The Sovereign Default Risk of Giant Oil Discoveries*

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Abstract

I document that sovereign spreads significantly increase following giant oil field discoveries. This is puzzling from the point of view of canonical sovereign default models because spreads in these models decrease when future income increases—which is consistent with countercyclical spreads in the data. To reconcile existing theory with this novel observation, I develop a sovereign default model with production and oil discoveries. Financial frictions and technology generate an endogenous default penalty that varies across sectors. I discipline the model using data from Mexico and find that the oil sector is significantly less exposed to these endogenous costs of sovereign default. This allows the model to successfully generate the puzzling responses to giant oil discoveries while jointly matching other standard business cycle regularities that are explained by standard models.

Keywords: Sovereign risk, oil discoveries, news shocks.

JEL Codes: F34, F41.

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1 Introduction

Between 1970 and 2012, sixty-four countries discovered at least one giant oil field, and fourteen of these countries had a default episode in the following ten years.[1] This paper studies how these discoveries impact sovereign risk and debt accumulation.

I build on the work of Arezki, Ramey, and Sheng (2017), who document the effects of giant oil field discoveries on macroeconomic aggregates. These discoveries can be interpreted as news of higher future income since there is an average gap of 5.4 years between a discovery and when production on the field starts. Following a discovery, countries experience a current account deficit which reverts around the time when the field becomes productive. This is consistent with the permanent income hypothesis, since an increase in GDP is only observed after production on the field starts. Following their methodology, I estimate the effect of discoveries on the sovereign spreads and I find that it is large and positive: they increase by up to 1.2 percentage points following a discovery of median size. In addition, I document that government consumption and borrowing also increase following a discovery, while private consumption remains mostly unchanged.

These joint responses of spreads and government borrowing are puzzling from the point of view of standard sovereign default theory for two reasons. First, government borrowing increases despite the higher cost. In the data—and in standard models—government borrowing increases when spreads are low, not high. Second, spreads increase following oil discoveries, which are large and positive shocks to income. In the data, spreads are countercyclical and default events happen when output is relatively low. A key assumption for standard models to replicate these co-movements is an output cost of default that is asymmetrically increasing with income (see the discussion in Arellano (2008) and the literature thereafter). If all output were subject to the same increasing costs from an eventual default then news of an oil discovery would reduce default incentives and spreads. In fact, they increase in the data.

This evidence suggests that income from the oil sector may have different effects on default incentives than income from other sources, which stresses the importance of a detailed theory of the real cost of default. There is ample literature that argues how disruption in financial markets are at the core of GDP contractions and productivity losses during default episodes and sovereign

[1] A giant oil field contains at least 500 million barrels of ultimately recoverable oil. "Ultimately recoverable reserves" is an estimate (at the time of the discovery) of the total amount of oil that could be recovered from a field.

debt crises (see Reinhart and Rogoff (2011), Bocola (2016), Arellano, Bai, and Bocola (2017)). I develop a quantitative sovereign default model with oil discoveries, firms that face financial frictions, and production in different sectors that reconciles existing theory with the responses of spreads to oil discoveries from the data. Default in the model causes an endogenous efficiency loss as the economy gets excluded from international credit markets. This is because firms in the model require working capital to purchase a subset of imported inputs, so when access to credit markets is disrupted these inputs are replaced by domestic and other imported imperfect substitutes. This core mechanism of the model builds on the production structure and financial fictions developed by Mendoza and Yue (2012), but allows for technology and working-capital needs to differ across sectors. I calibrate the model to Mexico, which is a typical small-open economy widely studied in the sovereign debt and emerging markets literature. Using data from Mexico's input-output matrix, I document that the oil sector uses less intermediate inputs than the rest of the economy and that a smaller share of these are imported. Another advantage of using Mexico as a calibration benchmark is that oil extraction is mostly done by a large government-run firm, which was a constitutionally sanctioned monopoly between 1938 and 2014. This allows me to use financial statements from this firm to directly discipline the oil sector's reliance on working capital, which also turns out to be smaller than in the rest of the economy.

The differences in technology and financing requirements imply that the oil sector is less exposed to the efficiency losses that stem from the credit disruptions that come with default events. Thus, when the relative size of the oil sector increases—as is the case after a giant oil discovery—a larger share of consumption is financed with a source of income that is less affected by a potential default, effectively lowering the utility loss of defaulting at any given state. Default incentives and spreads increase, while the relatively large size of oil discoveries increases borrowing to front-load consumption despite its higher costs. This is how the model successfully generates the puzzling responses to giant oil discoveries while jointly matching other business cycle regularities, the latter driven by standard productivity shocks. As in the data, the oil sector in the model is operated by a government-owned company. The main results, however, are not dependent on this assumption, as I show that they remain unchanged in an alternative model with the oil sector run by private firms. The key mechanism relies on the differences in technology and financing needs that shape the sector's exposure to the real costs of default, not on who operates it.

Finally, I explore the welfare implications of oil discoveries under different scenarios. In the benchmark model average gains are 7.74 percent, expressed in consumption equivalent units. These are large, but small compared to the average increase in government consumption of 16 percent. Interestingly, the gains are smaller if domestic private firms operate the oil sector. This is because now total consumption benefits from the relatively lower cost of default, as opposed to these lower costs only benefiting government consumption in the benchmark model. Selling the oil field to foreigners yields gains almost as high as in the benchmark case because the sale reduces default incentives for future governments, who would otherwise receive higher oil rents that are immune to the costs of defaulting.

Related literature.—This paper contributes to the quantitative sovereign default literature following Aguiar and Gopinath (2006) and Arellano (2008), which extend the approach developed by Eaton and Gersovitz (1981). They introduce models that feature countercyclicality of net exports and interest rates, which are consistent with the data from emerging markets. This paper presents evidence of a relatively rare, but large, income shock that has an opposite relationship with spreads. The main contribution is to reconcile standard sovereign default theory with this finding. Importantly, I show that this can be done by building on the canonical model of the real cost of default in general equilibrium developed by Mendoza and Yue (2012).

This paper is closely related to Hamann, Mendez-Vizcaino, Mendoza, and Restrepo-Echavarria (2023). They study the relationship between oil exports, proved oil reserves, and sovereign risk. There are three key differences between their and my empirical work. The first has to do with the magnitude of the shocks that are studied. By definition, proved reserves do not immediately incorporate giant oil discoveries and the size of their year-to-year changes is much smaller.[2] The second is that, unlike changes to proved reserves, giant oil field discoveries are less frequent and less prone to strategic control by the government. The third is that the data on oil discoveries in my paper allow for a quasi-natural experiment approach to identify their effect. The different nature of the shocks and their economic implications motivate a different theoretical approach as well. They develop a model in which the dynamics of existing reserves interact with sovereign risk through the government's strategic decision to manage said reserves (in their model, reserves act as an implicit form of capital that is controlled by the government). In contrast, the model that

[2] See Appendix A for a detailed discussion of the differences between these measures.

I develop in Section 3 features large oil discoveries whose size and occurrence are not controlled by the government and have a lag between discovery and production. My model focuses on how differences in technology and financial frictions across sectors affect overall default incentives. In a related paper, Drechsel and Tenreyro (2018) study the role of fluctuations in international commodity prices on business cycles in commodity exporters. They develop a small-open economy model in which these fluctuations affect both the competitiveness of the economy and its borrowing terms, as higher commodity prices are associated with lower spreads between the country's borrowing rate and world interest rates. The nature of the shocks they study is different from the oil discoveries that I study in two dimensions. First, commodity prices are driven by high-frequency shocks, while oil discoveries are relatively rare. Second, the sign of the correlation between commodity prices and sovereign spreads is negative, while it is positive for that between spreads and oil discoveries.

This paper also contributes to the literature that studies the role of news as drivers of business cycles (see Beaudry and Portier (2014), Jaimovich and Rebelo (2008), and Arezki, Ramey, and Sheng (2017)). The model in Section 3 builds on the work in these papers and connects it with the sovereign default literature. In a related paper, Dvorkin, Sanchez, Sapriza, and Yurdagul (2020) study the effects of news shocks about future productivity on sovereign default risk and also develop a sovereign default model that connects with the news-in-business-cycles literature. They find that these productivity news shocks have a larger contemporaneous impact on spreads than a comparable shock to labor productivity and study their implications for the optimal management of debt maturity. The oil discoveries that I study have similarly large effects but the opposite sign, which drives my focus on the key mechanism driving this puzzling behavior.

Layout.—Section 2 presents the empirical analysis and discusses the evidence that motivates the theoretical framework. Section 3 presents the model. Section 4 performs the quantitative analysis. Section 5 concludes.

2 Sovereign spreads and oil discoveries

In this section, I document that sovereign spreads and government borrowing in emerging economies increase following giant oil discoveries. I use a simple quantitative model of sovereign default with oil discoveries to illustrate why these responses are puzzling and potential drivers of the co-movements. Then, in the following section, I present a richer model with production that reconciles both the novel empirical findings with the business cycle regularities of emerging economies.

2.1 Data

The data on giant oil field discoveries in the world was collected by Horn (2014) and the Global Energy Systems research group at Uppsala University. The size of a newly discovered oil field is measured by its "ultimately recoverable reserves" (URR), which is an estimate (at the time of the discovery) of the total volume of oil that could be recovered from a field. An oil field is considered "giant" if it contains at least 500 million barrels of URR. The data in Horn (2014) include all giant oil field discoveries in the world between 1960 and 2012.

To estimate the effects of discoveries on macroeconomic variables, I build on the work by Arezki, Ramey, and Sheng (2017), who construct a measure of the net present value (NPV) of oil discoveries relative to the GDP of the country where the discovery happened. They construct this measure as follows:[3]

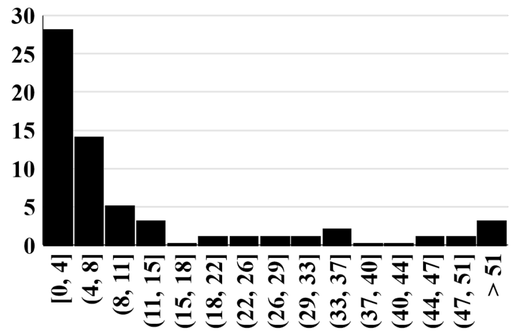
$$NPV_{i,t} = \frac{\sum_{j=5}^{J} \frac{q_{i,t+j}}{(1+r_i)^j}}{GDP_{i,t}} \times 100 \tag{1}$$

where $q_{i,t+j}$ is the annual gross revenue in year $t+j$ from the field discovered in country i in period t, r_i is the annual discount rate for country i, and $GDP_{i,t}$ is annual GDP of country i at year t. The authors use country-specific risk-adjusted discount rates r_i, which are calculated using the relationship between the average of sovereign spreads over a long period, available for a small set of emerging countries, and an index of political risk ratings, available for a wider set of countries. This implies that the $NPV_{i,t}$ measure discounts flows more for countries where political risk is high on average. The sum in the numerator starts at 5 because there is a time delay of 5.4 years on average between a discovery and the start of production in the data. The annual gross revenue $q_{i,t+j}$ is derived from an approximated production profile that starts five years after the announcement of the discovery and up to an exhaustion year J, which is greater than 50 years for a typical giant oil field. Appendix B of Arezki, Ramey, and Sheng (2017) presents a detailed explanation of the

[3] For more details on the construction of the NPV see Section IV.B. in Arezki, Ramey, and Sheng (2017).

approximation of the production profile $q_{i,t+j}$ based on data on existing oil fields at different stages of exhaustion and on details on the process of extraction.[4] What is essential is that the calculation of $q_{i,t+j}$ is scaled by the size of the discovery in therms of its URR.

Figure 1: Distribution of NPV of giant oil discoveries



Percent of GDP, EMBI countries, 1993 –2012. The largest discovery in the sample was in Kazakhstan in 2000 with a NPV of 467.

There are 37 emerging economies with sovereign spreads data in JP Morgan's Emerging Markets Bonds Index (EMBI), which starts in 1993.[5] Considering these economies and the years 1993–2012, there are 61 giant oil field discoveries in 15 of the 37 countries. The average and median NPV were 18 and 4.5 percent of GDP, respectively. Figure 1 depicts the distribution of the NPV of these discoveries.

