the predictors of the outcome variable between the synthetic control and a simple average. We see that the synthetic control method does a better job of replicating the pre-treatment characteristics of Mexico relative to a simple average. In particular, neither the synthetic control nor the simple average is good at matching the pre-treatment average of equity and bond flows of Mexico. However, even if we exclude those predictors, we get the same set of countries with strictly positive weights: Czech Republic ($w_2 = 79.10\%$), Poland ($w_3 = 8.80\%$), and South Africa ($w_4 = 12.10\%$).

To evaluate the economic and statistical significance of the treatment effect, we conduct placebo tests as in Abadie et al. (2010) where we find a sizeable effect of the treatment over the exchange rate. On the one hand, in panel B2A of Figure B2 in Appendix B we display the placebo runs for countries with a pre-treatment Root Mean Square Prediction Error (RMSPE) of, at most, 5 times the pre-treatment RMSPE of Mexico.[7] We observe that the peso experienced one of the largest contractions after the policy announcement. On the other hand, in panel B2B, we display the post-pre-treatment RMSPE ratio for Mexico and all other countries in the donor pool, where we observe that Mexico has one of the highest ratios, meaning that estimating a gap of the magnitude of Mexico under a random permutation of the intervention is around 15%.

Regarding the volatility of the peso, we analyze the impact that the policy announcement had on the implied volatility of at-the-money options for the USD/MXN exchange rate ranging from 1 week to 1 year. As with the level of the exchange rate, to prevent extrapolation bias, we filter the time series using the HP filter with smoothing parameter $\lambda = 14,400$. For each maturity h, we estimate the synthetic counterfactual. In Table 4 we display the set of countries that get a positive weight to construct the synthetic counterfactual. For almost all of the maturities, Brazil and Turkey are key for replicating the pre-treatment dynamics of the USD/MXN option-implied volatilities.

Countries	1 Week	2 Weeks	1 Month	2 Months	3 Months	6 Months	9 Months	1 Year
Brazil	86%	91%	91%	83%	76%	58%	51%	40%
Korea	0%	0%	0%	0%	0%	0%	0%	4%
Malaysia	2%	2%	2%	3%	4%	9%	0%	0%
Poland	0%	0%	0%	0%	0%	0%	24%	18%
Turkey	12%	7%	7%	14%	20%	33%	25%	38%

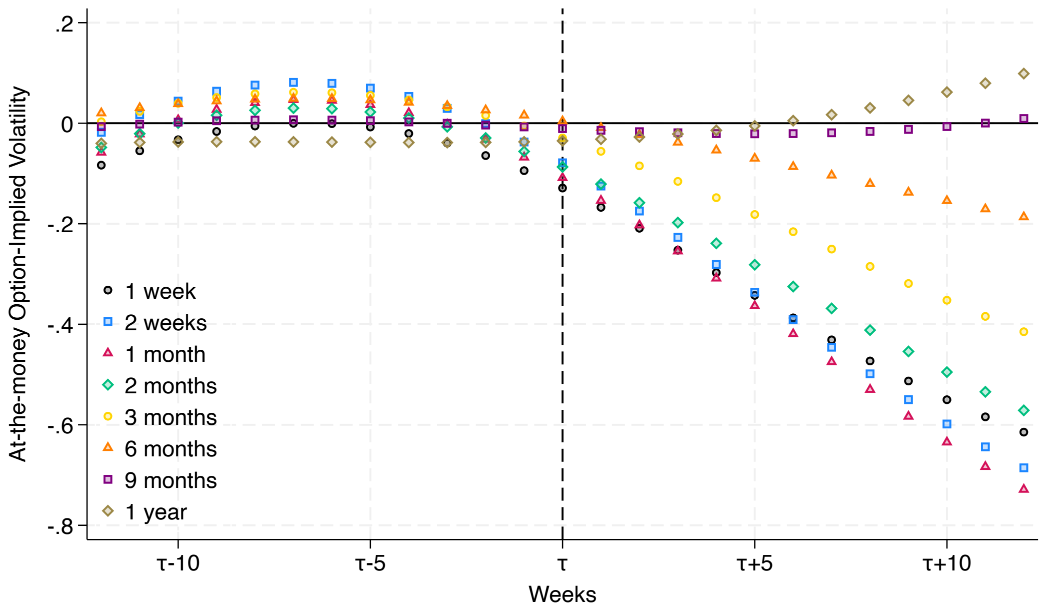
Note: For each maturity h of the at-the-money implied volatility of the MXN/USD exchange rate, we estimate the synthetic control using as predictor variables the 3-month percentage change in the exchange rate, the risk-reversal measure, equity and bond flows for mutual funds, ETFs, and institutional investors, and lagged observations of the outcome variable.

TABLE 4: Set of Weights for Each Maturity

In Figure 9 we present the estimated treatment effect for each horizon h where we observe a "good" pre-treatment adjustment since the average treatment effect using the pre-intervention sample is approximately zero for each h.[8] After the policy announcement, the

[7] To make a fair comparison, we only show the dynamic treatment effect for countries that had a "good" pre-treatment fit (i.e., exceeds in at most κ times the pre-treatment RMSPE of the treated unit). As is standard in the literature that uses the synthetic control method, this cut-off value (i.e., $\kappa = 5$) is completely arbitrary. In this figure, in addition to Mexico, we only display the estimated treatment effect for China, Czech Republic, Malaysia, Peru, Poland, Qatar, Saudi Arabia, South Africa, Turkey, and Abu Dhabi.

[8] As with the results of the trend exchange rate as the outcome variable, there seems to be some anticipation effect since there is a gap between the observed and synthetic values prior the announcement of the policy; however, this is driven by the filtering technique used to smooth the outcome variable.



Note: The markers correspond to the estimated treatment effect (i.e., the difference between the observed and synthetic implied volatility). t corresponds to the week in which the policy was announced by the Bank of Mexico. For almost all horizons h the countries with strictly positive weights are Brazil, Malaysia, and Turkey.

FIGURE 9. Effect over ATM Implied Volatilities

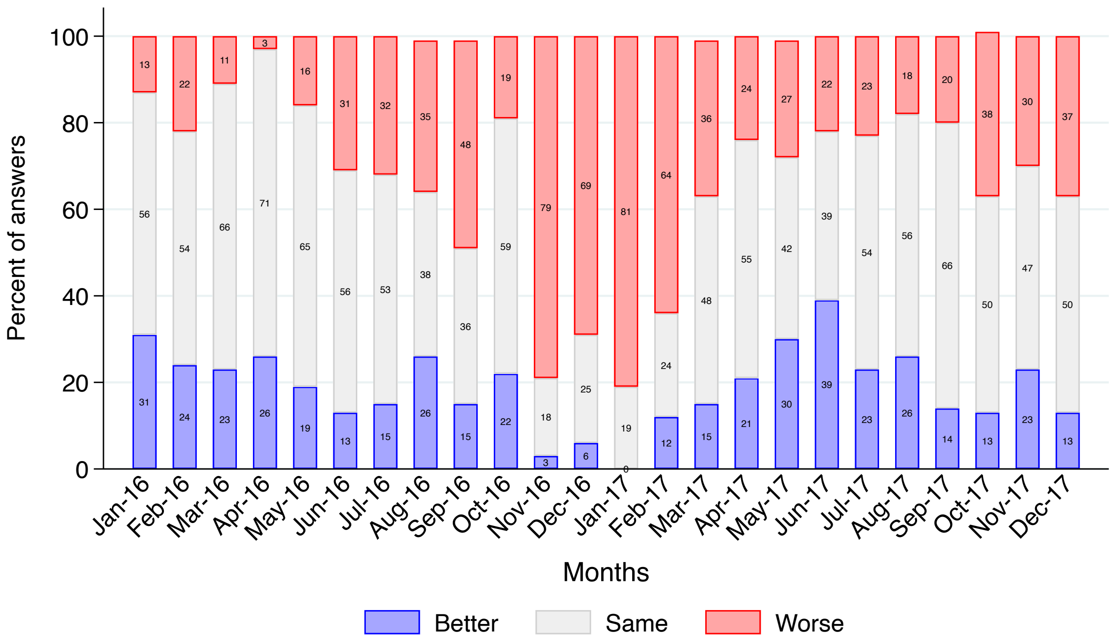
implied volatility of the exchange rate decreases for most of the horizons and the effect is larger the shorter the maturity h. These results align quantitatively and qualitatively with our findings from the linear models for option-implied volatilities discussed in the previous subsection. In particular, the magnitud of the causal effect is comparable to the point estimates from equation (3). Figure B4 in Appendix B presents the placebo runs for each maturity and all countries in the donor pool. For short maturities, we observe that the outcome variable for Mexico experiences one of the largest contractions and that, as maturity increases, the effect fades away.

Our results are qualitatively in line with the findings of Chamon et al. (2017) for the case of Brazil. In particular, we also find that the local currency appreciated relative to the US dollar by approximately 15 cents and the 3-month option-implied volatility decreased by approximately 40 cents per US dollar. One distinguishing feature of our analysis regarding the option-implied volatility of the exchange rate is that we disentangle the effect of the intervention by maturity, finding that the announcement was mostly effective in the very short run and that, for those maturities, the effect took more than 3 months to disappear.

2.5 Expectations of the Private Sector

The Bank of Mexico conducts monthly surveys to economic specialists in the private sector to assess the expectations regarding the economic outlook for the Mexican economy in the next 6 months to a year. These economic specialists are national and international analysis groups in the private sector. According to the information displayed in the monthly bulletins, most of the responses are received between the second and third week of each month, and the bank publishes the results the first week of the following month. Also, the Central Bank records the expectations of these specialists regarding the value of the nominal exchange rate (i.e., Pesos per US dollar) for month t to month $t + 12$. In other words, they will report their expectations about the value of the currency in the month they took the survey and for the following 12 months.

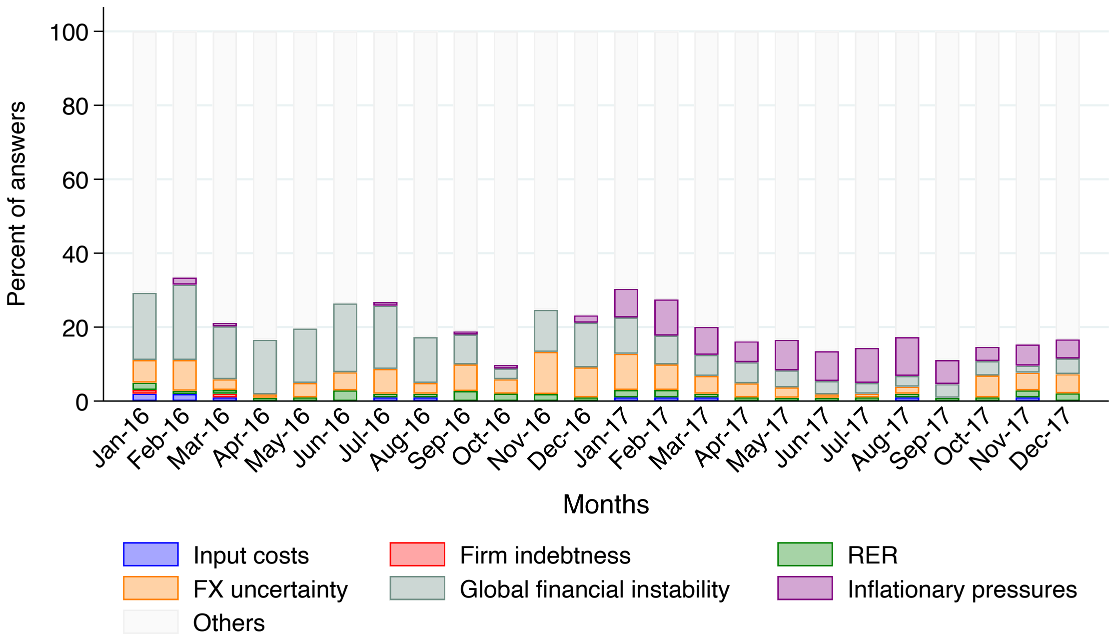
In this subsection, we present some of the results of the survey conducted by the Central Bank during the years 2016 and 2017. In particular, we display the percent of responses to two specific questions. The first one is: "How do you think the business climate for the productive activities of the private sector will evolve in the next six months compared to the last six months?". The second one is: "In your opinion, during the next six months, what would be the three main limiting factors to the growth of economic activity?". We also present the median response regarding the expected level of the exchange rate for months t to month $t + 12$.



