The Sovereign Default Risk of Giant Oil Discoveries*

Carlos Esquivel†

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Abstract

I document that sovereign interest rate 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 expected future income increases—which is consistent with spreads being countercyclical in the data. To reconcile existing theory with this novel observation, I augment a standard model with two assumptions: oil discoveries as news of higher future income, and this oil income is not affected by default. The estimated response from the data strongly supports the second assumption because, with it, spreads in the model increase following a discovery and decrease without it. Oil discoveries generate large welfare gains despite their effect on default risk, but these gains triple if the government sells the field to foreign investors instead. These larger gains mostly stem from removing the higher temptation for future governments to default. (JEL Codes: F34, F41, Q33)

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†Assistant Professor at Rutgers University; Email: carlos.esquivel@rutgers.edu; Web: https://www.cesquivel.com

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 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, standard models feature an output cost from default that is assumed to be increasing with income. This assumption is key for the models to generate countercyclical spreads and default events when output is low, both of which are consistent with the data (see the discussion in Arellano (2008) and the literature thereafter). If all forms of higher future income were to increase the cost of an eventual default then news of an oil discovery should reduce default incentives and spreads. They increase in the data.

This evidence suggests that income accrued to the government from oil rents is different from other sources of income. In particular, unlike income from taxation, oil rents collected by the government may not be affected by a default. Bocola (2016) and Arellano, Bai, and Bocola (2017) study how GDP and productivity are lower during default crises because of how they disrupt the functioning of domestic financial markets, which contracts credit available in the economy. Oil

[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.

production, however, may be insulated from this disruption if it is carried out mainly by foreign firms (who have access to foreing financial markets) or by state-owned enterprises (who can substitute private credit with taxation and other means available to the State).[2]

I develop a sovereign default model with long-term debt, news (with a lag, as in the data) of oil discoveries, and the assumption that oil income is not affected by default. There is a small-open economy populated by a benevolent government and a household. The household has preferences for private and public consumption and receives an endowment of private income each period. The government collects a proportional income tax on private income and chooses public consumption. In addition, the government makes borrowing and default decisions on behalf of the household, and collects oil rents. I abstract from any details regarding oil production or the volatility of oil rents that may stem from swings in the international price of oil. The key component to explain the data is that oil rents are an alternative source of income to the government that is not affected by the government's financial standing. When the government defaults, private income is penalized with an asymmetric cost like the one proposed by Arellano (2008), which directly reduces tax revenue. Oil rents, however, are unaffected by this cost.

I calibrate the model to the Mexican economy, which is a typical small-open economy widely studied in the sovereign debt and emerging markets literature. Mexico did not have any giant oil field discoveries between 1993 and 2012, which is the period analyzed in this paper.[3] This lack of discoveries allows me to discipline the parameters of the model with business cycle data that does not have any variation that could be driven by oil discoveries. Despite its simplicity, the model replicates the responses to oil discoveries from the data quite well. As in the data, spreads start increasing when news of a discovery arrives and peak right before production starts. This is because, all else equal, the government has more incentives to default when oil rents are high since these are not affected by the penalty of a potential default. In other words, it is relatively less costly for the government to default with a giant oil field. Since the debt is long-term, this higher future default risk is priced-in for all of the periods starting when the discovery is announced, and

[2] Toews and Vézina (2022) and Sheng and Zhao (2024) present evidence of a significant increase in foreign direct investment following giant oil discoveries, which is consistent with these fields being developed by foreign firms.

[3] An interesting case would be the Mexican default in 1982, which was preceded by two giant oil discoveries (in 1977 and 1979), each with an estimated net present value of potential revenues of 50 percent of Mexico's GDP at the time. Unfortunately, we lack data on sovereign spreads for those years, which are crucial to discipline the parameters in the model that control default incentives.

spreads gradually increase as this higher risk becomes more imminent. The responses of the other variables are also in line with those in the data. There is a current account deficit when the news arrives which reverts once the field becomes more productive. By assumption, GDP only increases once the field is productive and not when news arrives, as documented by Arezki, Ramey, and Sheng (2017).

To highlight the role of the assumption that oil rents are immune from the default penalty, I explore two changes to the benchmark model. First, I consider a model in which oil rents are part of private income, which is taxed by the government and affected as a whole by the default penalty. This would be consistent with the oil industry being controlled completely by the domestic private sector and oil rents being taxed as regular income. Second, I consider a model in which the government collects oil rents but faces a partial oil embargo in the event of a default. In both cases, an oil discovery immediately improves the government's borrowing terms and spreads drop. This response of spreads, which is at odds with the data, is because the cost of defaulting is now larger with a giant oil field. The responses of the current account and government consumption are still consistent with the permanent income hypothesis. These examples highlight how the treatment of oil income in default is key to understanding the response of spreads in the data.