Following the empirical strategy described below, I estimate the effect of giant oil discoveries on sovereign spreads, GDP, the current account, net government debt, and private and government consumption. All macroeconomic data are from the World Development Indicators (WDI) database collected by the World Bank except for net government debt, which is from the Fiscal Monitor Database constructed by the IMF.

2.2 Empirical strategy

Giant oil discoveries have two unique features that allow for the use of a quasi-natural experiment approach to identify their effect. First, while policy and oil prices may drive exploration decisions,

[4] Another important assumption that the authors make regarding gross revenues $q_{i,t+j}$ is that the price of oil remains the same for the subsequent years after an oil discovery. This assumption is made for convenience because projecting future oil prices is complicated and oil prices are highly persistent in the data, with a behavior similar to that of a random walk.

[5] The 37 countries are: Argentina, Belize, Brazil, Bulgaria, Chile, China, Colombia, Dominican Republic, Ecuador, Egypt, El Salvador, Gabon, Ghana, Hungary, Indonesia, Iraq, Jamaica, Kazakhstan, Republic of Korea, Lebanon, Malaysia, Mexico, Pakistan, Panama, Peru, Philippines, Poland, Russian Federation, Serbia, South Africa, Sri Lanka, Tunisia, Turkey, Ukraine, Uruguay, Venezuela, and Vietnam.

the actual timing of discoveries is exogenous due to uncertainty around oil and gas exploration. Second, there is a time delay of 5.4 years on average between discovery and production.[6] This significant delay allows the treatment of giant oil discoveries as news shocks about higher future income.

Following Arezki, Ramey, and Sheng (2017), I estimate the effect of giant oil discoveries using a dynamic panel model with a lag of discovery sizes:

$$y_{i,t} = \rho y_{i,t-1} + \sum_{s=0}^{10} \psi_s NPV_{i,t-s} + \alpha_i + \mu_t + \xi' X_{i,t} + \varepsilon_{i,t} \tag{2}$$

where $y_{i,t}$ is the dependent variable; $NPV_{i,t}$ is the discounted net present value of a discovery in country i in year t; α_i controls for country fixed effects; μ_t are year fixed effects; $X_{i,t}$ is a vector of additional control variables; and $\varepsilon_{i,t}$ is the error term.[7]

The vector $X_{i,t}$ includes contemporaneous and up to ten lags of the interaction $\mathbb{I}_{\text{disc},i,t-s} * \log p_{oil,t}$, where $\log p_{oil,t}$ is the natural logarithm of the international price of oil in year t and $\mathbb{I}_{disc,i,t-s}$ is an indicator function of whether country i had an oil discovery in period $t-s$. These interaction terms allow the response of $y_{i,t}$ to the price of oil to vary after a discovery in anticipation of higher oil income in the near future. In addition, the vector $X_{i,t}$ includes the term $R^{oil}_{i,1993} * \Delta \log p_{oil,t}$, where $\Delta \log p_{oil,t}$ is change in the natural logarithm of the international price of oil from period $t-1$ to t and $R^{oil}_{i,1993}$ are oil rents as a percentage of GDP for country i at the beginning of the sample. This controls for shocks to the price of oil scaled by the sector's relative importance in each economy in 1993, predating all discoveries in the sample of spreads.

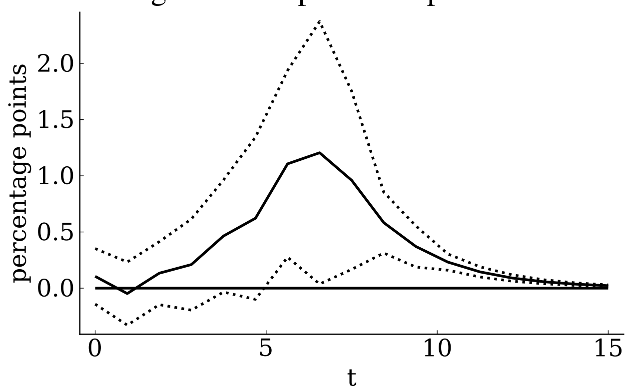
[6] Arezki, Ramey, and Sheng (2017) mention that experts' estimates suggest that it takes between four and six years for a giant oil discovery to go from drilling to production. They also made their own calculation and found that the average delay between discovery and production is 5.4 years.

[7] Following Arezki, Ramey, and Sheng (2017), I include country-specific quadratic trends for the regressions of variables $y_{i,t}$ that are non-stationary in the sample. These are GDP, private and government consumption, and spreads. For the first three variables the Im-Pesaran-Shin test (Im, Pesaran, and Shin (2003)) fails to reject the null hypothesis that all panels contain a unit root. The test rejects the null for spreads, but the augmented Dickey-Fuller test (Dickey and Fuller (1979)) on each individual time series of spreads rejects a unit root on only 8 of the 37 series, so out of an abundance of caution I also control for country-specific quadratic trends in this regression.

2.3 The puzzling response of spreads and borrowing

Response in the data.—Figure 2 shows the impulse-response function of spreads to an oil discovery of median size (4.5 percent of GDP).[8] Following a discovery, spreads steadily increase and, by the sixth year after the discovery was announced, the increase peaks at 1.2 percentage points.[9]

Figure 2: Response of spreads



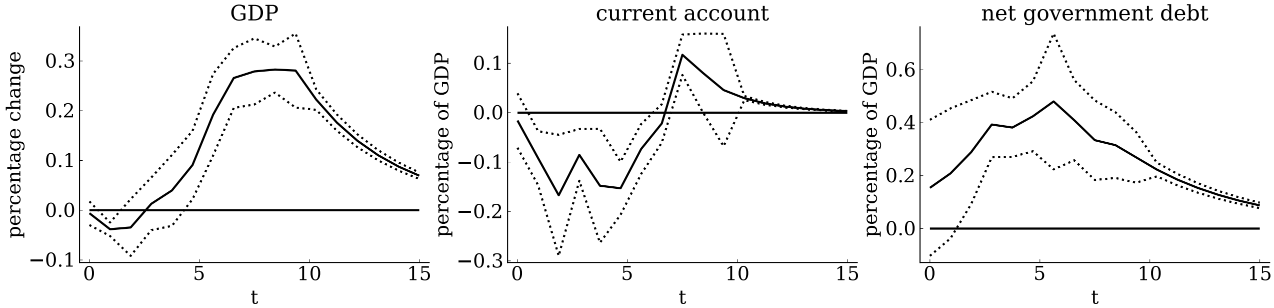
Impulse response to an oil discovery with net present value equal to the median size of 4.5 percent of GDP. The dotted lines indicate 90 percent confidence intervals based on a Driscoll and Kraay (1998) estimation of standard errors, which yields standard error estimates that are robust to general forms of spatial and temporal clustering.

As documented by Arezki, Ramey, and Sheng (2017), the behavior of other macroeconomic aggregates in the data following an oil discovery is consistent with the permanent income hypothesis in an open economy: the economy runs a current account deficit to increase consumption given the higher present value of income, which reverts once the higher income is realized.

[8]Impulse-response functions are computed as $\Delta y_{i,t} = \rho \Delta y_{i,t-1} + \sum_{s=0}^{10} \psi_s NPV_{i,t-s}$ using the estimated coefficients of equation (2).

[9]As documented by Hamann, Mendez-Vizcaino, Mendoza, and Restrepo-Echavarria (2023), the dynamics of proved oil reserves have a significant impact on the evolution of credit worthiness of emerging economies who are oil exporters. Appendix A.1 presents robustness checks for the regression of spreads in which I control for contemporaneous and up to ten lags of the natural log of proved oil reserves $res_{i,t}$ at year t in country i. The results are robust to these controls.

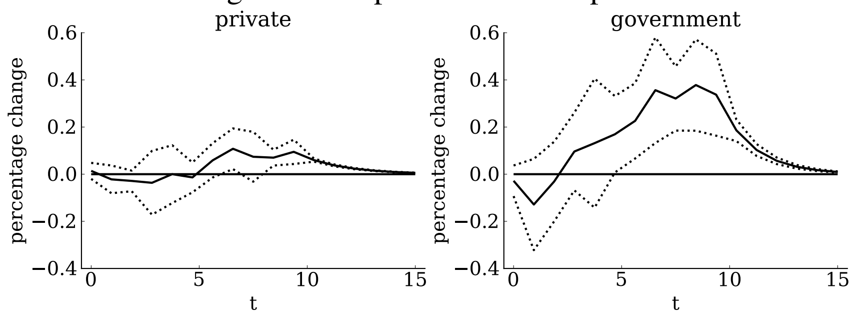
Figure 3: Response of GDP, current account, and government debt



Impulse response to an oil discovery with net present value equal to the median size of 4.5 percent of GDP. The dotted lines indicate 90 percent confidence intervals based on a Driscoll and Kraay (1998) estimation of standard errors, which yields standard error estimates that are robust to general forms of spatial and temporal clustering.

Figure 3 replicates this part of their analysis and also shows the estimated response of government debt, which increases despite the higher spreads.[10] In fact, oil discoveries mostly fuel an increase in government consumption, while the effect on private consumption is negligible as shown in Figure 4.[11]

Figure 4: Response of consumption



Impulse response to an oil discovery with net present value equal to the median size of 4.5 percent of GDP. The dotted lines indicate 90 percent confidence intervals based on a Driscoll and Kraay (1998) estimation of standard errors, which yields standard error estimates that are robust to general forms of spatial and temporal clustering.

Response in the canonical model.—Quantitative models of sovereign default perform very well in reproducing the dynamics of borrowing and default risk in emerging economies. As noted by Arellano (2008), and the literature thereafter, a crucial assumption is that the economy suffers a real default penalty that is asymmetric and increasing in output. This assumption, along with

[10]These estimates use all the available years and countries considered in Arezki, Ramey, and Sheng (2017). Restricting the sample to only the 37 emerging economies in the EMBI yields qualitatively similar, albeit noisier, estimates. These are reported and discussed in Appendix A.2.

[11]Arezki, Ramey, and Sheng (2017) also document an increase in aggregate investment. Toews and Vézina (2022) and Sheng and Zhao (2024) further investigate these effects on investment and show that the increase is mostly driven by Foreign Direct Investment flows. As discussed below, what is key to understanding the response of spreads is the implications of oil discoveries on the cost of default in terms of consumption, regardless of who operates the oil firms. Thus, I abstract from analyzing any form of capital accumulation for simplicity.

persistent output shocks, generates cycles of low spreads and high borrowing when income is high, and capital outflows accompanied by high spreads or default crises when income is low. The response of spreads documented above is puzzling from the point of view of these models because a giant oil discovery is a large positive shock to future income that would reduce default incentives in such a model.