Note: Own elaboration with data from *Banco de México*. The question being asked is: "How do you think the business climate for the productive activities of the private sector will evolve in the next six months compared to the last six months?". The bars represent the percent of responses for each option.

FIGURE 10. Percent of responses to survey on business climate

Figure 10 displays the results for the first question. After Donald Trump's victory in the Presidential Election of 2016, the percent of responses that considered that the business climate was better than the previous 6 months dropped by a significant amount: from 22% of the surveyed specialists the month before the election to only 3% in November of 2016. More strikingly, the month that Trump took office, 81% of the specialists considered that there was a worse business climate while the remaining 19% considered it remained constant. In Figure 11 the responses to question 3 are presented. In this case, at the end of 2016 and beginning of 2017, a larger fraction of specialists considered that "FX uncertainty" and "Real exchange rate (RER)" were among the three main limiting factors for economic growth; however, that fraction went down after February of 2017.



Note: Own elaboration with data from *Banco de México*. The question being asked is: "Taking into account the current economic-financial environment: Do you think that the country's economy is currently better than a year ago?". The bars represent the percent of responses for each option.

FIGURE 11. Percent of responses regarding three main limiting factors to economic growth

Even though we cannot attribute a causal impact of the DNDF policy announcement on the responses to the previous questions in the surveys, it is thought provoking to see that: (i) there is trend reversion on the percent of responses that considered either a worse business climate after February of 2017, and (ii) that the fraction of specialists that considered FX uncertainty as one of the main limiting factors for economic growth went down after the policy announcement.

In terms of the expectations of the specialists of the private sector regarding the value of the peso vis-à-vis the US dollar, in Figure 12 we display the median for month t to month $t + 12$ starting at November of 2016. There are three things worth highlighting. First, after Trump took office in January of 2017 (i.e., the highest curve in the figure), private sector expectations were that the nominal exchange rate was going to depreciate and that it would be a persistent pattern for the next 12 months. Second, during and after February 2017, the private sector expected a lower level for the USD/MXN exchange rate, as can be seen on the red curve and the curves after that month. Finally, third, around October of 2017, agents expected a higher exchange rate, which could potentially explain the extension announce-

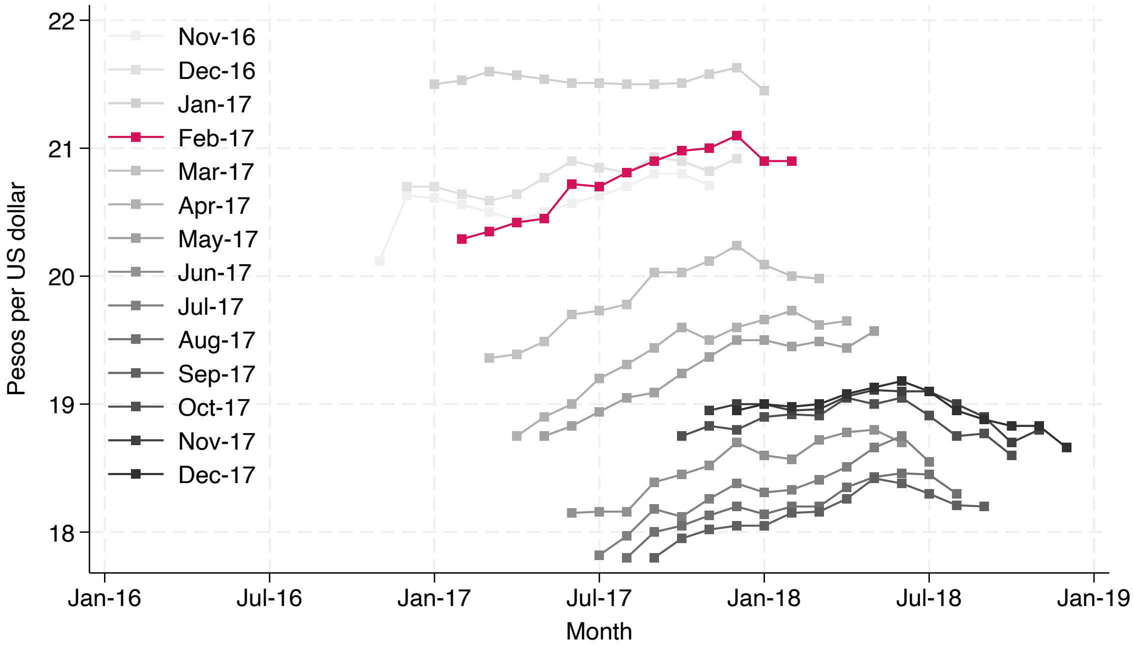


FIGURE 12. Expectations of the exchange rate at month t to $t + 12$

ments by the Central Bank at the end of October and December of 2017.

This evidence is suggestive that announcing the DNDF policy mainly affected private agents' expectations about future USD/MXN exchange rates by decreasing the probability of a severe depreciation. In other words, once the Bank of Mexico announced that it will provide insurance against the exchange rate depreciation, this potentially led to a reduction of the likelihood of a nonfundamental shock on the FX market by preventing a coordination failure of private agents' beliefs. This is the main mechanism that we highlight in our model presented in the next section.

3 Model

We have shown that the Bank of Mexico's announcement effectively reduced the exchange rate volatility and made the Mexican Peso appreciate against the US dollar, whereas the policy did not have any significant effect when it came to the implementation of the auctions. We interpret that the policy effectively changed private agents' expectations and beliefs while not directly affecting the macroeconomic fundamentals of Mexico, so we rationalize this by studying a model that features self-fulfilling crises even when there is no fundamental risk associated with income.

3.1 Environment

3.1.1 Private Block

Households The economy consists of homogeneous households of unit measure. Households maximize lifetime utility subject to the budget and borrowing constraints specified as

$$\max_{\{c_t, M_{t+1}, d_{t+1}\}_{t\geq 0}} \mathbb{E}_0 \left[\sum_{t=0}^{\infty} \beta^t \left(u(c_t) + v\left(\frac{M_{t+1}}{p_t}\right)\right)\right] \tag{4}$$

$$\text{s.t. } p_t^T c_t^T + p_t^N c_t^N + \tilde{R}_{t-1}\frac{e_{t-1}d_t}{R} + M_{t+1} = p_t^T y^T + w_t h_t + \frac{e_t d_{t+1}}{R} + M_t + \Pi_t - T_t, \tag{5}$$

$$c_t = \left(\phi (c_t^T)^{\frac{\gamma-1}{\gamma}} + (1-\phi)(c_t^N)^{\frac{\gamma-1}{\gamma}}\right)^{\frac{\gamma}{\gamma-1}}, \tag{6}$$

$$\frac{e_t d_{t+1}}{R} \leq \kappa(p_t^T y^T + w_t h_t + \Pi_t) \tag{7}$$

where p_t^T and p_t^N are prices of tradables and nontradables, respectively. The household income is composed of the endowment of tradables $p_t^T y^T$ and the labor income $w_t h_t$ from the production of nontradables. We consider a deterministic economy where the tradables endowment is constant. We assume that the law of one price holds, with the tradable good being the numeraire in the world economy, so the price of the tradables is equivalent to the nominal exchange rate, i.e., $p_t^T = e_t$.

Households borrow debt d_{t+1}/R units of dollars through FX trading facilities in period t at an interest rate $\tilde{R}_t$. Households also demand nominal balances M_{t+1} as their utility depends on the real balance of money they have at the time t. T_t is a lump-sum tax imposed by the central bank, which we describe in the following section. Finally, Π_t is the rebated profit from the financial facilities.

The intratemporal optimal choice between tradable and nontradable consumption satisfies

$$\frac{p_t^N}{e_t} = \frac{1-\phi}{\phi}\left(\frac{c_t^N}{c_t^T}\right)^{-\frac{1}{\gamma}}, \tag{8}$$

and the price aggregator p_t is obtained as

$$\left(\phi^\gamma e_t^{1-\gamma} + (1-\phi)^\gamma \left(p_t^N\right)^{1-\gamma}\right)^{\frac{1}{1-\gamma}} = p_t. \tag{9}$$

The money demand is determined by the first-order condition with respect to M_{t+1},

$$\frac{1}{p_t} v' \left(\frac{M_{t+1}}{p_t} \right) = \frac{u_T(t)}{e_t} - \beta \mathbb{E}_t \left[\frac{u_T(t+1)}{e_{t+1}} \right], \tag{10}$$

where $u_T(\cdot)$ denotes the partial derivative of $u(\cdot)$ with respect to the tradable consumption.

The local currency value of external debt is limited to a fraction of total income within the period common in the literature, including Bianchi (2011). The first-order condition with respect to d_{t+1} yields the following Euler equation:

$$(1-\mu_t)\frac{u_T(t)}{e_t} = \beta \tilde{R}_t \mathbb{E}_t \left[\frac{u_T(t+1)}{e_{t+1}} \right], \tag{11}$$

where $\mu_t \geq 0$ is the Lagrangian multiplier on the borrowing constraint.[9] The complementary slackness condition associated with the borrowing constraint is given by

$$\mu_t \left(\kappa(e_t y^T + w_t h_t + \Pi_t) - \frac{e_t d_{t+1}}{R} \right) = 0, \quad \mu_t \geq 0. \tag{12}$$

Nontradables Production Nontradable goods are produced by homogeneous firms with linear production technology $y_t^N = h_t$ and households inelastically supply labor up to $\bar{h}$ units.[10] The equilibrium hours worked are $h_t \leq \bar{h}$ due to downward wage rigidity such that $w_t \geq w_{t-1}$. There is unemployment such that $h_t < \bar{h}$ only when the wage is restricted to its lower bound w_{t-1}. Hence, we have the following

$$(w_t - w_{t-1})(h_t - \bar{h}) = 0, \tag{13}$$

as a complementary slackness condition that holds in the equilibrium. The linear production function implies that the price of nontradables satisfies

$$p_t^N = w_t, \tag{14}$$

which implies that the price of nontradables is subject to downward rigidity as well.

Financial Intermediaries We consider a unit measure of homogeneous, risk-averse financial institutions that intermediate external debt from foreign lenders to the households and invest in the foreign economy. The financial institutions adopt the zero net-capital strategy and they intermediate d_{t+1} units of dollars subject to the international interest rate R. Then they charge the interest rate $\tilde{R}_t$ on the local currency value of dollars they lend to the

[9]We put λ_t as the multiplier on the period budget constraint and $\lambda_t \mu_t$ as the multiplier on the borrowing constraint. Solving for the Lagrangian yields that $\lambda_t = u_T(t)$ and equation (11).