Finally, I explore the welfare implications of oil discoveries under different scenarios. In the benchmark model average gains are 3.4 percent, expressed in consumption equivalent units. These are large, but small compared to the average increase in government consumption of 12 percent. When the government faces a potential oil embargo upon default welfare gains of a discovery more than double to 7.3 percent. Finally, I consider a model in which the government sells its claim to the additional rents from the giant oil field to foreigners. Gains in this case are 10.4 percent and the government chooses to use most of the proceeds from the sale to pay outstanding debt.

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. Hatchondo and Martinez (2009) and Chatterjee and Eyigungor (2012) extend the baseline framework to include long-term debt, which allows the models to jointly account for the debt level, the level and volatility of spreads around default episodes, and other cyclical factors. 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 by pointing out how income from oil rents may not be subject to the types of real default costs studied in the literature.

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. 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). In contrast, the model that I develop in Section 3 features large oil discoveries with a lag between discovery and production, and focuses on how the nature of oil rents collected by the government affects default incentives.

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 contributes by connecting it with the sovereign default literature. To my knowledge, this is the first paper to study the effect of news on business cycles and default risk in a general equilibrium model with endogenous default.

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

This section documents the effects of giant oil discoveries on the sovereign spreads of 37 emerging economies in JP Morgan's Emerging Markets Bonds Index (EMBI).[4] I use a measure of the net present value (NPV) of oil discoveries as a percentage of the GDP of the country in the year of discovery, which was constructed by Arezki, Ramey, and Sheng (2017) and described below.

2.1 Giant oil field discoveries data

Giant oil discoveries increase the availability and potential exploitation of natural resources. Their size is large relative to the GDP of the countries where they happen. In order to make this comparison, Arezki, Ramey, and Sheng (2017) construct a measure of their net present value (NPV) as a percentage of GDP at the time of discovery as follows:[5]

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

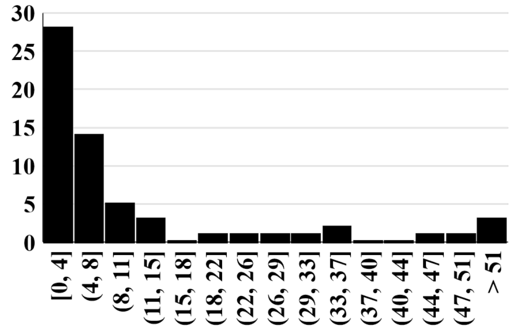
where $q_{i,t+j}$ is the annual gross revenue in year $t+j$ from the field discovered in country i in period t, r_i is the annual discount rate for country i, and $GDP_{i,t}$ is annual GDP of country i at year t. The authors use country-specific risk-adjusted discount rates r_i, which are constructed 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 way, the $NPV_{i,t}$ measure discounts flows more for countries where political risk is high. In the data there is a time delay of 5.4 years on average between a discovery and the start of production. 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

[4]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.

[5]They use the data on giant oil discoveries in the world collected by Horn (2014) and the Global Energy Systems research group at Uppsala University. For more details of the construction of the NPV see Section IV.B. in Arezki, Ramey, and Sheng (2017).

than 50 years for a typical giant oil field.[6] Crucially, the calculation of $q_{i,t+j}$ is scaled by the size of the discovery, which is measured in terms of "ultimately recoverable reserves" (URR). This is an estimate (at the time of the discovery) of the amount of oil that could be eventually recovered from a field given the existing technology.

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.

Considering the 37 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.

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, 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.[7] 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

[6] Gross revenues $q_{i,t+j}$ consider the same price of oil for subsequent years, assuming that the price of oil follows a random walk. This assumption is made for convenience because projecting future oil prices is complicated and oil prices are highly persistent in the data. See Appendix B of Arezki, Ramey, and Sheng (2017) for a detailed explanation of the approximation of the production profile of giant oil discoveries.

[7] Arezki, Ramey, and Sheng (2017) mention that experts' empirical 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.

a dynamic panel model with a distributed lag of discoveries:

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

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.[8]

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 1993, predating any discoveries in the sample.

2.3 The puzzling response of spreads

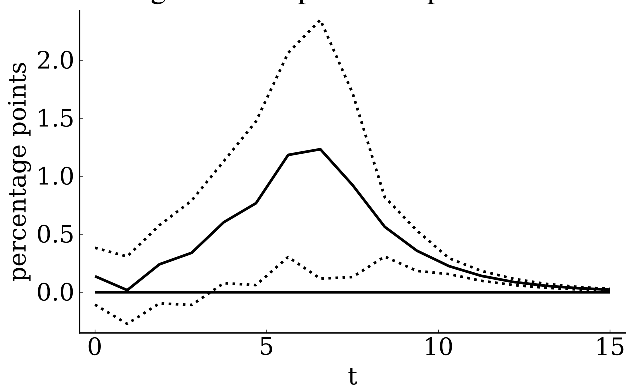
Figure 2 shows the impulse-response function of spreads to an oil discovery of median size (4.5 percent of GDP).[9] Following a discovery, spreads steadily increase and, by the sixth year after the discovery was announced, the increase peaks at 1.2 percentage points.[10]

[8]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, consumption, the real exchange rate, and the spreads. For these variables the augmented Dickey-Fuller test fails to reject a unit root in all countries.