To illustrate this, consider the model in Arellano (2008) augmented with oil income and discoveries. Since I use this model for illustrative purposes, I present here a minimal description of the environment and relegate additional details to Appendix B. There is a small-open economy populated by a household with preferences for consumption represented by $\mathbb{E}_0\left[\sum_{t=0}^{\infty}\beta^t u\left(c_t\right)\right]$ and a benevolent government that makes borrowing and default decisions. Each period, the economy receives an income endowment z_t and oil rentsR_t^{oil}. Oil rents can take two values

$$R_t^{\text{oil}} = R^{\text{oil}}\left(n_t\right) = \begin{cases} R_L^{\text{oil}} & \text{if } n_t \leq T_{\text{wait}} \\ R_H^{\text{oil}} & \text{if } n_t = T_{\text{wait}}+1, \end{cases} \tag{3}$$

where $R_L^{\text{oil}} < R_H^{\text{oil}}$ and $n_t \in \{-1,0,1,...,T_{\text{wait}},T_{\text{wait}}+1\}$ indicates how many periods have passed since a giant oil field was discovered. The variable n_t follows a Markov chain with transition probability matrix

$$P = \begin{bmatrix} 1-\pi_{\text{disc}} & \pi_{\text{disc}} & 0 & \cdots & \cdots & 0 \\ 0 & 0 & 1 & 0 & \cdots & 0 \\ 0 & 0 & 0 & \ddots & 0 & 0 \\ 0 & 0 & 0 & \cdots & 1 & 0 \\ 0 & 0 & 0 & \cdots & 0 & 1 \\ \pi_{\text{ex}} & 0 & 0 & \cdots & 0 & 1-\pi_{\text{ex}} \end{bmatrix}, \tag{4}$$

where π_{disc} is the probability of discovery of a giant oil field and π_{ex} is the probability of exhaustion. This formulation captures the delay between discovery and production that is observed in the data. The government issues one-period non-contingent debt and cannot commit to repay it. Debt is purchased by risk-neutral international investors who behave competitively and consider the government's default incentives when pricing the debt. When the government is in good financial standing the resource constraint of the economy is

$$c_t + b_t = y_t + q_t b_{t+1}, \tag{5}$$

where q_t is the market price of government debt and $y_t = z_t + R_t^{\text{oil}}$ is total income. If the government defaults then it is excluded from financial markets for a stochastic number of periods and consumption equals total income in default

$$c_t = y_t^{def}, \tag{6}$$

where $y_t^{def} = h_z(z_t) + h_{oil}\left(R_t^{\text{oil}}\right)$. As discussed in Arellano (2008), the following functional form for h_z generates an asymmetric income cost of default that allows the model to generate procyclical borrowing and countercyclical spreads:

$$h_z(z_t) = \begin{cases} z_t & \text{if } z_t \leq \mu_z \kappa_z \\ \mu_z \kappa_z & \text{if } z_t > \mu_z \kappa_z, \end{cases} \tag{7}$$

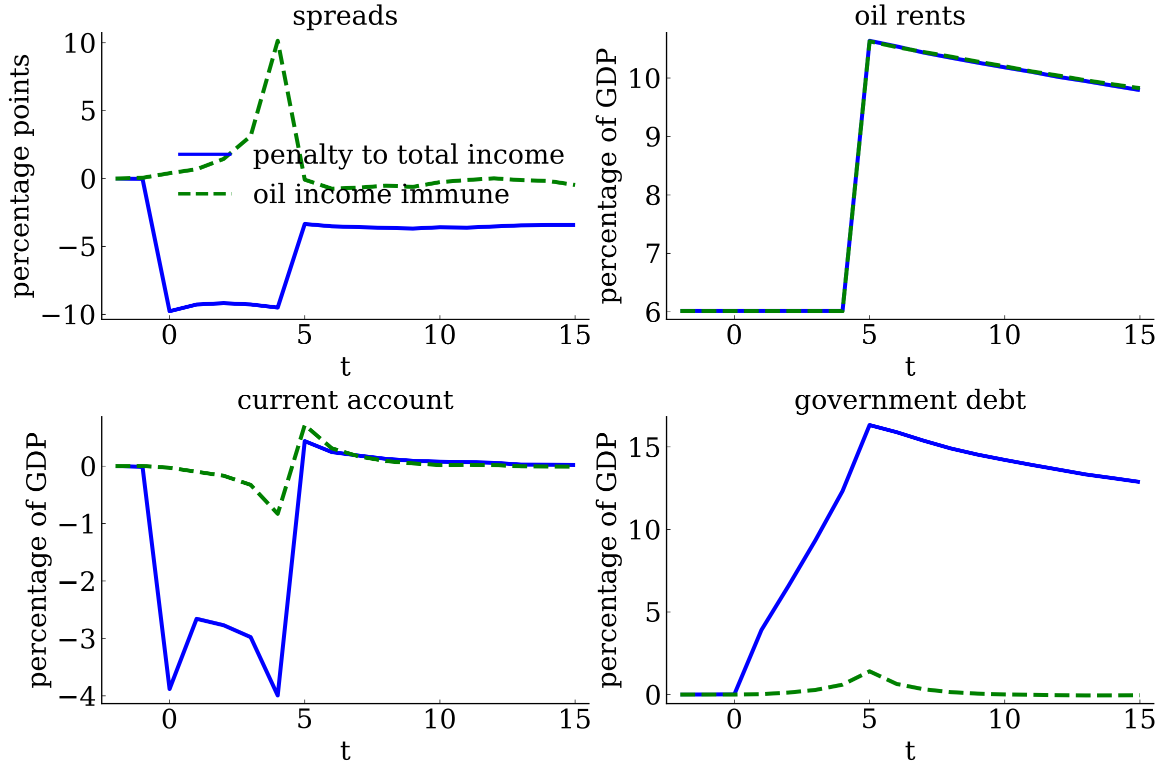
where μ_z is the mean value of z_t and $\kappa_z > 0$ controls the severity of the default penalty. For h_{oil} I consider two cases: one in which income from oil rents are equally penalized in default

$$h_{oil}^{Bench}\left(R_t^{\text{oil}}\right) = \begin{cases} R_t^{\text{oil}} & \text{if } R_t^{\text{oil}} = R_L^{\text{oil}} \kappa_{oil} \\ R_L^{\text{oil}} \kappa_{oil} & \text{if } R_t^{\text{oil}} > R_L^{\text{oil}} \kappa_{oil}, \end{cases} \tag{8}$$

which I refer to as the "canonical model", and one in which they are immune to the default penalty $h_{oil}^{Immune}\left(R_t^{\text{oil}}\right) = R_t^{\text{oil}}$. I calibrate the model using the parameter values from Arellano (2008) and setting $R_L^{\text{oil}} = 0.06$ and $R_H^{\text{oil}} = 0.08$, so that oil rents are roughly 6 and 8 percent of average GDP in each regime.[12] Then, I simulate 10,000 oil discoveries in both economies and compute the average paths of spreads, the current account, and government debt around them. Figure 5 presents the changes in these variables relative to the period before a discovery.

[12] The details of this calibration are in Appendix B.

Figure 5: Average responses to oil discoveries



Each time series considers 10,000 economies in their ergodic state without any oil discoveries since $t = -50$. The lines are the difference between the values in each period and the values in period t_{-1}.

The top-right panel presents the evolution of oil rents, which is by construction identical in both cases. Importantly, when the oil discovery happens in period 0 there is certainty that income will be higher in period 5, so the responses of the current account and government debt are in line with the permanent income hypothesis: the government borrows to front-load consumption given that income in the future will be higher.[13] The stark difference is in the response of spreads. Spreads in the canonical model sharply decrease because the potential penalty of defaulting when $R_5^{\text{oil}} = R_H^{\text{oil}}$ is much higher. The government takes advantage of these more favorable borrowing terms and increases its borrowing by a larger amount. Once $R_5^{\text{oil}} = R_H^{\text{oil}}$ then spreads increase slightly due to the risk of the oil field being exhausted, but they remain lower than before the discovery despite the higher borrowing. This is the prediction from the canonical model that is at odds with the data.

The alternative model in which oil income is immune to the default penalty generates a response of spreads that is in line with the data, while also generating an increase in borrowing, al-

[13] The magnitudes are different because the responses correspond to two different environments with the exact same parameter values. What is important is the direction of the responses: an increase in the current-account deficit and in the stock of government debt.

though smaller due to the higher cost from the increase in spreads. The following section presents a richer model in which the default penalty emerges endogenously as a result of financial frictions. Differences in technology and financing requirements in the oil sector imply a relatively small effect of default on oil production, which allows the model to reconcile the responses of spreads to oil discoveries with standard business cycle statistics.

3 Model

The model builds on Mendoza and Yue (2012), who develop a general equilibrium model of both sovereign default and business cycles with endogenous production. Some imported inputs require working capital financing and default triggers an asymmetric efficiency loss when these inputs are replaced by imperfect substitutes as the economy gets excluded from credit markets. I incorporate an oil sector that faces the same financial frictions as the rest of the economy, but allow for the parameters that control its financing needs and technology to be different. In the quantitative analysis in Section 4 I discipline these differences using data for Mexico and elucidate their role in reconciling the empirical findings from Section 2 with standard business cycle statistics.

3.1 Environment

There is a small-open economy populated by a representative household, firms, and a benevolent government. There are three production sectors in the domestic economy: a sector of final goods f, a sector of domestic intermediate goods d, and an oil sector o. Oil and the final good are traded in international markets; domestic intermediates are not.

Final goods sector.—Final goods are produced by a competitive firm owned by the household using a Cobb-Douglas technology:

$$y_{ft} = z_t \left(M_f \left(m^d_{ft}, m^*_{ft} \right) \right)^{\alpha_{Mf}} \left(L_{ft} \right)^{\alpha_{Lf}} K^{\alpha_K}, \tag{9}$$

where $0 < \alpha_{Mf}, \alpha_{Lf}, \alpha_K < 1$, $\alpha_{Mf} + \alpha_{Lf} + \alpha_{Kf} = 1$, L_{ft} is labor hired by the firm for a wage w_t,

$K = 1$ is fixed, and z_t is a productivity shock that follows an AR(1) process

$$\log z_{t+1} = \rho \log z_t + \sigma_z \varepsilon_{t+1} \tag{10}$$

where ρ is a persistence parameter, and ε_t are iid and follow a standard normal distribution.[14] The function M_f is an Armington aggregator of domestic m^d_{ft} and imported m^*_{ft} materials:

$$M_f\left(m^d_{ft}, m^*_{ft}\right) = \left[\lambda_f \left(m^d_{ft}\right)^{\frac{\mu-1}{\mu}} + \left(1-\lambda_f\right)\left(m^*_{ft}\right)^{\frac{\mu-1}{\mu}}\right]^{\frac{\mu}{\mu-1}} \tag{11}$$

where $\mu > 1$ is the Armington elasticity of substitution and λ_f is the weight of domestic materials.[15]

Oil sector.—Oil is produced by a competitive firm owned by the government. This assumption is motivated by the fact that I use Mexico as a calibration benchmark, where oil production is mostly carried out by a government-run company (Petroleos Mexicanos, or PEMEX).[16] The results, however, are mostly unchanged if the oil firm is run by either domestic or foreign private firms as long as consumption in the economy benefits from revenue from oil rents (see Section 4 below). The oil firm uses technology

$$y_{ot} = z_t \left(M_o\left(m^d_{ot}, m^*_{ot}\right)\right)^{\alpha_{Mo}} \left(L_{ot}\right)^{\alpha_{Lo}} N_t^{\alpha_N} \tag{12}$$

where $0 < \alpha_{Mo}, \alpha_{Lo}, \alpha_N < 1$, $\alpha_{Mo} + \alpha_{Lo} + \alpha_N = 1$, L_{ot} is labor hired by the oil firm, and N_t denotes the size of the available oil field. The function M_o is an Armington aggregator of domestic and

[14] I abstract from capital accumulation in all sectors, including oil, out of simplicity. As discussed below, what is crucial for the model to explain the responses of spreads to oil discoveries is the oil sector's exposure to financial frictions relative to that of the rest of the economy.

[15] Estimates of the Armington elasticity of substitution between domestic and foreign goods range between 2.5 and 5.1 (see Bajzik, Havranek, Irsova, and Schwarz (2020)).

[16] Up until 2014 this company was a constitutionally-sanctioned monopoly, with an explicit prohibition of private-sector participation in oil exploration or production. In that year, the Mexican Congress reformed the Constitution to allow for private sector participation, but the industry has continued to be mostly dominated by the same government-run firm.

imported materials similar to that of the final good sector:

$$M_o\left(m_{ot}^d, m_{ot}^*\right) = \left[\lambda_o\left(m_{ot}^d\right)^{\frac{\mu-1}{\mu}} + (1-\lambda_o)\left(m_{ot}^*\right)^{\frac{\mu-1}{\mu}}\right]^{\frac{\mu}{\mu-1}}, \tag{13}$$

but with a potentially different weight of domestic materials λ_o.[17] The size of the oil field takes two values $N_t \in \{N_L, N_H\}$ with $N_L < N_H$. As with the simple model above, there is an underlying variable $n_t \in \{-1, 0, 1, ..., T_{\text{wait}}, T_{\text{wait}}+1\}$ that indicates how many periods have passed since a giant oil field was discovered so that $N_t = N_L$ when $n_t \leq T_{\text{wait}}$ and $N_t = N_H$ when $n_t > T_{\text{wait}}$. This underlying indicator variable n_t follows a Markov chain with the transition matrix described in equation 4.