[10]We abstract from labor disutility for simplicity.

households. We impose mean-variance utility for the financial institutions specified as

$$\max_{d_{t+1}} W_t = \mathbb{E}_t[\Pi_{t+1}] - \frac{\omega}{2}\text{Var}_t[\Pi_{t+1}], \tag{15}$$

$$\text{s.t. } \Pi_{t+1} = \tilde{R}_t e_t \frac{d_{t+1}}{R} - e_{t+1}d_{t+1}, \tag{16}$$

which yields the optimal condition with respect to d_{t+1} as

$$d_{t+1} = \frac{1}{\omega \text{Var}_t\left[e_{t+1}\right]}\left(\frac{\tilde{R}_t}{R}e_t - \mathbb{E}_t e_{t+1}\right), \tag{17}$$

and any non-zero level of debt implies deviation from the uncovered interest rate parity.

When the central bank offers a forward contract to the financial intermediaries, then the financial intermediaries get to choose the fraction θ_t of its debt to be covered by the forward contract with forward rate f_t. Its objective changes to

$$\max_{d_{t+1},\theta_t\in[0,1]} W_t = \mathbb{E}_t[\Pi_{t+1}] - \frac{\omega}{2}\text{Var}_t[\Pi_{t+1}], \tag{18}$$

$$\text{s.t. } \Pi_{t+1} = \tilde{R}_t e_t \frac{d_{t+1}}{R}\left((1-\theta_t) + \theta_t\frac{e_{t+1}}{f_t}\right) - e_{t+1}d_{t+1}, \tag{19}$$

which yields optimal conditions with respect to d_{t+1} and θ_t as:

$$d_{t+1} :: \quad d_{t+1} = \frac{1}{\omega\left(\frac{\tilde{R}_t}{R}\frac{e_t}{f_t}\theta_t - 1\right)^2 \text{Var}_t[e_{t+1}]}\left(\frac{\tilde{R}_t}{R}\left(1-\theta_t+\theta_t\mathbb{E}_t\frac{e_{t+1}}{f_t}\right)e_t - \mathbb{E}_t e_{t+1}\right), \tag{20}$$

$$\theta_t :: \quad d_{t+1} = \frac{\mathbb{E}_t e_{t+1} - f_t + \xi_t - \eta_t}{\omega\left(\frac{\tilde{R}_t}{R}\frac{e_t}{f_t}\theta_t - 1\right)\text{Var}_t\left[e_{t+1}\right]}, \tag{21}$$

where ξ_t and η_t are the Lagrangian multipliers on constraints of $\theta_t \geq 0$ and $\theta_t \leq 1$ scaled by the denominator of (21). The two optimal conditions can be combined to get the covered interest rate parity condition specified as:

$$f_t = \frac{\tilde{R}_t}{R}e_t, \tag{22}$$

when the boundary constraints on θ_t do not bind. In other words, the financial intermediaries choose either full insurance ($\theta_t = 1$) or no insurance ($\theta_t = 0$) whenever there is a deviation from the covered interest rate parity. The central bank's forward rate affects the nominal exchange rate and domestic interest rate through (22) in the equilibrium.

3.1.2 Policy Block

The central bank has two main policy instruments. First, it sets the money supply M_t. In equilibrium, the marginal utility terms satisfy (10) given a level of M_t.

Second, the central bank sets the forward rate f_t to insure private agents against exchange rate depreciation. While implementing the forward rate policy, the central bank pays the previous period's DNDF settlement out of its external asset a_t at the beginning of the period. We assume that the central bank's asset pays out gross interest of R.[11] We also impose that the central bank has to maintain a minimum level of asset position $\underline{a}$ at the end of each period after paying out DNDF settlements to private agents.[12] Hence, the central bank's external asset evolves according to the following rule:

$$\frac{a_{t+1}}{R} = \max\left\{a_t - \left(\frac{1}{f_{t-1}} - \frac{1}{e_t}\right)\theta_{t-1}\tilde{R}_{t-1}e_{t-1}\frac{d_t}{R}, \underline{a}\right\}. \tag{23}$$

To focus on the role of insurance provision, we assume that the central bank pays out all of the revenues from an increase in the money supply and taxes the private agents only to replenish the assets whenever it falls below $\underline{a}$. Hence, the lump-sum tax T_t is determined to satisfy the central bank's balance sheet constraint in domestic currency units as

$$T_t = -(M_{t+1} - M_t) + e_t\left(\frac{a_{t+1}}{R} - a_t + \left(\frac{1}{f_{t-1}} - \frac{1}{e_t}\right)\tilde{R}_{t-1}e_{t-1}\theta_{t-1}\frac{d_t}{R}\right). \tag{24}$$

3.1.3 Market Clearing

The market clearing condition for nontradables is given as $c_t^N = y_t^N$. Plugging this and (24) into the household sequential budget constraint, we obtain the following resource constraint of tradable goods:

$$c_t^T + (d_t - a_t) = y_t^T + \frac{d_{t+1} - a_{t+1}}{R}. \tag{25}$$

The labor market is cleared by Walras' Law.

3.1.4 Sunspot Shock

The deterministic version of the economy features multiple equilibria depending on households' beliefs on the aggregate level of debt, consistent with the literature (Schmitt-Grohé

[11] While we denote a_t as the central bank's external asset following the convention of the literature, one can also conceptualize it as the central bank's equity that is provided by the fiscal law in reality. Indeed, the Bank of Mexico paid the private institutions out of its equity when implementing the DNDF program.

[12] An alternative way of ensuring that the central bank does not use the forward contracts to inject an infinite amount of resources to the private sector would be to specify a cap to the number of dollars that the central bank can sell through the forwards. This would introduce a capacity constraint in the financial intermediaries' problem.

and Uribe (2021); Bianchi and Coulibaly (2024)). As will be discussed in the following section, there can be a self-fulfilling crisis with exchange rate depreciation when households collectively become pessimistic and deleverage. Realization of the crisis solely depends on whether or not there is such a coordination failure of the households' beliefs, which leads to model indeterminacy.

We consider such coordination failure of the households' beliefs on future exchange rates to be the source of nonfundamental risk, that can lead to unexpected fluctuations of the exchange rate. Hence, we specify a random forecasting error ν_t on nominal exchange rate that is realized each period as follows:

$$\nu_t = e_t - \mathbb{E}_{t-1}e_t, \quad \nu_t \sim F, \tag{26}$$

where F is an exogenous distribution.[13] Our approach is similar to Bianchi and Nicolò (2021) who also specify forecasting errors to estimate and solve models with indeterminacy.

3.1.5 Competitive Equilibrium

We define the competitive equilibrium of this economy under any sequence of forward rates as follows.

Definition 1 (Equilibrium under DNDF Policy). *Given initial conditions $\{f_{-1}, w_{-1}, d_0, a_0\}$, shocks $\{\nu_t\}_{t=0}^{\infty}$ and an arbitrary sequence of $\{f_t, M_t\}_{t=0}^{\infty}$, the competitive equilibrium is defined as a sequence of allocations $\{c_t^T, c_t^N, c_t, h_t, d_{t+1}, \Pi_t, \theta_{t+1}, \mu_t\}_{t=0}^{\infty}$, prices $\{e_t, p_t^N, p_t, w_t, \tilde{R}_t\}_{t=0}^{\infty}$, and $\{a_{t+1}, T_t\}_{t=0}^{\infty}$ such that*

1. *Given initial debt d_0, tradables endowment y^T, prices, and policy $\{f_t, T_t, a_{t+1}\}_{t=0}^{\infty}$, households maximize their life-time utility and firms maximize profit each period. That is, equations (5)–(6) and (8)–(14) hold.*

2. *Given the forward rate f_t and prices, financial intermediaries maximize their static profit Π_t defined by (19). That is, equations (20) and (21) hold.*

3. *Given the initial asset a_0 and the forward rates $\{f_t\}_{t=0}^{\infty}$, and the external debt of the households $\{d_t\}_{t=0}^{\infty}$, the central bank asset a_{t+1} evolves according to (23) and the lump sum tax T_t satisfies (24) each period.*

4. *Markets clear and (25) holds.*

The competitive equilibrium exists for an arbitrary choice of forward rates and money supply by the central bank. We now proceed to discuss how the central bank's choice of policy affects the equilibrium, focusing on the role of forward rate policy.

[13]The distribution F needs not be a continuous distribution. As we describe in the next section, the forecasting error would follow a discrete distribution even in the absence of a fundamental shock as the exchange rate would either stay constant at the steady state level or depreciate in a sunspot equilibrium.

3.2 Discussion of Assumptions

We discuss the relevance of some of the simplifying assumptions to our analyses of the effects of forward rate policy.

Currency Choice of Central Bank Assets. We abstract from constructing the central bank's problem of choosing the optimal currency portfolio choice. While we impose that the central bank's assets are foreign reserves denominated in foreign currency, our discussion so far does not rely on the currency denomination of the central bank's assets. What matters is whether or not the private agents believe that the central bank has enough resources to pay private agents the DNDF settlements when the exchange rate actually depreciates today. This is when $\bar{a}$ is sufficiently low in the model. In reality, the DNDF settlement does not directly affect the central bank's foreign reserves, and this would reinforce market participants' beliefs that the central bank can pay for DNDF settlements if necessary.

Private FX Forward Market. We abstract from specifying a private FX forward market as an outside option for the agents to reflect that the FX forward market is segmented in Mexico. Local banks and financial institutions did not have much access to the private FX forward market because the available insurance was prohibitively expensive, and providing them with a tool to hedge the exchange rate risk was one of the main reasons for the Bank of Mexico to introduce the DNDF policy. Hence, we focus on analyzing the effects of introducing a forward contract to an economy without any private FX forward market.

4 Equilibrium Analysis

We provide an intuition for the sunspot shocks by studying the equilibrium indeterminacy in a deterministic version of the baseline model. We incorporate the possibility of multiple equilibria in a deterministic environment as the source of nonfundamental risk by allowing for a stochastic realization of forecasting error on the exchange rate. Hence, the discussion in this section could be considered as a microfoundation of the sunspot shock we introduce in the baseline model. We analyze how the forward rate policy affects the multiple equilibria.

4.1 Steady State Equilibrium

For expositional purposes, we focus on a special case where $\beta R = 1$. The central bank is endowed with zero initial assets with a sufficiently low $\underline{a} < 0$.[14] We define a steady state equilibrium where all the allocations are constant and there is no unemployment over time. The money supply is kept constant at a level that satisfies the money demand equation and there is no inflation. Under constant allocations with $a_0 = 0$, the central bank keeps its asset

[14] In this case, we interpret $\underline{a}$ as the maximum deficit that the central bank can run with.

constant by not transferring resources to private agents and setting the forward rate f equal to the exchange rate e.

In a deterministic environment in the absence of uncertainty, the financial intermediaries would borrow an infinite amount of debt as long as they earn positive profits. Hence, we consider the case where the intermediaries raise zero profit $\Pi = 0$. Since the intermediaries' problem becomes degenerate, the external debt is directly chosen by the households to satisfy (11). Choice of θ_t also becomes indeterminate, so we impose that a constant fraction of $\theta \in (0, 1]$ is covered by the forward contract when $f = e$. Then the interest rate parity condition implies $\tilde{R}_t = R$ at the steady state by

$$\tilde{R}_t e_t = R e_{t+1} \tag{27}$$

which is reduced to (22) when $\theta = 1$.

The resource constraint (25) and the market clearing condition for nontradables imply that

$$c^T = y^T - \frac{R-1}{R} D_0, \tag{28}$$

given an initial level of aggregate debt D_0. The steady-state exchange rate e satisfies

$$\frac{w_{-1}}{e} = \frac{1-\phi}{\phi} \left(\frac{\overline{h}}{c^T} \right)^{-\frac{1}{\gamma}}, \tag{29}$$

given w_{-1} with downward wage rigidity and $y^N = \overline{h}$ under full employment. Plugging this into the borrowing constraint (7), the steady-state borrowing limit is given by:

$$\kappa R \left(y^T + \frac{p^N}{e} y^N \right) = \kappa R \left(y^T + \left(\frac{1-\phi}{\phi} \right)^{\gamma} \left(\frac{w_{-1}}{e} \right)^{1-\gamma} \left(y^T - \frac{R-1}{R} D_0 \right) \right) \equiv \overline{d}^{ss}(D_0), \tag{30}$$

and $\overline{d}^{ss}(D_0)$ is a decreasing function of D_0 as in Bianchi and Coulibaly (2024). Hence, there exists a fixed point such that $\hat{D} = \overline{d}^{ss}(\hat{D})$ and we focus on the case where the initial debt is $D_0 < \hat{D}$, so that there exists a steady-state equilibrium such that allocations are constant. The borrowing constraint does not bind in that equilibrium because the private agents' Euler equation also implies $\mu = 0$ when $f = e$. In sum, the steady-state allocation we consider here is identical to the steady state without DNDF policy and the central bank's external asset considered by Bianchi and Coulibaly (2024).

For further analysis, we make the following assumption to hold in steady state.

Assumption 1. *Given initial debt D_0, initial wage w_{-1}, and interest rate R, the elasticity of substi-*

tution γ satisfies the following condition:

$$\left(\frac{1-\gamma}{\gamma}\right) \times \left(\frac{R-1}{R}\right) < 1. \tag{31}$$

Assumption 1 imposes a lower bound for γ so that the elasticity of substitution between tradables and nontradables is sufficiently high. We also impose $R < 2$ so that the international interest rate does not exceed 100%. Note that empirically relevant values of γ around 0.5 as surveyed by Akinci (2011) satisfy Assumption 1. We consider values of $\gamma \in (0, 1)$ that satisfy this assumption in the analysis henceforth.

4.2 Multiple Equilibria under DNDF Policy

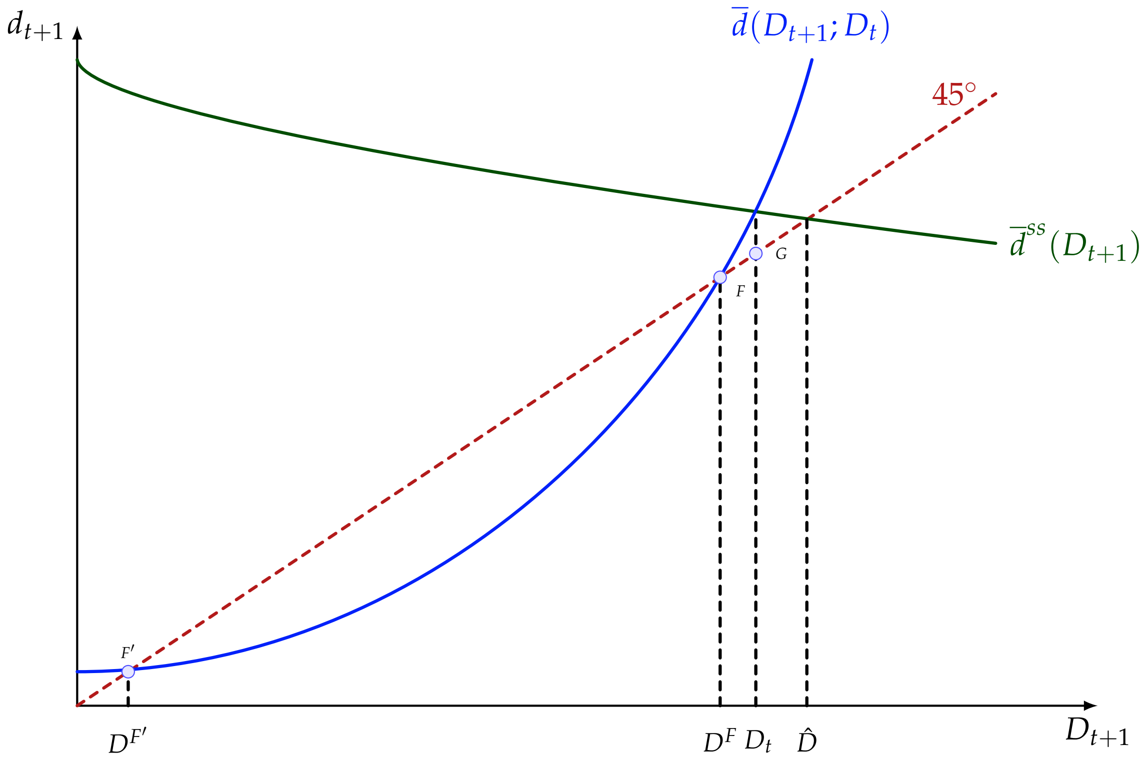
The economy without DNDF policy features multiple equilibria at time t as proved by Schmitt-Grohé and Uribe (2021) and Bianchi and Coulibaly (2024) when the initial debt D_0 exceeds a certain threshold. We now analyze how the DNDF policy imposed in the steady state affects these multiple equilibria.

Consider a deterministic case in which there is no DNDF policy and the economy has been at the steady state with initial aggregate debt D_0 until period t and reaches a different steady state in period $t+1$ with aggregate debt D_{t+1} chosen at period t. We assume that the central bank prevents nominal wage from rising to keep the inflation rate as low as possible as it takes into account the households' utility associated with real money balance. Bianchi and Coulibaly (2024) show that a steady-state equilibrium and at least one self-fulfilling crisis equilibrium, in which borrowing is constrained at a lower level than $D_t = D_0$, can exist when D_t is above a threshold level. These equilibria are marked as points F, F', and G in Figure 13. We begin with a brief explanation of the multiplicity of equilibria in our model.

The horizontal axis of Figure 13 is the aggregate debt D_{t+1} and the vertical axis is each individual's debt choice d_{t+1}. The downward sloping line is the steady state debt limit $\overline{d}^{ss}(D_{t+1})$ defined over potential values of D_{t+1}. This is the debt limit that would have prevailed if all agents began with debt D_{t+1} and lent D_{t+1}. The dashed upward-sloping curve is each individual's borrowing limit in time-t equilibrium,

$$\overline{d}(D_{t+1}; D_t) \equiv \kappa R \left(y^T + \left(\frac{1-\phi}{\phi}\right)^{\gamma} \left(\frac{w_{t-1}}{e_t}\right)^{1-\gamma} \left(y^T + \frac{D_{t+1}}{R} - D_t\right)\right), \tag{32}$$

as a function of aggregate debt D_{t+1} chosen at time t given initial debt D_t. This is the debt limit up to which each individual can borrow when he expects all other people to borrow D_{t+1}. $\overline{d}(D_{t+1}; D_t)$ is an increasing function of D_{t+1} because higher debt issuance today increases consumption and raises the income from nontradable production. This expression is convex because larger tradable consumption increases the relative price of nontradables.



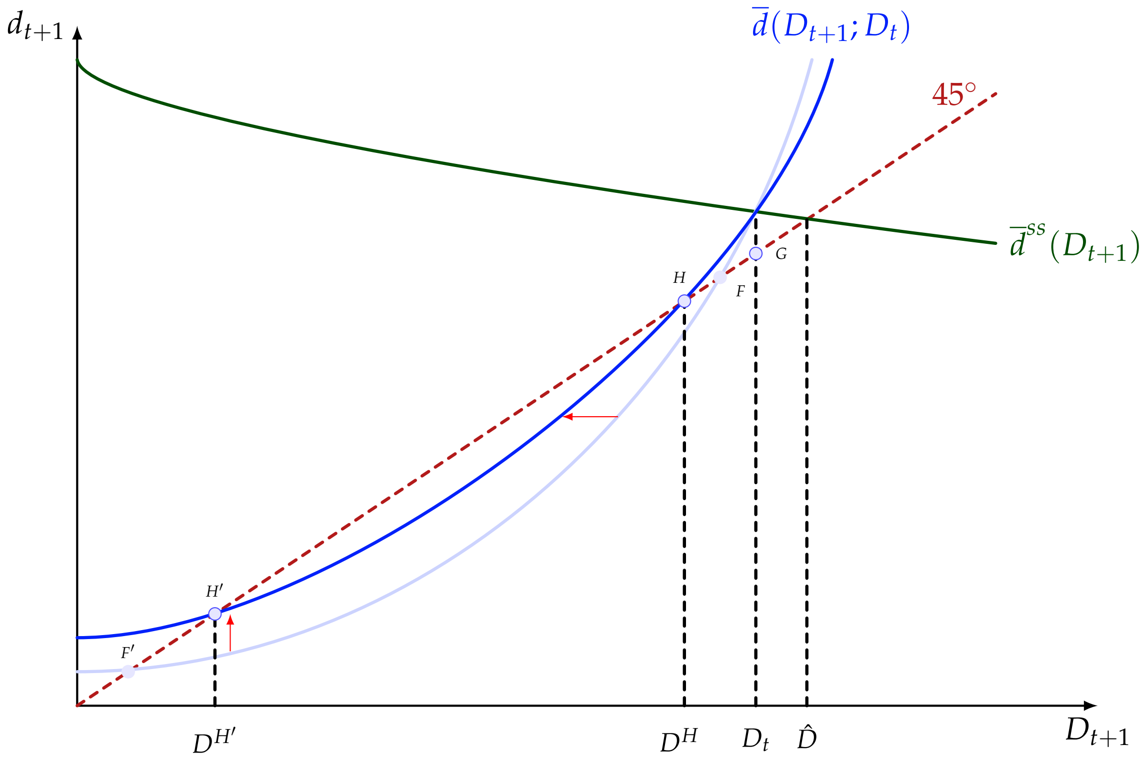
Note: Solid and dashed upward-sloping curves are the equilibrium debt limit $\overline{d}(D_{t+1}; D_t)$ when aggregate debt is D_{t+1} given initial debt D_t in economies with and without the DNDF policy, respectively. Downward-sloping curve $\overline{d}^{ss}(D_{t+1})$ plots the steady state debt limit for each values of D_{t+1}.

FIGURE 13. Multiple Equilibria without DNDF Policy

Since private agents are homogeneous, we consider symmetric equilibria where everyone borrows $d_{t+1} = D_{t+1}$ and all possible equilibria are located on the 45-degree line. One possible equilibrium is the steady-state equilibrium where $d_{t+1} = D_{t+1} = D_t$. This corresponds to point G in Figure 13 and the steady-state debt limit $\overline{d}^{ss}(D_{t+1})$ intersects the equilibrium debt limit $\overline{d}(D_{t+1}; D_t)$ at $D_{t+1} = D_t$. This is the case when each person expects all others to borrow D_t as well in time t and correspondingly borrows D_t. However, when all the private agents become pessimistic and believe that everyone else will deleverage at time t, there can be a self-fulfilling crisis and the borrowing constraint binds as shown by Bianchi and Coulibaly (2024).[15] These are points F or F' where the dashed upward-sloping line meets the 45-degree line. The exchange rate depreciates and lower consumption induces unemployment in the crisis equilibria F and F'. Private agents' Euler equation provides that the borrowing constraint binds with $\mu_t > 0$ at these deleveraging equilibria.