Imported materials and financial frictions.—Imported inputs m_{it}^* for both $i \in \{f, o\}$ are a Dixit-Stiglitz aggregator

$$m_{it}^* = \left(\int_0^1 \left(m_{jit}^*\right)^{\frac{\nu-1}{\nu}} dj\right)^{\frac{\nu}{\nu-1}} \tag{14}$$

that combines a continuum of differentiated imported varieties m_{jit}^* for $j \in [0,1]$ with an elasticity of substitution $\nu > 1$. These inputs are purchased in international markets for prices p_j^*, which are time invariant. Following Mendoza and Yue (2012), I assume that a subset Ω_i of imported varieties needs to be paid for in advance using working capital contracted at a rate r_t^* (these credit contracts are paid within the same period). Let $d_t = 1$ denote that the government is in default and $d_t = 0$ that it is in good financial standing. When $d_t = 0$ then $r_t^* = r^*$ equals the international risk-free rate, which is fixed. When the government is in default $d_t = 1$, the entire economy looses access to global financial markets, which implies that working capital is not available for any of the firms $r_t^* = \infty$. Without loss of generality, let $\Omega_i = [0, \theta_i]$ for $\theta_i \in (0,1)$. This assumption implies that when access to Ω_i is hampered by exclusion from financial markets imported inputs do not vanish entirely, but rather firms are forced to produce using a less efficient mix. I allow for θ_f and θ_o to be different, which implies that the oil and the final good firms may face a different shadow price

[17] I assume that the Armington elasticity μ is the same in both sectors out of simplicity and because estimates that are specific for the oil sector are unavailable. As Mendoza and Yue (2012) discuss, the main mechanism in the model remains unchanged for any reasonable choice of μ, as well as for the Dixit-Stiglitz curvature parameter ν described below.

for their purchases of imported intermediates

$$P_i^*(d_t) = \left[\int_0^{\theta_i} \left((1+r_t^*)\,p_j^*\right)^{1-\nu} dj + \int_{\theta_i}^1 \left(p_j^*\right)^{1-\nu} dj\right]^{\frac{1}{1-\nu}} \tag{15}$$

where P_i^* is the standard CES price index. Importantly, allowing θ_f and θ_o to differ allows the oil sector to have different working-capital requirements than the rest of the economy.

Domestic intermediates.—Domestic intermediate goods are produced by a competitive firm owned by the households using labor and technology

$$y_{dt} = A\,(L_{dt})^{\eta}, \tag{16}$$

where $\eta \in (0,1)$, and $A > 0$ captures the presence of fixed sectoral productivity and physical capital installed. The firm sells y_{dt} to the firms in the oil and final goods sectors for a price p_{dt}, which is determined in equilibrium.

Profits.—All firms choose production plans each period to maximize their profits:

$$\begin{aligned}
\pi_{ft} &= y_{ft} - p_{dt} m_{ft}^d - P_f^*(r_t^*)\,m_{ft}^* - w_t L_{ft} \\
\pi_{ot} &= p_{ot} y_{ot} - p_{dt} m_{ot}^d - P_o^*(r_t^*)\,m_{ot}^* - w_t L_{ot} \\
\pi_{dt} &= p_{dt} y_{dt} - w_t L_{ot},
\end{aligned}$$

where π_{ft}, π_{ot}, and π_{dt} are the profits of the final good firm, the oil firm, and the domestic intermediates firm, respectively. The price of the final good is the nummeraire and I assume that the price of oil is fixed $p_{ot} = 1$ for simplicity.[18]

Household.—The household has preferences represented by $\mathbb{E}_0\left[\sum_{t=0}^{\infty} \beta^t u(c_t, g_t, L_t)\right]$, where

[18]Modeling the behavior of the price of oil is a difficult task because of the inherent characteristics of the world market for oil (see Bornstein, Krusell, and Rebelo (2022)). Equation 12 assumes that the oil sector is exposed to the same productivity shock z_t as the rest of the economy. Incorporating exogenous shocks to the price of oil (consistent with the small-open economy assumption) would imply that oil income depends on the product $\tilde{z}_{ot} = z_t p_{ot}$, which is isomorphic to assuming a separate productivity shock to the sector. Drechsel and Tenreyro (2018) develop a small-open economy model in which commodity prices and spreads co-move in a similar fashion as productivity shocks and spreads do. They find that shocks to commodity prices account for a significan share of business cycle fluctuations in emerging economies. Since the purpose of this paper is not to disentangle the role of different shocks (like productivity and oil prices) on driving business cycles, I abstract from these details and let all high-frequency fluctuations (i.e. period by period in the model) to be driven by the single productivity shock z_t.

$\beta \in (0,1)$ is the discount factor, c_t is private consumption of the final good, g_t is government consumption of the final good, and L_t is labor supplied to the domestic firms. The period utility is

$$u(c,g,L) = \frac{\left(c - \frac{L^{1+\frac{1}{\omega}}}{1+\frac{1}{\omega}}\right)^{1-\sigma} - 1}{1-\sigma} + \psi_g \frac{g^{1-\sigma_g} - 1}{1-\sigma_g}, \tag{17}$$

where σ and σ_g are the CRRA parameters for private and government consumption, respectively, ω is the Frisch elasticity of labor supply, and ψ_g is a utility weight on government consumption. I follow Greenwood, Hercowitz, and Huffman (1988) in removing the wealth effect on labor supply by specifying a utility that depends on private consumption net of labor disutility, which is a standard assumption in open-economy business cycle models. The budget constraint of the household is

$$c_t \leq (1-\tau)\left[w_t L_t + \pi_{ft} + \pi_{dt}\right], \tag{18}$$

where τ is an income tax collected by the government.

Government debt and default.—For simplicity, I assume τ is fixed, which is consistent with low-frequency changes in income tax rates. The government issues long-term, non-contingent bonds b_t in international financial markets. Following Hatchondo and Martinez (2009) and Chatterjee and Eyigungor (2012) I assume that bonds mature probabilistically at a rate γ. The law of motion of bonds is:

$$b_{t+1} = (1-\gamma)\, b_t + i_{b,t} \tag{19}$$

where $i_{b,t}$ is the amount of bonds issued in period t. When the government is in good financial standing, its budget constraint is

$$g_t + \gamma b_t \leq \tau\left[w_t L_t + \pi_{ft} + \pi_{dt}\right] + \pi_{ot} + q_t i_{b,t}, \tag{20}$$

where q_t is the price of government debt that is purchased by risk-neutral competitive foreign investors. If the government defaults then the economy is excluded from financial markets and regains access with probability ϕ. As is standard, I assume that the government reenters financial markets with no debt. The government's budget constraint in default it is

$$g_t \leq \tau \left[w_t L_t + \pi_{ft} + \pi_{dt}\right] + \pi_{ot}. \tag{21}$$

3.2 Recursive formulation and equilibrium

The state of the economy is (b,x), where $x = (z,n,d)$. Before defining the recursive problem of the government, it is worth noting that the government is the only agent that faces a dynamic problem (choosing b_{t+1}) so the following definition becomes useful.

Static equilibrium.—Given $x = (z,n,d)$, a *static equilibrium* is allocations for the household $\{c,L\}$ allocations for the final good firm $\left\{y_f, L_f, m_f^d, m_f^*\right\}$, allocations for the oil firm $\{y_o, L_o, m_o^d, m_o^*\}$, allocations for the domestic intermediate firm $\{y_d, L_d\}$, and prices $\{p_d, w\}$ such that: (i) given the prices, the allocations for the firms maximize their profits; (ii) the labor supply satisfies the household's first-order condition $L = ((1-\tau)w)^{\omega}$; (iii) private consumption satisfies

$$c = (1-\tau)\left[y_f - m_f^* P_f^*(d) + wL_o\right];$$

and (iv) the prices $\{p_d, w\}$ are such that the markets for labor and the domestic intermediate clear:

$$\begin{aligned} L_f + L_d + L_o &= L \\ m_f^d + m_o^d &= y_d. \end{aligned}$$

As mentioned above, the shadow price of imported intermediates $P_f^*(d)$ depends on the default status. Also, to simplify notation, I omitted the dependence of these equilibrium objects on x, which will be explicit in what follows.

The value of the government at the beginning of a period in good financial standing is

$$V(b,z,n) = \max_{d\in\{0,1\}} \left\{dV^D(z,n) + (1-d)V^P(b,z,n)\right\} \tag{22}$$

where its value in repayment is

$$V^P(b,z,n) = \max_{g,b'} \left\{ u(c(x),g,L(x)) + \beta \mathbb{E}\left[V\left(b',z',n'\right)\right]\right\} \tag{23}$$

$$\begin{aligned} s.t. \qquad & g + \gamma b \leq \tau \left[y_f(x) - m_f^*(x) P_f^*(0) + w(x) L_o(x) \right] + \pi_{ot}(x) + q\left(b',z,n\right)\left[b' - (1-\gamma) b\right] \\ & \pi_{ot}(x) = y_o(x) - m_o^*(x) P_o^*(0) - w(x) L_o(x) \\ & x = (z,n,0) \end{aligned}$$

and its value in default is

$$V^D(z,n) = u(c(x),g,L(x)) + \beta\phi\mathbb{E}\left[V\left(0,z',n'\right)\right] + \beta(1-\phi)\mathbb{E}\left[V^D\left(z',n'\right)\right] \tag{24}$$

$$\begin{aligned} s.t. \qquad & g = \tau \left[y_f(x) - m_f^*(x) P_f^*(1) + w(x) L_o(x) \right] + \pi_{ot}(x) \\ & \pi_{ot}(x) = y_o(x) - m_o^*(x) P_o^*(1) - w(x) L_o(x) \\ & x = (z,n,1). \end{aligned}$$

Note that the government takes as given the static equilibrium, which only depends on the realized shocks and on the government's default decision. Now we can define the recursive equilibrium in a standard fashion.

Recursive equilibrium.—A *recursive equilibrium* is value and policy functions V, V^P, V^D, d, b^P, g for the government, and a price schedule q such that: (i) given q, the value and policy functions solve equations 22, 23, and 24; and (ii) the price schedule is such that lenders break even in expectation

$$q\left(b',z,n\right) = \frac{\mathbb{E}\left[d\left(b',z',n'\right)\left[\gamma + (1-\gamma) q\left(b'',z',n'\right)\right]\right]}{1+r^*}, \tag{25}$$

where $b'' = b^P(b',z',n')$ is the government's debt issuance in the following period given (b',z',n').

3.3 Discussion

The model features two costs from defaulting: temporary financial autarky and inefficient allocations of imported intermediate goods. The first is exogenous and triggers the second endogenously through the working-capital requirements implied by the financial friction. Let the price of all imported varieties be $p_j^* = 1$ for all j. Then, the shadow price of the bundle of imported intermediates in good standing and default is, respectively:

$$P_i^*(d=0) = \left[\theta_i (1+r^*)^{1-\nu} + (1-\theta_i)\right]^{\frac{1}{1-\nu}}$$
$$P_i^*(d=1) = (1-\theta_i)^{\frac{1}{1-\nu}},$$

and it is clear that $P_i^*(d=0) < P_i^*(d=1)$ as long as $\nu > 1$ (which holds by assumption). The inability to purchase the intermediate goods in Ω_i implies a less efficient aggregation of m_i^*, which is reflected in a higher shadow price in default. All else equal, the oil and final good firms demand fewer imported materials which implies lower quantities of all other production inputs (since the Armington aggregator and Cobb-Douglas technologies are homothetic). This is the mechanism developed by Mendoza and Yue (2012) through which output drops endogenously in default. Moreover, they show that this drop is larger for high realizations of z_t due to "strong" convexity of the Cobb-Douglas production function.