We now analyze how the DNDF policy affects the multiple equilibria in Figure 14. Consider that the economy has been at the steady state with initial debt D_0 and the central bank's zero asset position until period $t-1$. We specifically focus on a case where the central bank

[15] Such equilibrium exists when the slope of $\overline{d}(D_{t+1}; D_t)$ at $D_{t+1} = D_t$ is greater than 1 and D_t is larger than a threshold level. Technically, this yields the result that the debt limit $\overline{d}(D_{t+1}; D_t)$ decreases faster than D_{t+1} and intersects the 45-degree line as D_{t+1} decreases.



Note: Solid and dashed upward-sloping curves are the equilibrium debt limit $\overline{d}(D_{t+1}; D_t)$ when aggregate debt is D_{t+1} given initial debt D_t in economies with and without the DNDF policy, respectively. Downward-sloping curve $\overline{d}^{ss}(D_{t+1})$ plots the steady state debt limit for each values of D_{t+1}.

FIGURE 14. Multiple Equilibria under DNDF Policy

transfers resources to private agents only at period t if the exchange rate depreciates. This is the case when the forward rates chosen at period t and onwards satisfy $f_j = e_{j+1}, \forall j \geq t$, thereby ensuring that the fraction of debt being covered by the forward contract is kept constant at θ without reaching its boundaries. The economy reaches an equilibrium with constant consumption, debt, and full employment from period $t+1$. In this sense, we impose a forward rate rule for f_t that depends on the aggregate debt D_{t+1} chosen at time t such that

$$f_t(D_{t+1}) = \frac{\phi}{1-\phi}\left(\frac{\overline{h}}{y^T - (1-\beta)D_{t+1}}\right)^{\frac{1}{\gamma}} w_{t-1}. \tag{33}$$

This rule of $f_t(D_{t+1})$ corresponds to the steady-state level of the exchange rate when the initial debt is given as D_{t+1} starting from time $t+1$. It is increasing in D_{t+1} as larger debt at the new steady state implies lower consumption and a higher price of tradable goods in equilibrium.

With the DNDF policy specified as above, the borrowing limit that private agents face at period t becomes

$$\overline{d}(D_{t+1};D_t) \equiv \kappa R\left(y^T + \left(\frac{1-\phi}{\phi}\right)^\gamma \left(\frac{w_t}{e_t}\right)^{1-\gamma}\left(y^T + \frac{D_{t+1}-a_{t+1}}{R} - D_t + a_t\right)\right)$$
$$= \kappa R\left(y^T + \left(\frac{1-\phi}{\phi}\right)^\gamma \left(\frac{w_t}{e_t}\right)^{1-\gamma}\left(y^T + \frac{D_{t+1}}{R} - D_t + \underbrace{\frac{e_t - e}{e_t}\theta D_t}_{\text{DNDF Settlement}}\right)\right), \quad (34)$$

as the central bank has been imposing $f = e$ until period $t-1$ with $\underline{a}$ being sufficiently low such that the private agents know that the central bank can pay out the DNDF settlement. As mentioned in the previous section, impose that the households buy a constant amount s of dollars in the initial steady state.

As in the case without the DNDF policy, $\overline{d}(D_{t+1};D_t)$ is an increasing and convex function of D_{t+1} given D_t. We now show that the exchange rate depreciates in a self-fulfilling crisis with $D_{t+1} < D_t$ as in Bianchi and Coulibaly (2024).

Remark 1. *Exchange rate depreciates in a self-fulfilling crisis such that $D_{t+1} < D_t$.*

Proof. See Appendix C.1. ∎

One immediate result of Lemma 1 is that the DNDF settlement partly offsets the decrease in c_t^T in a sunspot equilibrium. This increases the borrowing limit uniformly across all values of $D_{t+1} < D_t$. Hence, the policy trivially relaxes the borrowing constraint compared to the case without policy. Moreover, the policy restricts the space of D_{t+1} where the sunspot equilibrium can take place at time t.

Remark 2. *Crisis equilibrium requires that $D_{t+1} < D_t - \frac{e_t - e}{e_t}R\theta D_t$.*

Proof. See Appendix C.2. ∎

Lemma 2 implies that private agents should become more pessimistic for there to be a self-fulfilling crisis relative to the economy without policy, so that sufficiently high capital outflows and current account reversal take place. In the crisis equilibrium, unemployment happens as in Bianchi and Coulibaly (2024).

We illustrate how the DNDF policy would affect the multiple equilibria in Figure 14. Since the central bank's transfer from the forward contract increases the borrowing limit for all values of $D_{t+1} < D_t$, we can draw $\overline{d}(D_{t+1};D_t)$ under policy as the solid upward-sloping line in Figure 14. It intersects with the steady state debt limit $\overline{d}^{ss}(D_{t+1})$ when $D_{t+1} = D_t$ because there will be no payment without any depreciation. Self-fulfilling crises can potentially occur in two candidate points H and H'.

As noted earlier in Lemma 2, private agents have to become more pessimistic for a crisis to happen under the policy than in the economy without policy, which implies larger deleveraging in the crisis equilibrium and moves F to H. Without the DNDF policy, there can be a self-fulfilling crisis even when the private agents become pessimistic only slightly and believe others to deleverage to D^F. The policy requires agents to be more pessimistic and believe that the aggregate debt reduces to at least D^H for there to be a crisis.

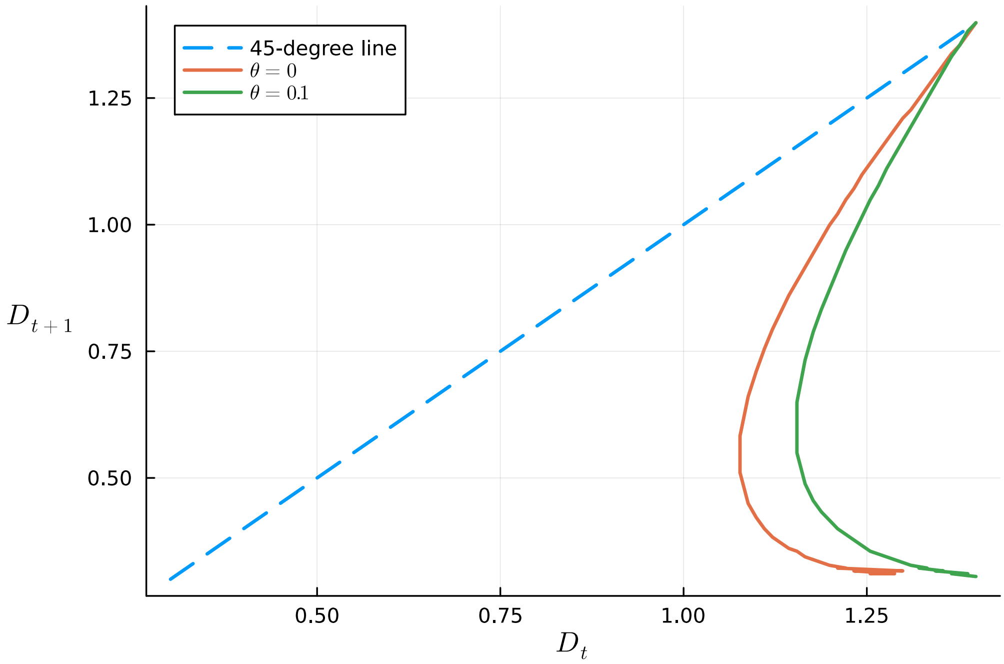
The DNDF settlement boosts the debt limit across values of $D_{t+1} < D_t$ in Figure 14. Whether the self-fulfilling crisis will be completely eliminated depends on the parametrization of the model, but even if the crisis were not to be eliminated by the DNDF settlement, we see that the policy allows private agents to borrow more in the worst possible equilibrium by shifting it from F' to H' in Figure 14. Hence, the DNDF policy reduces the severity of the worst possible equilibrium and mitigates the downside risk of the crisis.

We lastly study how the DNDF settlement under the forward rate rule (33) affects the feasibility of multiple equilibria. Bianchi and Coulibaly (2024) show that the existence of multiple equilibria depends on the level of initial debt D_t that the households begin with, and the crisis equilibrium does not exist when the initial debt D_t is below a threshold level. The threshold level of debt also exists in the economy with the forward rate rule (33) if the equilibrium borrowing limit (34) is an increasing convex function of D_{t+1} and a decreasing function of D_t.[16] Intuitively, the minimum level of D_t such that the equilibrium borrowing limit curve is tangent to the 45-degree line in Figure 14 would increase as the DNDF settlement monotonically increases the borrowing limit.

In Figure 15, we numerically show that the DNDF payment by the central bank reduces the crisis region of initial debt as it shifts the policy function D_{t+1} rightward when $\theta > 0$. So the range of D_t that is susceptible to having the self-fulfilling crisis shrinks under the DNDF policy, and the lower bound of D_t such that the crisis equilibrium exists goes up. Recall that the DNDF settlement increases the borrowing limit in a crisis equilibrium when the exchange rate depreciates for a given level of initial debt. Hence, there exists a range of initial debt D_t such that the introduction of the forward rate policy eliminates a self-fulfilling crisis.

We have shown so far that the simple DNDF policy in a deterministic environment can contribute to preventing a self-fulfilling crisis when the initial debt is not too high. Even if the policy does not fully prevent the crisis under higher values of initial debt, it still mitigates the magnitude of the crisis by boosting up the tradable consumption of the households and the equilibrium borrowing limit. As we have discussed earlier, the policy requires households to be more pessimistic for there to be a crisis. This corresponds to the earlier implication from the data that the DNDF announcement appreciated the Mexican Peso by effectively managing private agents' sentiments about the value of the Mexican Peso.

[16] See Appendix C.3 for details.



Note: We obtain the policy function D_{t+1} in the crisis equilibria for $\theta = 0$ and $\theta = 0.1$. The parameter values in the numerical example are as follows: $R = 1.04$, $\beta = 1/R$, $\chi = 0.1$, $\gamma = 0.4$, $\phi = 0.2$, $\kappa = 0.3$, $y^T = 1$, $W_{-1} = 1$. We also keep the money supply constant at the initial steady state level.

FIGURE 15. Effect of DNDF Policy on Debt $D_{t+1}(D_t)$

4.3 Comparison to Capital Controls

We now consider an alternative environment where the central bank can impose a capital control tax τ_t on external debt. We consider the tax τ_t as a tax on debt repayment made at time t and it is known at time $t-1$ when the households make borrowing choices. Hence, we augment the representative household's budget constraint as

$$p_t^T c_t^T + p_t^N c_t^N + (1+\tau_t)e_t d_t + \tilde{d}_t + M_{t+1} = p_t^T y^T + w_t h_t + \frac{e_t d_{t+1}}{R} + \frac{\tilde{d}_{t+1}}{\tilde{R}_t} + M_t + T_t, \quad (35)$$

where all the notations are the same as in the baseline model. The only difference is that T_t is a lump-sum transfer in this notation. All the optimal conditions are identical to the baseline model except for the Euler equation with respect to d_{t+1}, which is now obtained as

$$(1-\mu_t)u_T(t) = \beta R(1+\tau_{t+1})u_T(t+1). \quad (36)$$

In this alternative environment, the central bank has two main policy instruments – money supply M_{t+1} and the capital control tax τ_{t+1} set at time t. We assume that the central bank rebates all the revenues to the private agents. Hence, the lump-sum transfer T_t is determined to satisfy the central bank's balance sheet constraint in domestic currency units as

$$T_t = (M_{t+1} - M_t) + \tau_t e_t d_t. \tag{37}$$

We can define the competitive equilibrium of this economy under any sequence of forward rates as follows.

Definition 2 (Equilibrium under Capital Control)**.** *Given initial conditions $\{w_{-1}, d_0\}$ and an arbitrary sequence of $\{\tau_{t+1}, M_t\}_{t=0}^{\infty}$, the competitive equilibrium is defined as a sequence of allocations $\{c_t^T, c_t^N, c_t, h_t, d_{t+1}, \mu_t\}_{t=0}^{\infty}$, prices $\{e_t, p_t^N, p_t, w_t, \tilde{R}_t\}_{t=0}^{\infty}$, and $\{T_t\}_{t=0}^{\infty}$ such that*

1. *Given initial debt d_0, tradables endowment y^T, prices, and policy $\{\tau_{t+1}, T_t\}_{t=0}^{\infty}$, households maximize their life-time utility and firms maximize profit each period.*

2. *The lump-sum transfer T_t satisfies (37) each period.*

3. *Markets clear.*

As in the baseline model with DNDF policy, the competitive equilibrium exists for an arbitrary choice of tax rates and money supply by the central bank. We consider the steady state equilibrium when $\beta R = 1$ and y^T is constant over time as in the baseline model. At the steady state, money supply is constant and $\tau_0 = \tau_t = 0$ so that the government does not transfer resources to the households.

We have shown that the DNDF policy can effectively mitigate the self-fulfilling crisis with Remarks 1 and 2. We now show that capital controls can be used to eliminate the sunspot equilibrium and make the borrowing constraint never bind in the deterministic environment.

We consider a deterministic environment where the economy has been at the steady state until period $t-1$ as in Section 4 but with one modification. The central bank chooses τ_{t+1} in period t so the economy can deviate from the steady state depending on its choice. However, we impose that there is full employment and borrowing is not constrained at period $t+1$ and the allocation stays constant from period $t+2$ and henceforth. Also, the central bank adjusts the money supply at period $t+1$ to satisfy the money demand equation in period $t+1$. In this scenario, the central bank can eliminate the self-fulfilling crisis at period t by imposing the following rule.

Remark 3. *Given initial aggregate debt D_t, the central bank can eliminate the crisis equilibria by announcing the policy rule $\mathcal{T}(D_{t+1}, D_t)$ that satisfies*

$$\begin{aligned} & u_T\left(y^T + \frac{D_{t+1}}{R} - D_t, \bar{h}\right) \\ = {} & (1 + \mathcal{T}(D_{t+1}, D_t))\, u_T\left(y^T - \frac{R-1}{R}(1 + \mathcal{T}(D_{t+1}, D_t))\, D_{t+1}, \bar{h}\right), \end{aligned} \tag{38}$$

when $D_{t+1} \leq D_t$.

Proof. See Appendix C.4. ■

This rule depends not only on D_{t+1} but also on D_t, because the central bank makes individuals find it never optimal to deleverage to $D_{t+1} < D_t$ when they believe the aggregate debt falls below D_t. It ensures that each individual's Euler equation at time t never holds with a positive value of μ_t, similar to a capital control policy that eliminates crises in Schmitt-Grohé and Uribe (2021). This is similar to an optimal policy with state-contingent commitment studied by Bianchi and Coulibaly (2024) in that the central bank lets private agents know of all possible tax rates of $\mathcal{T}(D_{t+1}, D_t)$ under different values of D_{t+1} in advance. It prevents the coordination failure of private agents, and they never find it optimal to borrow up to the borrowing limit. This result shares the same intuition with Burnside et al. (2004) that the government's liquidity provision that is not funded by seigniorage revenues can eliminate the self-fulfilling crisis.

While the capital control policy in (38) seems to dominate the DNDF policy rules such as (33), it is crucial that the central bank has to announce a menu of tax rates contingent to all possible values of D_{t+1} in advance to eliminate the crisis. The self-fulfilling crisis cannot be averted when the central bank cannot announce such preemptive state-contingent rule and has to commit to one value of τ_t throughout the period. Hence, the DNDF policy can be preferred over the capital controls by the central bank from a realistic perspective when it cannot provide a complete menu of tax rates to any possible choice of debt D_{t+1} today.

5 Concluding Remarks

In this paper, we provide evidence of the effect that the DNDF policy had on the Mexican Peso in the midst of the heightened exchange rate volatility in 2017. We show that the announcement of the policy appreciated the peso and it was successful in reducing the exchange rate volatility. Subsequent announcements regarding extensions to the program by the central bank had more muted effects and we do not find a statistically significant effect associated with the implementation of the policy. In terms of the option-implied volatility for different maturities, we show that the announcement had a larger effect on shorter maturities and the effect diminishes as the maturity of the financial instrument increases. To rationalize these findings, we introduce the central bank's provision of forward contracts into a small open economy model with a borrowing constraint. We show that the DNDF policy can reduce the severity of a self-fulfilling currency crisis when appropriately used. We leave the normative analysis of an optimal DNDF policy and its comparison to other commonly used FX intervention tools such as capital controls, foreign reserves accumulation, or exchange rate regimes as a potential avenue for future research.

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Appendix A Bank of Mexico Press Release

"On February 21, 2017, the Foreign Exchange Commission, composed of officials from the Ministry of Finance and Bank of Mexico, which is responsible for Mexico's foreign exchange policy, announced the implementation of a new foreign exchange market mechanism, which consists of non-deliverable forward (NDF's) auctions, which will be settled in *Mexican Pesos*. The mechanism aims to maintain the proper functioning of the local exchange market while supplying market participants with a foreign exchange hedging instrument to mitigate exposure to FX risk. The most important operational details of the mechanism are summarized below:

1. The program can size up to 20 billion US dollars taking into consideration the total nominal amount outstanding.
2. The maximum tenor of the NDF's will be 12 months.
3. Since the settlement of the forward is non-deliverable, the stock of international reserves is unaffected by the sale of these instruments.
4. Only local banks that can operate derivatives are allowed to present tenders for these instruments.
5. Auctions will be interactive, will last two minutes, and the allotment will be done at multiple price.
6. Bank of Mexico will roll over the total amount outstanding of the NDFs until the Foreign Exchange Commission deems it necessary.
7. The first auction will take place on March 6, 2017, for a total notional amount of one billion USD distributed along six maturities.

On March 6, 2017, the first Foreign Exchange hedge auction was held, for an amount of one billion USD divided into six terms."

Appendix B Synthetic Control Method

Let $\mathbb{Y}_1$ be a vector of dimension $(T \times 1)$ that contains the outcome variable of interest for Mexico with $1 \leq T_0 < T$ where T_0 denotes the number of pre-intervention periods and let $\mathbb{Y}_0$ be a matrix of dimension $(T \times J)$ that has the same outcome variable for the countries in the donor pool. In addition, let $\mathbb{X}_1$ denote a vector of dimension $(K \times 1)$ with K different predictors of the outcome variable for Mexico and let $\mathbb{X}_0$ denote a matrix of dimension $(K \times J)$ with the same predictors for the J countries in the donor pool. Also, let $\mathbb{W}$ be a vector of weights of dimension $(J \times 1)$ and $\mathbb{V}$ a diagonal matrix with non-negative values of dimension $(K \times K)$.

The objective of the method is to find the weights $\mathbb{W}^\star$ that allow us to match the pre-treatment characteristics of the treated unit. In other words, we need to solve the following minimization problem:

$$\min_{\mathbb{W} \in \mathcal{W}} ||\mathbb{X}_1 - \mathbb{X}_0\mathbb{W}||_{\mathbb{V}}^2 = \min_{\mathbb{W} \in \mathcal{W}} (\mathbb{X}_1 - \mathbb{X}_0\mathbb{W})^T \mathbb{V} (\mathbb{X}_1 - \mathbb{X}_0\mathbb{W}), \tag{B.1}$$

where

$$\mathcal{W} = \left\{ (w_2, \ldots, w_{J+1}) \middle| w_j \geq 0 \text{ and } \sum_{j=2}^{J+1} w_j = 1 \right\},$$

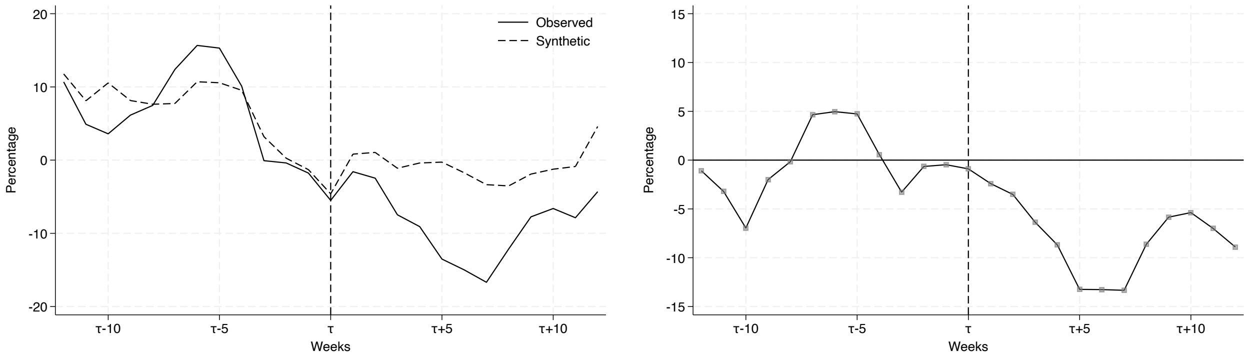
is the set of all non-negative weights that sum up to one. From the previous optimization problem, we can see that the solution for the weight vector will depend on our choice of the symmetric and positive semidefinite matrix $\mathbb{V}$. As in Abadie and Gardeazabal (2003), we choose the value of $\mathbb{V}$ such that it minimizes the mean squared prediction error of the outcome variable for the pre-intervention period:

$$\mathbb{V}^\star = \underset{\mathbb{V} \in \mathcal{V}}{\arg\min} (\mathbb{Z}_1 - \mathbb{Z}_0\mathbb{W}^\star(\mathbb{V}))^T (\mathbb{Z}_1 - \mathbb{Z}_0\mathbb{W}^\star(\mathbb{V})), \tag{B.2}$$

where $\mathbb{Z}_1$ is a vector of dimension $(T_0 \times 1)$ that contains the pre-treatment observations of the outcome variable for the treated unit (i.e., Mexico), $\mathbb{Z}_0$ is a matrix of dimension $(T_0 \times J)$ with the observations of the outcome variable for the J countries in the donor pool in the pre-intervention sample, and $\mathcal{V}$ is the set of all non-negative diagonal matrices. The optimal weights are then given by $\mathbb{W}^\star = \mathbb{W}^\star(\mathbb{V}^\star)$ and, thus, the synthetic counterfactual is given by $\mathbb{Y}_0\mathbb{W}^\star$. Then, we say that the estimator of the treatment effect is given by:

$$\hat{\alpha}_t = Y_{1,t} - \sum_{j=2}^{J+1} w_j^\star Y_{j,t} \quad \text{for } t \in \{T_0 + 1, \ldots, T\}. \tag{B.3}$$

As an alternative to using the HP-filtered exchange rate as the outcome variable, we construct a synthetic counterfactual using the three-month percentage change in the exchange rate as the outcome variable. Figure B1A displays the comparison between the observed three-month percentage change in the exchange rate and the synthetic counterfactual, while figure B1B presents the dynamic treatment effect. Also, in Table B1 we present the comparison between the pre-treatment characteristics of the treated unit, the synthetic control, and the ones associated with a simple average.



(A) Observed and synthetic

(B) Estimated treatment effect

Note: The solid line corresponds to the observed outcome variable while the dashed line is the synthetic control. τ corresponds to the week in which the policy was announced by the Bank of Mexico. Countries with strictly positive weights are: Brazil ($w_2^\star = 43.0\%$), Turkey ($w_3^\star = 48.10\%$), and India ($w_4^\star = 8.90\%$).