In the model presented above, the degree to which production in each sector is affected by this endogenous default penalty depends on three parameters: θ_i, which controls the sector's working-capital requirements; $1-\lambda_i$, which controls the relative importance of imported intermediate goods; and α_{Mi}, which controls the relative importance of the aggregate intermediate bundle M_i. In the following section, I discipline these parameters using data from Mexico's input-output matrix and the financial statements of the government-run oil firm. The data show that $\theta_o < \theta_f$, $1-\lambda_o < 1-\lambda_f$, and $\alpha_{Mo} < \alpha_{Mf}$. Thus, relative to the rest of the economy, the oil sector requires less working capital to purchase intermediate inputs, it uses a smaller share of imported materials, and intermediate goods comprise a smaller share of oil output. Overall, these differences in technology and financial frictions imply that the oil sector is less affected by default than the rest of the economy, which allows the model to explain the data as the simple model in Subsection 2.3 suggests.

4 Quantitative analysis

I solve numerically for the equilibrium using value function iteration. Following Hatchondo, Martinez, and Sapriza (2010), I compute the limit of the finite-horizon version of the economy using a non-linear optimization routine to solve for the borrowing decision in every state. I approximate value functions and the price schedules for debt using linear interpolation, and compute expectations over the productivity shock using a Gauss-Legendre quadrature.

4.1 Calibration

I calibrate the model to the Mexican economy. There are two reasons why Mexico is an ideal example. First, Mexico has been widely studied in the sovereign debt literature because its business cycle has the same properties as other emerging economies (see for example Aguiar and Gopinath (2007), and Aguiar, Chatterjee, Cole, and Stangebye (2016)). As noted by Bianchi, Hatchondo, and Martinez (2018), Mexico gives calibration targets for average levels of debt and spreads that are close to the median value for emerging economies. In short, Mexico is a typical emerging economy so the calibration allows the model to shed light on the average results from Section 2. Second, Mexico had a series of giant oil discoveries during the 1970s, the largest in 1977 and 1979 with roughly 21 and 12 million of URR, which imply NPV values of roughly 50 percent of Mexico's GDP each. Five years later, in 1982, Mexico defaulted on its debt. This is an example of the main dynamics studied in this paper.

A period in the model is one year and I mostly follow the calibration strategy in Mendoza and Yue (2012). There are two sets of parameters: the first (summarized in Table 1) is calibrated directly and the second (summarized in Table 2) is chosen using the simulated method of moments (SMM) to target a set of moments from the data. I set the CRRA parameters to $\sigma = \sigma_G = 2$, and the risk free interest rate to $r^* = 0.04$, which are standard values in the sovereign default literature. The Frisch wage elasticity is $\omega = 2.2$, which is a value typically used in RBC models of small open economies (see Mendoza (1991), Neumeyer and Perri (2005), and Mendoza and Yue (2012)). The probability of reentry to financial markets is $\phi = 0.25$ for an average exclusion of 4 years, which is the median value reported in Gelos, Sahay, and Sandleirs (2011) for a large set of default episodes. I set the income tax rate to $\tau = 0.15$ which is the average of the tax-revenue-to-GDP ratio for Mexico, I normalize $\psi_g = 1.0$, and set the debt-maturity parameter to $\gamma = 0.05$ which gives an average debt maturity of 20 years.

Table 1: Parameters calibrated directly

Parameter		Value	Source
CRRA parameters	$\sigma = \sigma_g$	2.0	Standard value
Frisch wage elasticity	ω	2.2	Standard value
Risk-free rate	r^*	0.02	Standard value
Probability of reentry	ϕ	0.25	4-year average exclusion
Income tax rate	τ	0.15	Average tax revenue / GDP
Utility from government consumption	ψ_g	1.0	Normalization
Maturity of debt	γ	0.05	Mexico's Ministry of Finance
Share of intermediates in final sector	α_{Mf}	0.46	Mexico's I-O table
Labor share in final sector	α_{Lf}	0.14	Mexico's I-O table
Capital share in final sector	α_K	0.40	Mexico's I-O table
Share of intermediates in oil sector	α_{Mo}	0.30	Mexico's I-O table
Labor share in oil sector	α_{Lo}	0.04	Mexico's I-O table
Resource and share in oil sector	α_N	0.66	Mexico's I-O table
Armington elasticity	μ	2.9	Mendoza and Yue (2012)
Weight of domestic inputs, final sector	λ_f	0.62	Mexico's I-O table
Weight of domestic inputs, oil sector	λ_o	0.72	Mexico's I-O table
Dixit-Stiglitz curvature parameter	ν	2.44	Mendoza and Yue (2012)
Labor share for domestic intermediates	η	0.27	$\frac{\alpha_{Lf}}{\alpha_{Lf}+\alpha_{Kf}}$
Size of small oil field	N_L	0.018	Oil sector 6% of GDP
Size of giant oil field	N_H	0.033	69% increase in oil capacity
Probability of discovery	π_{disc}	0.01	Oil discoveries data
Delay between discovery and production	T_{wait}	5	Oil discoveries data
Probability of exhaustion	π_{ex}	0.02	Oil discoveries data
Persistence of z_t	ρ	0.95	Standard value
Working capital requirement for oil sector	θ_o	0.44	PEMEX financial statements

To calibrate the technology parameters I rely on Mexico's Input-Output matrix for 2018, which is disaggregated at the Subsector level using the North American Industry Classification System (NAICS). I separately consider Subsector 211, which corresponds to Oil and Gas Extraction, and the total economy minus this Subsector 211. The shares of intermediate goods in gross output are $\alpha_{Mf} = 0.46$ and $\alpha_{Mo} = 0.30$. The I-O matrix provides a further disaggregation of imported and domestic purchases of intermediates. From these data I calibrate $\lambda_f = 0.62$ and $\lambda_o = 0.72$ as the ratios of purchases of domestic intermediates to the total (both net of taxes and subsidies). I set $\alpha_{Lf} = 0.14$ and $\alpha_{Lo} = 0.04$ as the ratios of labor compensation to the value of production, and $\alpha_K = 1 - \alpha_{Mf} - \alpha_{Lf}$ and $\alpha_N = 1 - \alpha_{Mo} - \alpha_{Lo}$. The value for α_{Lf} implies a labor share on value added of 0.27, which is low relative to what it is in advanced economies but in line with other estimates of the labor share in emerging economies (for example, Karabarbounis and Neiman

(2013) estimate that the total labor share of Mexico declined from 0.38 to 0.28 between 1993 and 2011). I set the labor share in the domestic intermediates sector to be the same as in the final goods sector $\eta = 0.27$. I take the values for the Armington elasticity of substitution $\mu = 2.9$ and the Dixit-Stiglitz curvature parameter $\nu = 2.44$ from Mendoza and Yue (2012). The size of the small oil field is set to $N_L = 0.018$ so that steady-state GDP in the oil sector represents 6 percent of total GDP, which is the average long-run value for Mexico since 1993. The average giant oil discovery in the data is 3.8 billion barrels of ultimately recoverable reserves and Mexico's proven reserves are 5.5 billion barrels, so an average discovery would imply a 69 percent increase in Mexico's current oil production capacity.[19] Thus, I set $N_H = 0.033$ so that steady-state oil output is 69 percent higher than with $N_t = N_L$. The probability of a discovery is $\pi_{\text{disc}} = 0.01$, which is the probability of new discoveries in the data. The probability of exhaustion is $\pi_{\text{ex}} = 0.02$ for an average field life of 50 years. I set the persistence of the productivity shock to $\rho = 0.95$, which is a standard value (the volatility is computed as part of the SMM exercise described below).

Two of the most important parameters for this calibration exercise are the shares of imported intermediates that have to be purchased with working capital θ_f and θ_o. With respect to θ_o, the fact that oil production in Mexico is mostly dominated by a single government-run firm presents an advantage because the firm's financial statements are publicly available. I use PEMEX's audited financial statements for 2018 (the same year as the input-output matrix) and compute the ratio of debt to suppliers (reported as a part of short-term liabilities in the balance sheet) divided by the total cost of sales, which is equal to 0.12. The value for $\lambda_o = 0.72$ above implies that a fraction 0.28 of materials are imported, so assuming that only imported materials require working capital (as in the model) I get a value for $\theta_o = 0.12/0.72 = 0.44$. Note that this assumption is rather strong, but conservative from the point of view of the mechanisms in place (a lower value of θ_o would imply that the oil sector is even less affected by default). Calibrating θ_f presents challenges due to data availability. Detailed data on working capital at the aggregate level is scarce for emerging economies, which is why Mendoza and Yue (2012) set θ_f as part of the SMM exercise. I do the same.

[19] This estimate is from the OPEC annual statistical bulletin, Table 3.1.

Table 2: Parameters set with SMM

Parameter		Value	Targets: Moment	Data	Model
Standard deviation of z_t	σ_z	0.024	GDP standard deviation	3.1%	3.2%
TFP of domestic intermediates	A	0.079	Output drop in default	-13.3%	-12.7%
Discount factor	β	0.922	Average spread	2.9%	2.7%
Working capital requirement for final sector	θ_f	0.643	Private working capital / GDP	8.1%	8.3%

Moments for GDP, spreads, and working capital are computed by simulating 2,000 time series of 400 periods after trimming the first 100 without any oil discoveries and that are in good financial standing in the initial period. For the output drop in default, I simulate 2,000 time series of 20,000 periods and compute the output drop whenver a default episode happens. GDP data are applied the HP Filter with a smoothing parameter of 100.

Table 2 summarizes the SMM exercise, which consists in choosing $\left(\sigma_z, A, \beta, \theta_f\right)$ jointly to target a standard deviation of GDP of 3.1 percent, an average drop of output in default of 13.3 percent, an average spread of 2.9 percent, and a share of working capital financing in GDP of 8.1 percent. The standard deviation of GDP corresponds to the cyclical component of real GDP in local currency units after applying an HP filter with a smoothing parameter of 100 using annual data from 1960 to 2019. As mentioned above, Mexico experienced a sovereign default in August 1982. The log deviation in 1983 from the pre-default linear trend is -0.133 (Arellano (2008) and Mendoza and Yue (2012) report a similar drop for the Argentinean default of 2001). The average spread is from the EMBI data used in Section 2 for the years between 1997 and 2019. Finally, I follow Schmitt-Grohe and Uribe (2007) and proxy working capital in the private sector as the fraction of M1 held by firms with an estimate for the U.S. that shows firms own about two-thirds of M1. Using Mexico's M1 data and the same two-thirds I get a target of 8.1 percent (Mendoza and Yue (2012) get 6 percent for Argentina).

4.2 Results

This section presents the main quantitative results for the benchmark model and uses two alternative models to disentangle the role of the differences in technology and working capital requirements. One is a version of the model that does not distinguish between aggregate and government consumption $\psi_g = 0$. This version is closer to the canonical sovereign debt model in which the benevolent government makes all choices on behalf of its constituents and has direct access to the resource constraint. As can be seen in the analyses that follow, this version of the model is closer to the data under certain metrics, but cannot address the differences in the response of government and private consumption by construction. The other alternative version of the model also has $\psi_g = 0$ and assumes that the oil sector has the same technology and working-capital requirements as the rest of the economy (i.e. $\alpha_{Mo} = \alpha_{Mf}$, $\alpha_{Lo} = \alpha_{Lf}$, $\lambda_o = \lambda_f$, and $\theta_o = \theta_f$). Comparing these two alternative models is akin to the comparison made with the simple model in Section 2. To make them comparable to the benchmark, I recalibrate $\left(\sigma_z, A, \beta, \theta_f\right)$ following the same SMM approach described above.

Business-cycle moments.—Table 3 reports untargeted business-cycle moments from the data and the different versions of the model. The benchmark model performs well in replicating most of the untargeted Mexican business-cycle co-movements. The long-run default probability and volatility of spreads are smaller than their data counterparts.[20] This is because the available data for spreads correspond to a relatively stable period for the Mexican economy. The same is true for the model with no government consumption and different technologies for the oil and final sectors. The average of the external debt-to-GDP ratio is 0.21 in the data and roughly half of that in the model. This is partly explained by the relatively small size of the government in the economy and the assumption that there are no lump-sum taxes or transfers. Note that the models with only aggregate consumption and a consolidated resource constraint produce larger debt-to-GDP ratios of 0.49 and 0.55, which are close to the average of the total-debt-to-GDP ratio in the data of 0.47.[21] This relatively small size of the government in the benchmark model also drives a relatively small volatility of the ratios of the trade balance and the current account to GDP.[22] Consumption, both public and private, are more volatile than GDP as in the data.