FIGURE B1. 3-month Percentage Change of the Nominal Exchange Rate

Variables	Observed	Synthetic	Average
3 month option-implied volatility	15.14	15.10	9.47
Stock returns	-1.20	2.96	3.84
Risk-reversal	2.02	2.99	1.83
Equity flows by MF and ETFs	18.42	64.66	-0.80
Equity flows by II.	26.54	73.07	12.19
Bond flows by MF and ETFs	49.32	34.47	10.22
Bond flows by II.	48.21	34.89	16.75
Outcome variable at $t = 1$	10.69	11.78	4.85
Outcome variable at $t = T_0/2$	15.67	10.70	2.56
Outcome variable at $t = T_0 - 1$	-1.77	-1.30	-2.66

Note: This table displays the pre-treatment mean of the predictors of the outcome variable (i.e., the three-month percentage change in the nominal exchange rate). The pre-treatment sample goes from December 1, 2016, to February 16, 2017. MF and ETF stand for mutual funds and exchange-traded funds, respectively. T_0 corresponds to the week of the announcement.

TABLE B1: Percentage Change in the Exchange Rate Predictor Means

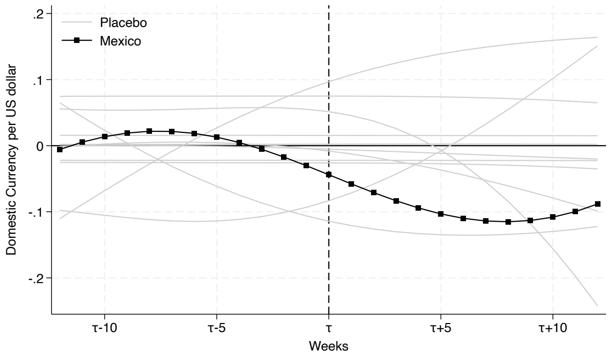
As it is standard in the literature that uses the synthetic control method, we conduct placebo tests following Abadie et al. (2010) by moving Mexico to the donor pool and estimating the synthetic control for the other countries. From the placebo runs we can evaluate the relative "rarity" of the treatment effect in Mexico and argue about the treatment's economic and statistical significance. On the one hand, panel B2A from Figure B2 displays the dynamic treatment effect (i.e., the difference between the observed and synthetic outcome variable) for countries with a pre-treatment Root Mean Squared Prediction Error (RMSPE) of, at most, 5 times the pre-treatment RMSPE of Mexico. The ratio is defined as:

$$Ratio_j = \frac{\sqrt{\frac{1}{T-T_0}\sum_{t=T_0+1}^{T}(Y_{j,t}-\hat{Y}_{j,t})^2}}{\sqrt{\frac{1}{T_0}\sum_{t=0}^{T_0}(Y_{j,t}-\hat{Y}_{j,t})^2}}, \tag{B.4}$$

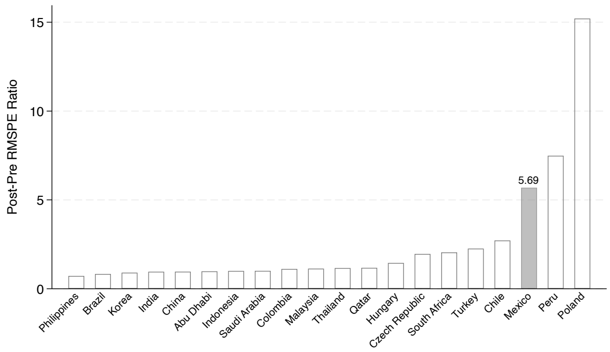
where $\hat{Y}_{j,t}$ corresponds to the synthetic counterfactual for country j. After the announcement of the policy, Mexico displays one of the largest treatment effects. On the other hand, panel B2B displays the post-pre treatment RMSPE ratio using the trend exchange rate as the outcome variable for Mexico and all countries in the donor pool, where we can observe that Mexico has one of the highest ratios, meaning that estimating a gap of the magnitude of the one of Mexico under a random permutation of the intervention is around 15%.

Regarding the estimates using the three-month percentage change in the USD/MXN nominal exchange rate, in panel B3A from Figure B3, we display the placebo runs for all countries in the donor pool. In this case, Mexico has the largest treatment effect reaching a 10 pp difference between the observed and synthetic outcome variable; however, the pre-treatment fit is worse than the one observed from the baseline estimation where we use the trend exchange rate as the outcome variable. In terms of statistical significance, panel B3B displays the corresponding post-pre-treatment RMSPE ratio. Relative to the baseline estimates, we find that the effect loses statistical significance since the probability of estimating a gap of the magnitude of Mexico under a random permutation of the intervention is around 33%.

Finally, Figure B4 displays the placebo runs for all countries in the donor pool for each maturity h of the implied volatility of USD/MXN exchange rate options. In terms of the members of the donor pool, we dropped Colombia and South Africa since, for some maturities, there are missing observations. Instead of 19 countries in the donor pool, we now have 17. We can see that, for very short maturities and near the end of the post-treatment sample, Mexico is in the tail of the empirical treatment distribution. That effect dissipates as we increase the maturity of the financial derivative. Also, we observe that the estimated effect takes more than 3 months to disappear.



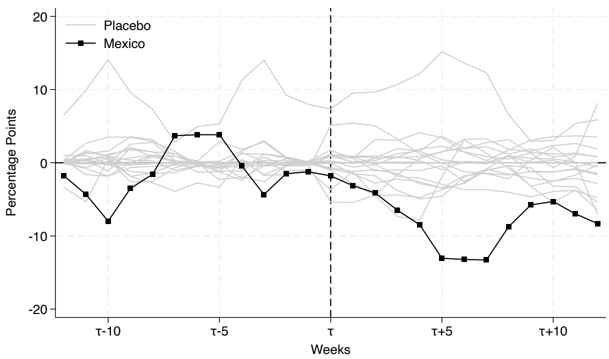
(A) Placebo runs



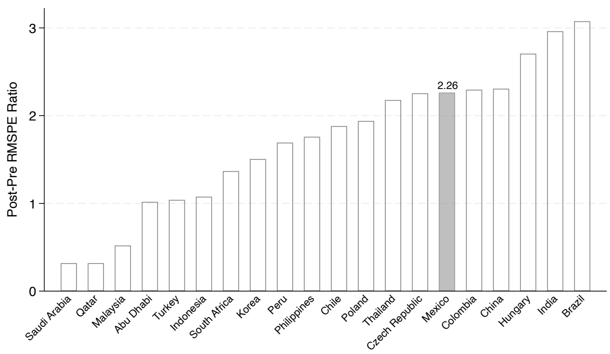
(B) Post-Pre-Treatment RMSPE Ratio

Note: The first panel displays the dynamic treatment effect for countries with a pre-treatment RMSPE of at most 5 times the pre-treatment RMSPE of Mexico. The bars represent the post-pre-treatment RMSPE for Mexico and all other countries in the donor pool.

FIGURE B2. Economic and Statistical Significance for Baseline Estimation



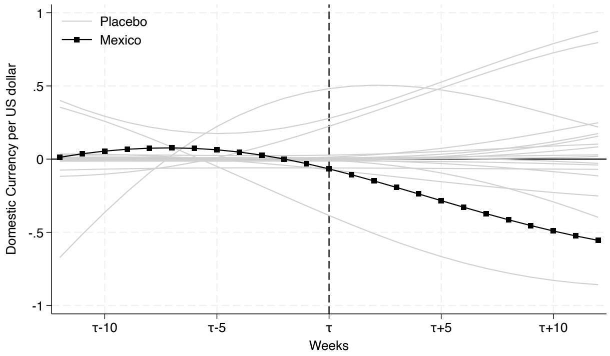
(A) Placebo runs



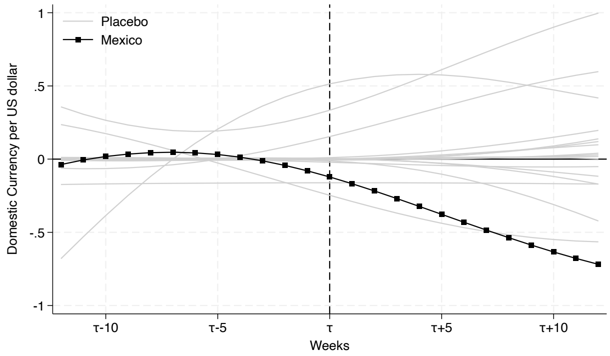
(B) Post-Pre-Treatment RMSPE Ratio

Note: The first panel displays the dynamic treatment effect for all countries in the donor pool. The bars represent the post-pre-treatment RMSPE for Mexico and all other countries in the donor pool.

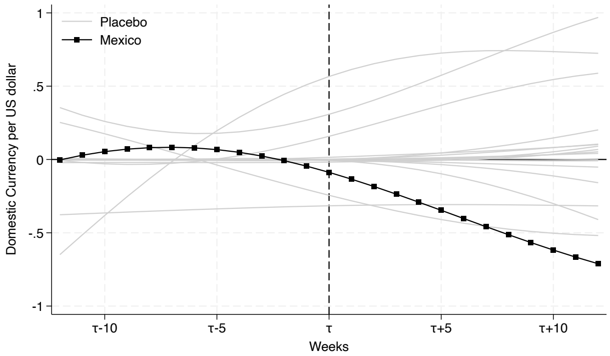
FIGURE B3. Economic and Statistical Significance for Alternative Outcome Variable



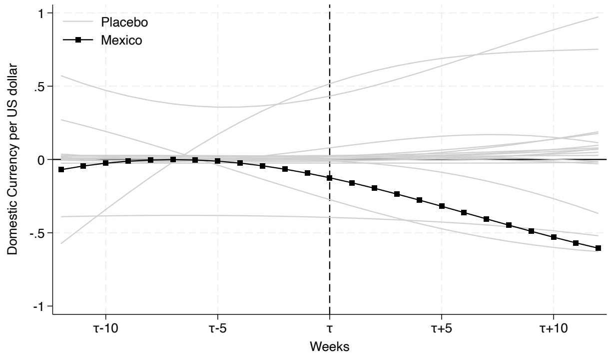
(A) 1 Week



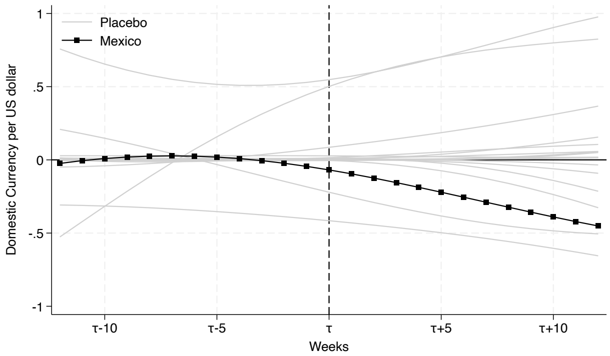
(B) 2 Weeks



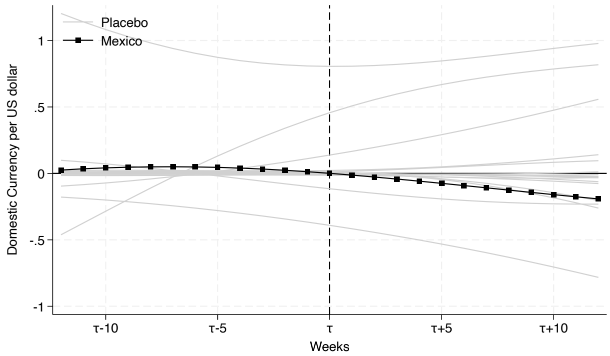
(C) 1 Month



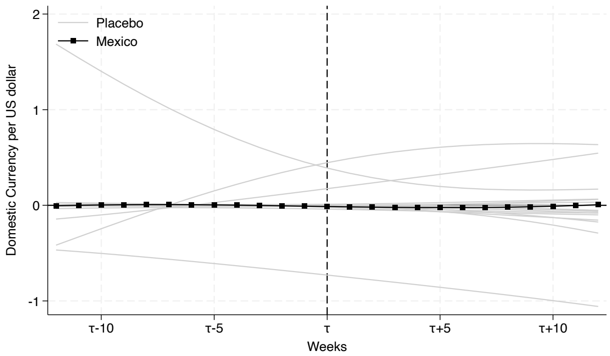
(D) 2 Months



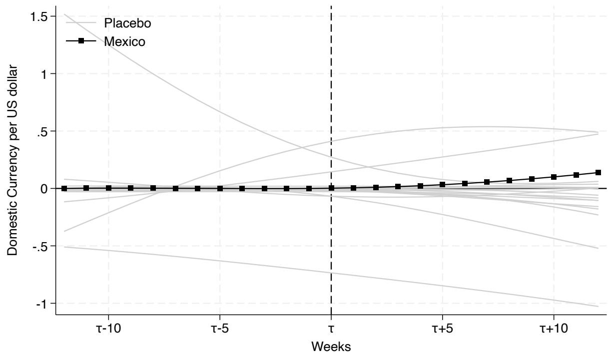
(E) 3 Months



(F) 6 Months



(G) 9 Months



(H) 1 Year

Note: Each panel displays the dynamic treatment effect for all countries in the donor pool using as outcome variable the implied volatility for horizon h. Relative to the donor pool from the baseline estimation, we drop Colombia and South Africa given missing observations for some of the maturities.

FIGURE B4. Placebo Runs for Implied Volatility

Appendix C Proofs and Derivations

C.1 Proof of Remark 1

We assume $u(c_t) = \log(c_t)$ and $v(x_t) = \chi \log x_t$ for simplicity. Under such parametrization, the money demand equation in time t satisfies

$$\frac{\chi}{\overline{M}} = \left(\frac{u_T\left(c_t^T, \left(\frac{1-\phi}{\phi}\frac{e_t}{w_{t-1}}\right)^{\gamma} c_t^T\right)}{e_t} \right) - \frac{1}{R} \times \left(\frac{u_N(y^T - (1-\beta)D_{t+1}, \overline{h})}{w_{t-1}} \right), \tag{D.1}$$

for $h_t < \overline{h}$. Recall that $c_t^T = y^T + \frac{D_{t+1}}{R} - D_t + \frac{e_t - e}{e_t}\theta D_t$. Total differentiation of (D.1) with respect to e_t and D_{t+1} yields

$$1 - \frac{e_t}{e_{t+1}}\frac{R-1}{R}\frac{1-\gamma}{\gamma}(1-\mu_t)^2\tilde{\phi}_t = \frac{de_t}{dD_{t+1}}\frac{Rc_t^T}{e_t}\left[-(1-\gamma)\tilde{\phi}_t - \gamma - \frac{e}{e_t}\frac{\theta D_t}{c_t^T}\right], \tag{D.2}$$

Since the forward rate policy we consider here satisfies $f_t = e_{t+1}$, we can also write the money demand equation as

$$\frac{\chi}{\overline{M}} = \left(1 - \frac{1-\mu_t}{R}\frac{e_t}{e_{t+1}}\right) \times \left(\frac{u_T\left(c_t^T, \left(\frac{1-\phi}{\phi}\frac{e_t}{w_{t-1}}\right)^{\gamma} c_t^T\right)}{e_t} \right), \tag{D.3}$$

so equation (D.3) and Assumption 1 imply that the left-hand side of (D.2) is positive. Hence, we have that $\frac{de_t}{dD_{t+1}} < 0$ when there is unemployment.

When there is full employment at time t, differentiating $\bar{h} = \left(\frac{1-\phi}{\phi}\frac{e_t}{w_{t-1}}\right)^{\gamma} c_t^T$ with respect to e_t and D_{t+1} yields

$$\frac{de_t}{dD_{t+1}}\frac{Rc_t^T}{e_t} = -\left[\gamma + \frac{e}{e_t}\frac{\theta D_t}{c_t^T}\right]^{-1} < 0, \tag{D.4}$$

so the exchange rate depreciates for all values of $h_t \in [0, \overline{h}]$.

C.2 Proof of Remark 2

We first show that the private agents' Euler equation is always violated when $D_{t+1} > D_t - \frac{e_t - e}{e_t}\theta D_t$. The Euler equation at period t should satisfy

$$(1-\mu_t)u_T\left(y^T + \frac{D_{t+1}}{R} - D_t + \frac{e_t - e}{e_t}\theta D_t, h_t\right) = u_T\left(y^T - \frac{R-1}{R}D_{t+1}, \overline{h}\right), \tag{D.5}$$

for $\mu_t \geq 0$. However, even when $h_t = \bar{h}$, the Euler equation cannot be satisfied for any non-negative μ_t because $c_t^T > c_{t+1}^T$ if $D_{t+1} > D_t - \frac{e_t - e}{e_t}\theta D_t$. Also, $e_t > e$ holds by Lemma 1. Hence, we have

$$h_t = \left(\frac{1-\phi}{\phi}\frac{e_t}{w_{t-1}}\right)^{\gamma} c_t^T > \left(\frac{1-\phi}{\phi}\frac{e}{w_{t-1}}\right)^{\gamma}\left(y^T - \frac{R-1}{R}D_t\right) = \bar{h}, \tag{D.6}$$

which violates the constraint for labor supply. Hence, this cannot constitute an equilibrium. Thus, a sunspot equilibrium exists only if $D_{t+1} < D_t - \frac{e_t - e}{e_t}R\theta D_t$.

C.3 Derivation of Properties of Equilibrium Borrowing Limit (34)

Recall that the equilibrium borrowing limit can be written as

$$\bar{d}(D_{t+1}; D_t) = \kappa R\left(y^T + \left(\frac{1-\phi}{\phi}\right)^{\gamma}\left(\frac{w_t}{e_t}\right)^{1-\gamma}\left(y^T + \frac{D_{t+1}}{R} - (1-\theta)D_t - \frac{e}{e_t}\theta D_t\right)\right). \tag{D.7}$$

A crisis equilibrium exists if $\bar{d}(D_{t+1}; D_t) = D_{t+1}$ for $D_{t+1} < D_t - \frac{e_t - e}{e_t}R\theta D_t$ and $c_t^T = y^T + \frac{D_{t+1}}{R} - D_t + \frac{e_t - e}{e_t}\theta D_t > 0$. First, we show that $\bar{d}(D_{t+1}; D_t)$ is an increasing function of D_{t+1} by

$$\frac{\partial \bar{d}(D_{t+1}; D_t)}{\partial D_{t+1}} = \kappa\left(\frac{1-\phi}{\phi}\right)^{\gamma}\left(\frac{w_t}{e_t}\right)^{1-\gamma}\left(1 + \left(\gamma - 1 + \frac{e}{e_t}\frac{\theta D_t}{c_t^T}\right)\frac{de_t}{dD_{t+1}}\frac{Rc_t^T}{e_t}\right) > 0, \tag{D.8}$$

because $\frac{de_t}{dD_{t+1}} < 0$ and

$$1 > \frac{de_t}{dD_{t+1}}\frac{Rc_t^T}{e_t}\left[-\tilde{\phi}_t - \gamma(1-\tilde{\phi}_t) - \frac{e}{e_t}\frac{\theta D_t}{c_t^T}\right] > \frac{de_t}{dD_{t+1}}\frac{Rc_t^T}{e_t}\left[1 - \gamma - \frac{e}{e_t}\frac{\theta D_t}{c_t^T}\right], \tag{D.9}$$

by (D.2). However, the sign of the second derivative of $\bar{d}(D_{t+1}; D_t)$ is indeterminate and depends on the value of θ.

Also, the borrowing limit decreases in the initial debt D_t as we have

$$\frac{\partial \bar{d}(D_{t+1}; D_t)}{\partial D_t} = -\kappa R\left(\frac{1-\phi}{\phi}\right)^{\gamma}\left(\frac{w_t}{e_t}\right)^{1-\gamma}\frac{(1 + (1-\gamma)\tilde{\phi}_t)\left(1 - \frac{e_t - e}{e_t}\theta\right)}{1 - (1-\gamma)(1-\tilde{\phi}_t) + \frac{e}{e_t}\frac{\theta D_t}{c_t^T}} < 0. \tag{D.10}$$

Hence, a threshold level $\underline{D}$ of self-fulfilling crisis exists if $\bar{d}(D_{t+1}; D_t)$ is a convex function of D_{t+1}, and the crisis does not take place if the initial debt is below $\underline{D}$. In this case, $\underline{D}$ satisfies $\left.\frac{\partial \bar{d}(D_{t+1}; D_t)}{\partial D_t}\right|_{D_t = \underline{D}} = 1$ which implies

$$-\kappa R\left(\frac{1-\tilde{\phi}_t}{\tilde{\phi}_t} + (1-\gamma)(1-\tilde{\phi}_t)\right)\left(1 - \theta + \frac{e}{e_t}\theta\right) - \tilde{\phi}_t - \gamma(1-\tilde{\phi}_t) = \frac{e}{e_t}\frac{\theta \underline{D}}{c_t^T}, \tag{D.11}$$

and D_{t+1} and c_t^T satisfy

$$\frac{D_{t+1}}{R} = \frac{\kappa}{\tilde{\phi}_t - \kappa(1-\tilde{\phi}_t)}\left(y^T - (1-\tilde{\phi}_t)\left(1-\theta+\frac{e}{e_t}\theta\right)\underline{\mathrm{D}}\right), \tag{D.12}$$

$$c_t^T = \frac{\tilde{\phi}_t + \kappa\tilde{\phi}_t}{\tilde{\phi}_t - \kappa(1-\tilde{\phi}_t)}y^T - \frac{\tilde{\phi}_t}{\tilde{\phi}_t - \kappa(1-\tilde{\phi}_t)}\left(1-\theta+\frac{e}{e_t}\theta\right)\underline{\mathrm{D}}, \tag{D.13}$$

while the exchange rate is determined by (10) under a constant money supply $\overline{M}$.

C.4 Proof of Remark 3

By Lemma 2 of Bianchi and Coulibaly (2024), the crisis equilibrium at period t implies unemployment with $h_t < \bar{h}$, so we have

$$u_T\left(y^T + \frac{D_{t+1}}{R} - D_t, h_t(D_{t+1}, D_t)\right) < u_T\left(y^T + \frac{D_{t+1}}{R} - D_t, \bar{h}\right) \tag{D.14}$$

with as the tradables and nontradables are complements. Then the central bank can pick $\mathcal{T}(D_{t+1}, D_t)$ to satisfy

$$u_T\left(y^T + \frac{D_{t+1}}{R} - D_t, \bar{h}\right) = (1+\mathcal{T}(D_{t+1}, D_t))\, u_T\left(y^T - \frac{R-1}{R}(1+\mathcal{T}(D_{t+1}, D_t))\, D_{t+1}, \bar{h}\right), \tag{D.15}$$

so that the Euler equation (36) at period t never holds with a positive μ_t. Such capital control policy is continuous in D_{t+1} because $\lim_{D_{t+1}\to D_t} \mathcal{T}(D_{t+1}, D_t) = 0$, trivially.