[20] Mexico has defaulted five times since it gained independence in 1821. Four of these, however, were during internal military conflicts (1827, 1854, 1914, and 1928) and were not necessarily related to the government being in financial peril. The 1982 default episode is the only one that closely resembles the episodes studied in the model, so the relevant default probability may be closer to 0.51 than to 2.54 percent. This lower value is also more consistent with the available data for spreads used in the calibration, which corresponds to a more stable period between 1997 and 2019. Targeting the default probability of 2.45 percent instead of the average spreads produces higher and more volatile spreads, but does not significantly change the results regarding their response to oil discoveries.

[21] See the Historical Public Debt Database collected by the IMF. The data for the total-debt-to-GDP ratio for Mexico is for the years 1982 to 2015.

[22] The model abstracts from other important sources of external imbalances like private borrowing. Mendoza and Yue (2012) circumvent this problem by assuming an exogenous quantity of resources being traded each period. They also show that this is inconsequential to the behavior of most of the other variables, so I choose to omit them for simplicity.

Table 3: Business cycle moments

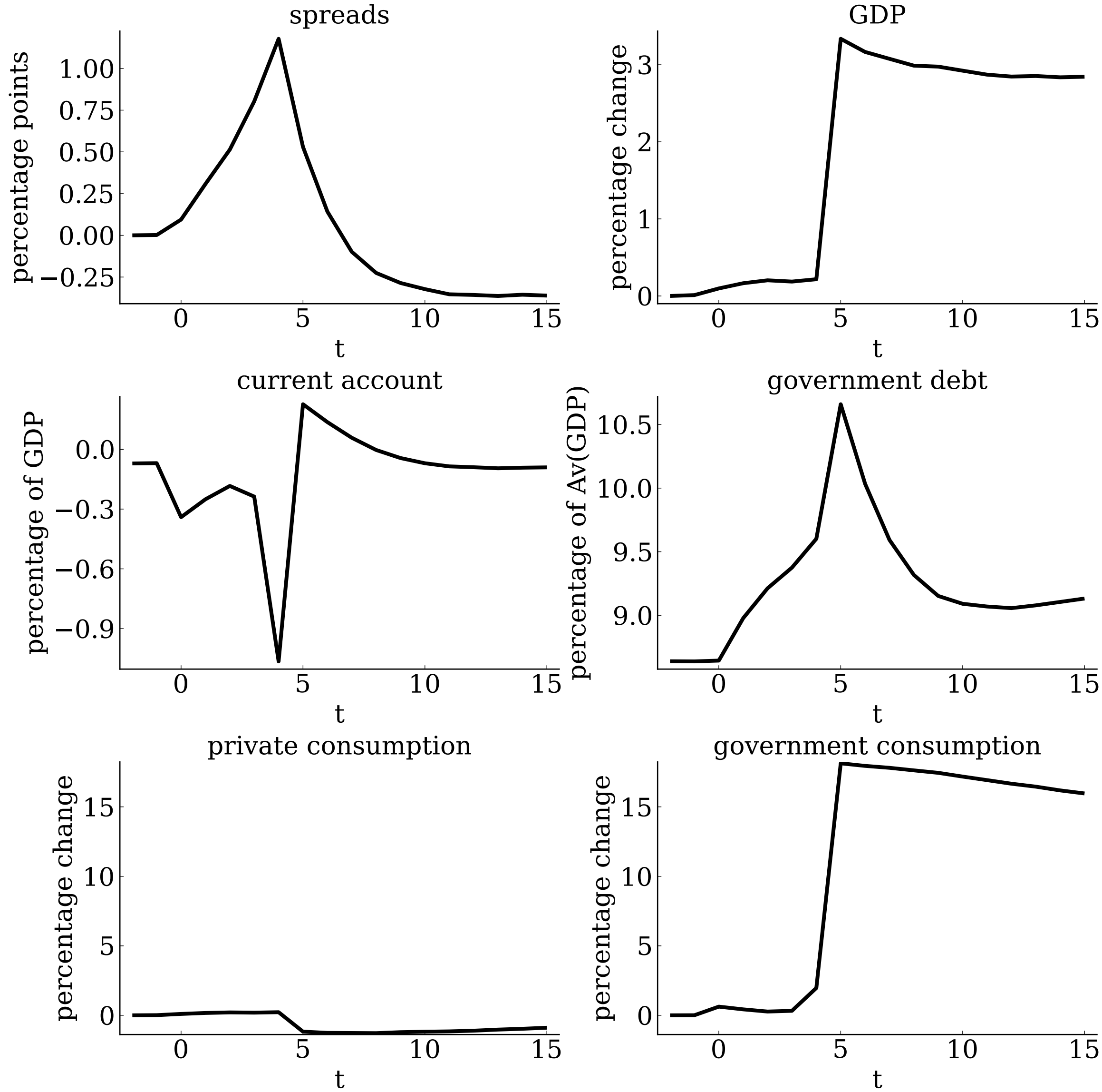
	$Pr(d=1)$	$\frac{b}{y}$	σ_{r-r^*}	$\frac{\sigma_c}{\sigma_y}$	$\frac{\sigma_g}{\sigma_y}$	$\sigma_{\frac{tb}{y}}$	$\sigma_{\frac{ca}{y}}$	$\rho_{r-r^*,y}$	$\rho_{\frac{tb}{y},y}$	$\rho_{\frac{ca}{y},y}$
data	2.45	0.21	1.4	1.45	1.05	2.57	2.14	-0.22	-0.19	-0.49
benchmark	0.76	0.09	0.92	1.02	1.03	0.13	0.37	-0.51	-0.35	-0.34
no government consumption	0.92	0.49	1.08	1.24	n.a.	1.27	2.17	-0.46	-0.28	-0.26
identical technology	1.16	0.55	1.05	1.20	n.a.	1.57	2.75	-0.46	-0.27	-0.28

Moments are computed by simulating 2,000 time series of 400 periods after trimming the first 100 without any oil discoveries and that are in good financial standing in the initial period. GDP and consumption data are applied the HP Filter with a smoothing parameter of 100.

Finally, note that the model is successful in generating countercyclical spreads and a countercyclical current account (procyclical borrowing). As it has been discussed in the literature, this feature is a direct result of the asymmetric default penalty on output (see Arellano (2008) and Mendoza and Yue (2012) for discussions of this mechanism, and Aguiar and Amador (2014) for an extended survey). A key observation here is that, as the spreads data for Mexico, these model samples do not include oil discoveries. Figure 6 below shows how spreads in the model increase following an oil discovery, along with borrowing and GDP, which are the puzzling joint responses documented in Section 2.

Responses to oil discoveries.—Figure 6 presents average model responses to an oil discovery. Each time series averages 10,000 paths around an oil discovery in period $t = 0$. The state in the initial period $t = -1$ of each path is a draw from the ergodic distribution with $N_t = N_L$, without any oil discoveries in the past 50 periods.

Figure 6: Average responses to oil discoveries

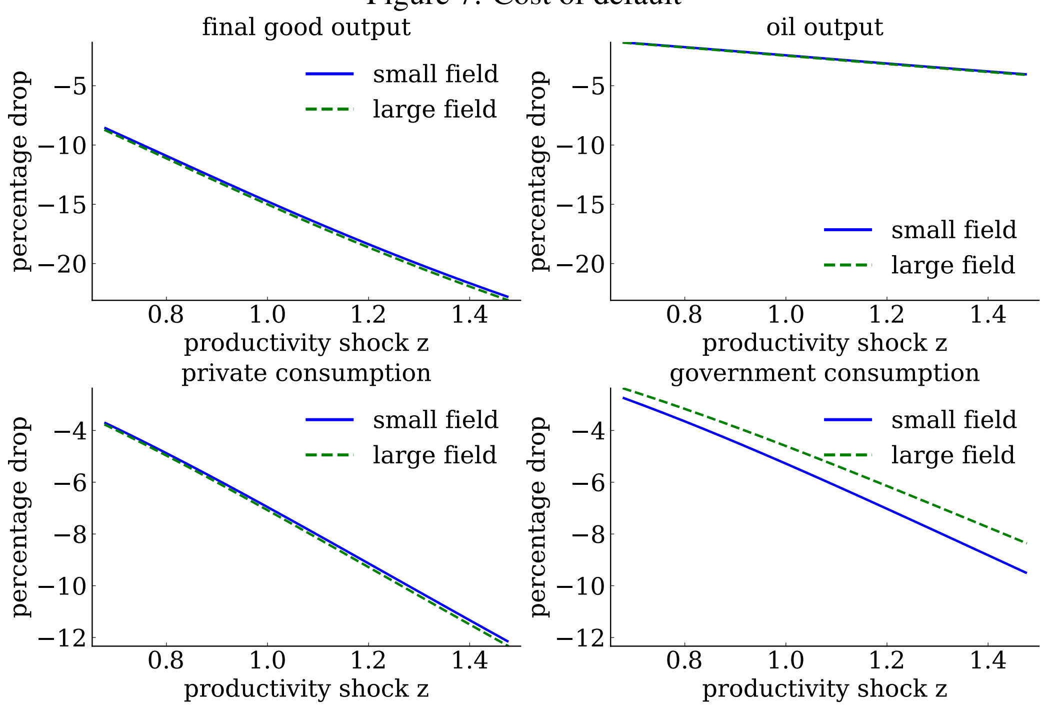


Each time series considers 10,000 economies in their ergodic state without any oil discoveries since $t = -50$. The lines are the difference between the values in each period and the values in period t_{-1}.

As in the data, spreads start to increase when news of a discovery arrives and peak in $t = 4$ right before production in the new field starts in $t = 5$. The responses of the other variables are in line with those in the data presented in Section 2. Despite higher spreads, government borrowing increases as a response to the large future increase in income from higher oil production, driving a current account deficit. Once the field becomes productive in period $t = 5$ the current account reverts, and both GDP and government consumption increase, while private consumption remains mostly unchanged. The government also uses this higher income to reduce the debt, which drives the decrease in spreads following the start of production in the new field.

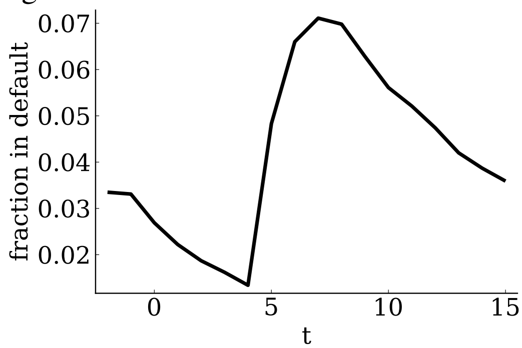
The role of technology and working-capital requirements.—Figure 7 presents the real cost of default that emerges endogenously in terms of output (top panels) and in terms of consumption (bottom panels). First, note that as in Mendoza and Yue (2012) the cost of default is proportionately larger with high realizations of the productivity shock. It is this asymmetry that allows the model to reproduce countercyclical spreads, procyclical borrowing, and default events in equilibrium. Second, note that the cost of default in the oil sector is smaller than in the rest of the economy. This is a direct result of the oil sector using fewer intermediate goods $\alpha_{Mo} < \alpha_{Mf}$, fewer imported intermediates $1-\lambda_f > 1-\lambda_o$, and requiring working capital for a smaller fraction of its imported materials $\theta_o < \theta_f$.

Figure 7: Cost of default



When the oil firm is operating a larger field then a larger fraction of government income depends on the sector that is less affected by default. This translates into a smaller (government) consumption-cost of default when the oil field is large. All else equal, the government has higher incentives to default when $N_t = N_H$ because the additional income from oil rents allows the government to "weather the storm" of lower tax revenue due to lower non-oil output in default.

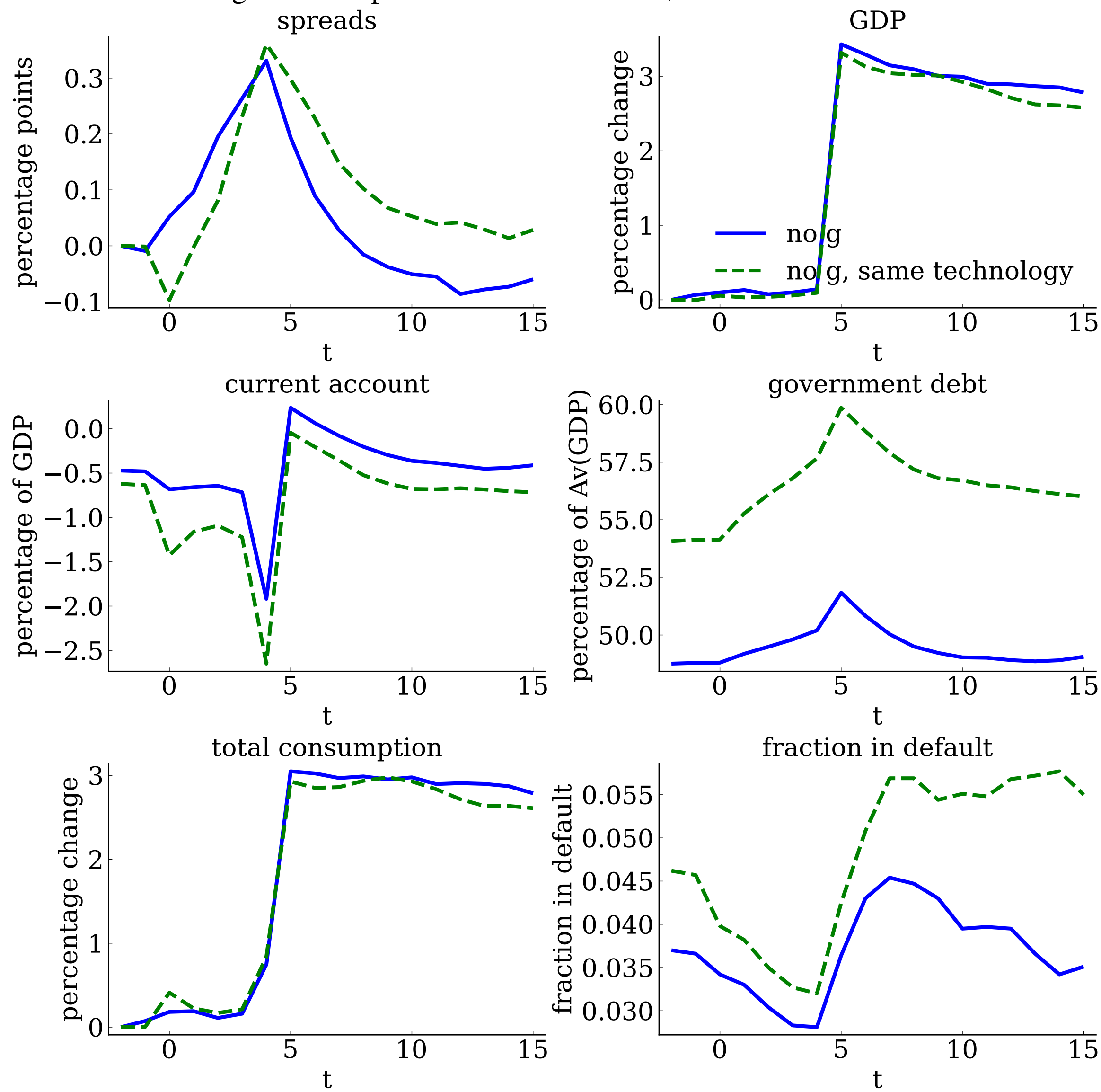
Figure 8: Fraction of economies in default



Each time series considers 10,000 economies in their ergodic state without any oil discoveries since $t = -50$. The lines are the difference between the values in each period and the values in period t_{-1}.

Figure 8 shows the fraction of economies that are in default around an oil discovery. With a small oil field roughly 3.5 percent of the economies in the simulation are in a default state at any given period. This fraction significantly increases once the government starts to receive larger oil rents from the field in $t = 5$. Since the debt is long-term, this higher default risk in $t = 5$ is priced-in in all preceding periods starting when the discovery happens in $t = 0$ and spreads gradually increase as higher default risk becomes more imminent.

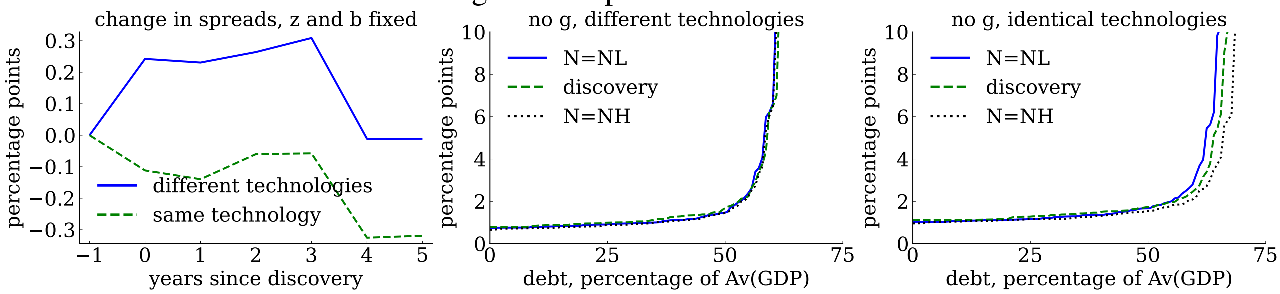
Figure 9: Responses to oil discoveries, alternative models



Each time series considers 10,000 economies in their ergodic state without any oil discoveries since $t = -50$. The lines are the difference between the values in each period and the values in period t_{-1}.

To further illustrate the role of differences in technology and working-capital requirements Figure 9 presents the same analysis as Figure 6 for the two alternative specifications of the model. Results are virtually the same in the model with no government consumption. The differences in technology and working-capital requirements imply a lower default cost in terms of aggregate consumption, just as is the case for government consumption in the benchmark model. In the model with identical technology spreads drop on impact when the discovery happens and then increase. This later increase is driven by a much more aggressive increase in government borrowing that takes advantage of the more favorable borrowing terms. Figure 10 illustrates this point by showing how the price schedule for government debt shifts differently in both models.

Figure 10: Spreads schedule



The left panel presents the change in spreads as information of a discovery emerges keeping the value of the shock and debt fixed at their long-run average. The middle and right panel show how the price schedules in terms of spreads shift in the alternative model with no government consumption and with identical technologies, respectively.

The left panel presents the change in spreads as information of a discovery emerges keeping the value of the shock and debt fixed at their long-run average without discoveries. For the case with different technologies, spreads increase initially and during the transition. They then drop once the larger oil field is active, but note that this is for the fixed lower debt level that was prevalent before the discovery. Once we take into account government borrowing, spreads are higher both because of the increase in borrowing and because of a shift upward of the price schedule for these higher levels of debt (see the dotted black line in the middle panel). For the case in which oil has the same technology and working-capital requirements the spreads schedule decreases on impact (the green dashed line in the right panel), continues to decrease along the transition, and remains much lower when the giant oil field is active (the dotted black line in the right panel). These increasingly more advantageous borrowing terms drives the larger increase in borrowing observed in Figure 9.

4.3 Welfare analysis

The model above reconciles the puzzling findings from Section 2 by noting that the higher default risk is driven by how default affects the oil sector differently. From a welfare point of view there is a tension between higher output from a giant oil discovery and higher default risk. Is it worth it to find and exploit giant oil fields?

I compute welfare gains of an oil discovery in terms of consumption equivalent units. Since households value both private consumption (net of labor disutility) and government consumption, I define welfare gains of a discovery in t as the percentage increse χ_t in both, such that households are indifferent between not discovering a giant field and discovering it. Since preferences are homothetic and $\sigma = \sigma^G$, we can write welfare gains in terms of the state and value functions

$$\chi(b,z) = 100 * \left[\left(\frac{V(b,z,0)}{V(b,z,-1)} \right)^{\frac{1}{1-\sigma}} - 1 \right],$$

where $n = -1$ indicates that the economy has not discovered an oil field and $n = 0$ indicates news of an oil discovery.

Table 4: Average welfare gains of giant oil discoveries

	benchmark (1)	oil firm operated by domestic private sector (2)	no government consumption (3)	sell oil rents from giant field to foreigners (4)
welfare gains	7.7	1.6	1.6	7.4

Welfare gains are computed in consumption equivalent units. The numbers are the averages of 1,000 discoveries randomly drawn from the ergodic distribution.

Table 4 presents the average welfare gains of oil discoveries in four versions of the model. Column (1) corresponds to the benchmark and shows that there are sizable welfare gains from oil discoveries, despite the increase in spreads. The gains of 7.7 percent, however, contrast with the average 16 percent increase in government consumption shown in Figure 6. The difference is explained by the higher default risk and by a composition effect because the government cannot increase private consumption—while the compensating variation does by construction. Column (2) corresponds to a version of the model in which the oil firm is operated by the domestic private sector and taxed in the same way as the rest of private income. In this case, the budget constraint of the government in good standing is

$$g_t + \gamma b_t \leq \tau \left[w_t L_t + \pi_{ft} + \pi_{dt} + \pi_{ot} \right] + q_t i_{b,t}$$

and in default it is

$$g_t \leq \tau \left[w_t L_t + \pi_{ft} + \pi_{dt} + \pi_{ot} \right].$$

Interestingly, welfare gains of oil discoveries are smaller in this case. As noted in Figure 7, the default penalty to private consumption is similar with and without the larger oil field because all the benefits from less exposure to the forces that drive the real cost of default are constrained to government consumption. In this alternative model, both government and private consumption benefit from the relatively lower exposure to default costs, which reduces the welfare benefits from oil discoveries significantly. Welfare gains of oil discoveries are also smaller if we consider the re-calibrated model with no government consumption described in the previous section (Column (3)). These results would evidently be different if the government were assumed not to be benevolent. The government could be more impatient than the households or have a relatively higher weight on government consumption $\psi_g > 1$. In either case, privatizing the oil sector would, by assumption, give more agency to the households by removing tools from a non-benevolent government, unambiguously increasing welfare regardless of the details in the oil sector. While these considerations are interesting, they are beyond the scope of this paper.

Finally, Column (4) presents the welfare gains from selling oil rents from the giant oil discovery to foreigners. Define total oil rents as $R_{ot} = \alpha_N y_{ot}$, the rents that corresponds to the giant oil field are

$$R^*_{ot} = \alpha_N \frac{y_{ot}}{N_H} \left[N_H - N_L \right],$$

if foreigners discount the future at a rate equal to the risk-free rate r^* then we can approximate the present value of these rents as

$$v = \left(\frac{1}{1+r} \right)^{\text{Twait}} \frac{1+r^*}{r^* + \pi_{\text{ex}}} R^*_{oss}$$

where R^*_{oss} assumes $z_t = 1$ during the life of the giant field for simplicity. The welfare gains in this case are close to the benchmark model. On one hand, the government receives a large windfall when the oil discovery happens, which is used to reduce debt and increase government consumption. On the other hand, the government foregoes the flows of R^*_{ot} during the life of the giant oil field. For this calibration, it turns out that these two opposing forces closely cancel each other.

5 Conclusion

In this paper, I documented a puzzling response of sovereign spreads to giant oil field discoveries: spreads increase significantly even though oil discoveries are news of higher future income. Spreads are countercyclical in the data and sovereign default theory has built on the assumption that the real costs of default are increasing in income to explain this regularity. To reconcile these findings with existing theory I developed a model in which the oil sector is endogenously less affected by a sovereign default than the rest of the economy. Critically, it is the oil sector's relatively lower dependence on imported intermediates and on working capital what drives this lower exposure. I discipline these differences using Mexico's Input-Output Matrix and financial statements from the largest oil firm in the country. The model successfully generates the joint responses to giant oil discoveries without sacrificing its ability to match business cycle regularities from the data.

Despite the increase in default risk that they generate, there are significant welfare gains from oil discoveries. Interestingly, these gains are smaller if the domestic private sector benefits directly from oil rents and remain large if the government sells the additional oil rents to foreigners. This is because selling the rents reduces default incentives for future governments, who would otherwise take advantage of higher oil rents and lower costs of defaulting to increase borrowing and default risk. Removing this temptation turns out to be very valuable.

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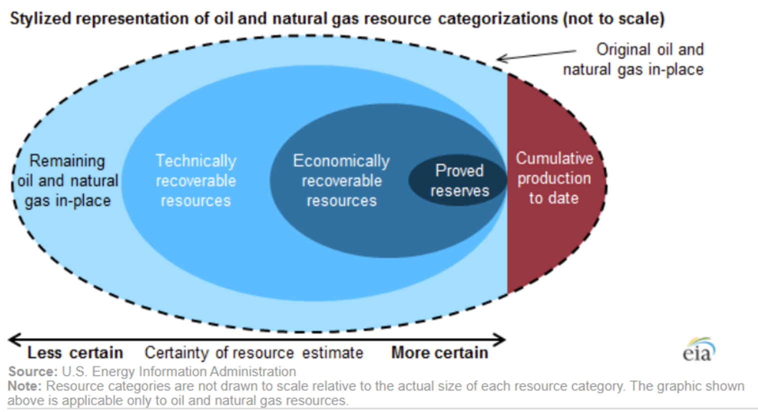
A Additional empirical results

A.1 Controlling for oil reserves

As documented by Hamann, Mendez-Vizcaino, Mendoza, and Restrepo-Echavarria (2023), the dynamics of proved oil reserves have a significant impact on the evolution of credit worthiness of emerging economies who are oil exporters. In order to understand my findings in light of their results it is important to note a conceptual distinction between proved oil reserves and URR. There is a range of categories to measure oil reserves. Figure 11 shows a conceptual diagram from the U.S. Energy Information Administration that illustrates the differences between these categories.

Figure 11: Oil and natural gas resource categories



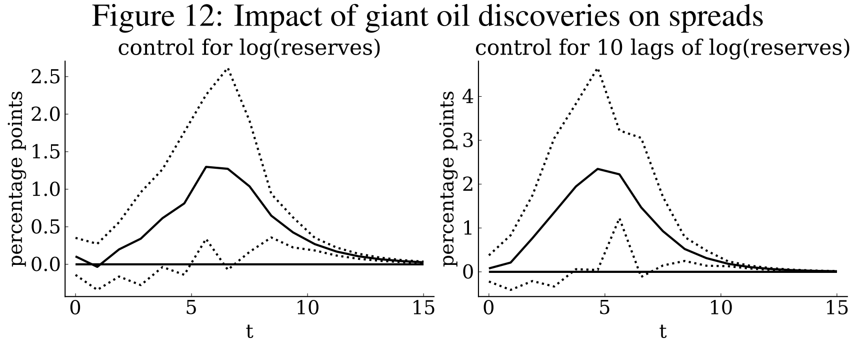
Each category implies a different level of uncertainty, where the most certain measure is proved reserves and the most uncertain is remaining oil and natural gas in-place. Oil and gas in-place refers to the total amount of resources within a geological formation. Technically recoverable resources includes oil and gas that can be produced based on current technology.[23] This is the estimate of URR that Arezki, Ramey, and Sheng (2017) use to construct the NPV of oil fields, which can be interpreted as the amount of oil in a field that is physically feasible to extract. Economically recoverable resources (ERR) are all URR that can be profitably produced given economic conditions (like the price of oil and variable costs of production) at the time of measurement. Finally, proved oil reserves require a higher standard of certainty to be considered profitably and physically recoverable. As ERR, proved reserves shrink and grow as the prices of oil and extraction inputs vary. URR do not.

[23]Geophysical characteristics of rocks, as well as physical properties of hydrocarbons (such as viscosity) prevent technology from producing the entirety of the ultimately recoverable reserves.

It is crucial to note that, by definition, the resources contained in giant oil field discoveries are not included in the measure of proved oil reserves at the time of the discovery. Instead, the oil in a field is gradually added to proved reserves once drilling starts and new information is collected about its feasibility and profitability.

Hamann, Mendez-Vizcaino, Mendoza, and Restrepo-Echavarria (2023) document how marginal changes in proved oil reserves impact the credit worthiness of oil exporting countries, identifying both long and short-run effects. The shocks these authors identify are driven by international economic conditions (like oil prices) and by endogenous extraction decisions, both of which are the main source of variation in proved oil reserves. There are three important differences between Hamann, Mendez-Vizcaino, Mendoza, and Restrepo-Echavarria (2023) and the work presented in this paper. The first has to do with the magnitude of the shocks at hand. By definition, the size of year-to-year changes in proved reserves is dwarfed by the size of giant oil discoveries. The second has to do with the fact that newly discovered giant oil fields cannot be immediately exploited; instead, they require a substantial amount of investment through several years in order to become productive. In contrast, proven reserves can be more easily exploited within shorter periods of time. These differences imply that discoveries may affect sovereign interest rate spreads in a way that marginal changes in proved reserves do not.

Figure 12: Impact of giant oil discoveries on spreads



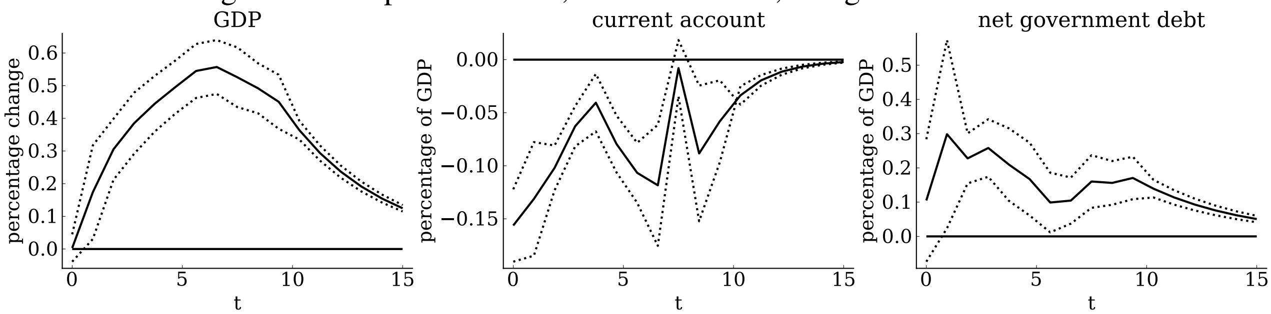
Impulse response to an oil discovery with net present value equal to 4.5 percent of GDP, which is the median size of discoveries in the sample. The dotted lines indicate 90 percent confidence intervals based on a Driscoll and Kraay (1998) estimation of standard errors, which yields standard error estimates that are robust to general forms of spatial and temporal clustering.

Figure 12 shows the dynamic response of the spreads following a discovery of median size. The left panel controls for the natural logarithm of contemporaneous proved reserves and the right panel controls for this and ten lags. The results are very similar to the benchmark results that do not control for reserves.

A.2 Estimates with restricted sample

Figure 13 presents the responses of GDP, the current account, and government debt by restricting the sample to the 37 emerging economies in the EMBI.

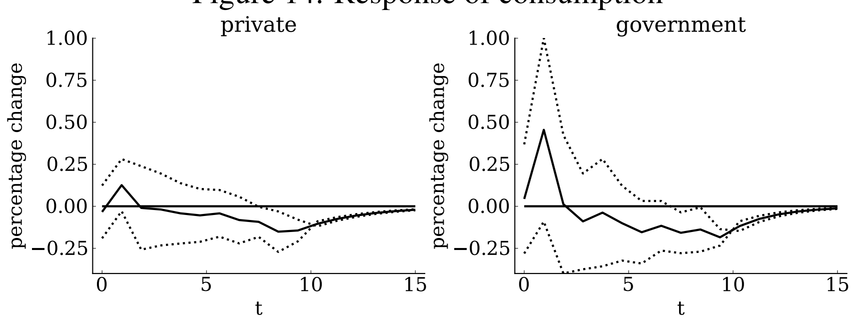
Figure 13: Response of GDP, current account, and government debt



Impulse response to an oil discovery with net present value equal to the median size of 4.5 percent of GDP. The dotted lines indicate 90 percent confidence intervals based on a Driscoll and Kraay (1998) estimation of standard errors, which yields standard error estimates that are robust to general forms of spatial and temporal clustering.

As discussed in the main text, GDP increases and peaks at around the time when the oil field becomes productive, the economies run a current account deficit and government debt increases. Interestingly, GDP starts increasing right after news arrives and the current account reversal is less pronounced. These interactions with production in the rest of the economy are interesting on their own and beyond the scope of this paper.

Figure 14: Response of consumption



Impulse response to an oil discovery with net present value equal to the median size of 4.5 percent of GDP. The dotted lines indicate 90 percent confidence intervals based on a Driscoll and Kraay (1998) estimation of standard errors, which yields standard error estimates that are robust to general forms of spatial and temporal clustering.

Figure 14 presents the responses of private and public consumption for the restricted sample. As is the case with the results presented in the main text, the response of public consumption is larger than that of private consumption.

B Canonical model with oil discoveries

Recursive formulation.—The state of the economy is (b,z,n). The value of the government at the beginning of a period in good financial standing is

$$V(b,z,n) = \max_{d\in\{0,1\}} \left\{ dV^D(z,n) + (1-d)V^P(b,z,n) \right\}, \tag{26}$$

where the value of repayment is

$$\begin{aligned} V^P(b,z,n) &= \max_{c,b'} \left\{ u(c) + \beta \mathbb{E}\left[V\left(b',z',n'\right) \right] \right\} \\ s.t. \qquad c+b &\leq z + R^{\text{oil}}(n) + q\left(b',z,n\right) b', \end{aligned} \tag{27}$$

where q is the price schedule of debt, and the value of default is

$$\begin{aligned} V^D(z,n) &= u\left(y^{def}(z,n)\right) + \beta\phi \mathbb{E}\left[V\left(0,z',n'\right)\right] + \beta(1-\phi)\mathbb{E}\left[V^D\left(z',n'\right)\right] \\ y^{def}(z,n) &= h_z(z) + h_{oil}\left(R^{\text{oil}}(n)\right), \end{aligned} \tag{28}$$

where ϕ is the probability of reentry to financial markets.

Equilibrium.—An equilibrium is value and policy functions and a price schedule q such that: (i) given q, the value and policy functions satisfy equations (26), (27), and (28); and (ii) the price schedule satisfy the lender's no-arbitrage condition:

$$q\left(b',z,n\right) = \frac{\mathbb{E}\left[\left(1-d\left(b',z',n'\right)\right)\right]}{1+r^*},$$

where r^* is the international risk-free rate.

Parameterization and calibration.—The income shock z_t follows an AR(1) process

$$\log z_t = \rho \log z_{t-1} + \sigma_z^2 \varepsilon_t,$$

where ε_t follow a standard normal distribution and are iid over time. The utility function is CRRA $u(c) = \frac{c^{1-\sigma}-1}{1-\sigma}$. Table 5 summarizes the calibration.

Table 5: Calibration of canonical model

Parameter		Value	Source
CRRA parameter	σ	2.0	Arellano (2008)
Discount factor	β	0.953	Arellano (2008)
Risk-free rate	r^*	0.01	Arellano (2008)
Probability of reentry	ϕ	0.282	Arellano (2008)
Persistence of z_t	ρ	0.945	Arellano (2008)
Standard deviation of z_t	σ_z	0.025	Arellano (2008)
Default penalty parameter	$\kappa_z = \kappa_{oil}$	0.969	Arellano (2008)
Low oil rents	R_L^{oil}	0.06	Data for Mexico
High oil rents	R_H^{oil}	0.08	
Lag between discovery and production	T_{wait}	5	Oil discoveries data
Probability of discovery	π_{disc}	0.01	
Probability of exhaustion	π_{ex}	0.02	