[9]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).

[10]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. The online Appendix contains 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.

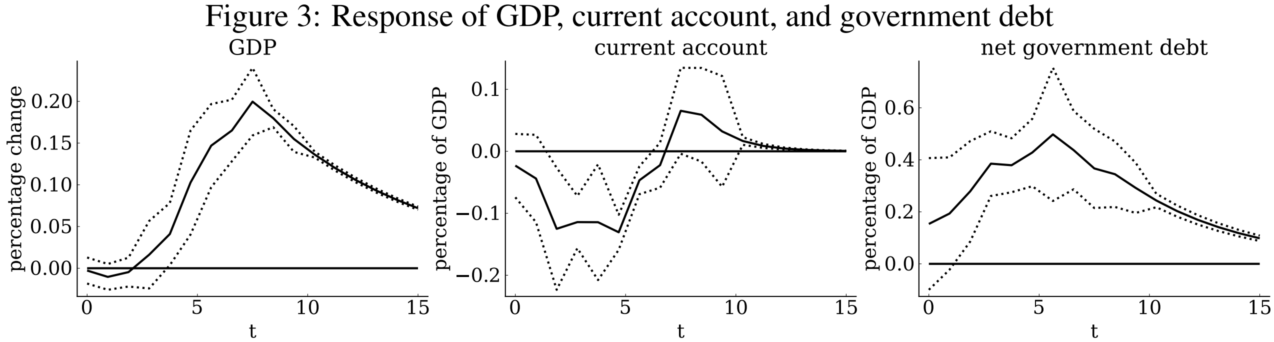
Figure 2: Response of spreads



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: following news of a discovery 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.

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

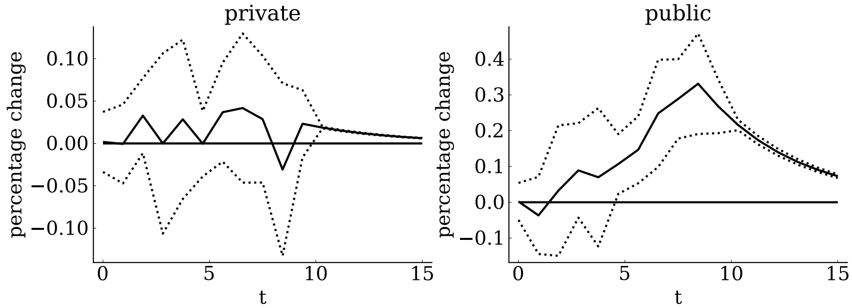


Impulse response to an oil discovery with net present value equal to the median size of 4.5 percent of GDP. The dotted lines indicate 90 percent confidence intervals based on a Driscoll and Kraay (1998) estimation of standard errors, which yields standard error estimates that are robust to general forms 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.[11] In fact, oil discoveries mostly fuel an increase in government consumption, while the effect of private consumption is negligible as shown in Figure 4.

[11] These estimates use all the available data 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 the Online Appendix.

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.

The joint responses of spreads and government borrowing to higher future income are puzzling from the point of view of standard sovereign default models. This is because higher future income in these models increases the cost of an eventual default, which in turn should reduce default incentives and spreads. Moreover, quantitative sovereign default models feature countercyclical spreads and procyclical borrowing, while the above estimates show that both spreads and borrowing increasing when income is expected to increase. This suggests that income from oil rents may be different from other sources of income in the sense that it may not be affected by a default. If that is the case then higher oil income reduces the relative cost of an eventual default as it acts as an alternative source of resources. This point is illustrated in the model in the following section.[12]

3 Model

The model builds on the tradition of quantitative sovereign default models following the seminal work of Eaton and Gersovitz (1981) and makes two key additions: news of oil discoveries (with a delay between discovery and production, as in the data) and differentiated default penalty for oil income.

[12] 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 in Section 3, what is relevant for the effect on spreads is that the additional source of income for the government is not affected by a potential default penalty, regardless of whether it comes from a tax on oil rents or its direct exploitation of the field.

3.1 Environment

There is a small-open economy populated by a representative household and a benevolent government. The government makes borrowing decisions in international financial markets and cannot commit to repay its debt.

Preferences and technology.—The household has preferences for sequences of private and public consumption represented by

$$U = \mathbb{E}_0 \left[\sum_{t=0}^{\infty} \beta^t u(c,g) \right], \tag{3}$$

where β is the discount factor, c is private consumption, g is government consumption, and $u(c,g) = \frac{c^{1-\sigma}}{1-\sigma} + \frac{g^{1-\sigma_G}}{1-\sigma_G}$. Each period, the household is endowed with z_t units of income that follows an AR(1) process

$$\log z_{t+1} = (1-\rho)\log \mu_z + \rho \log z_t + \sigma_z \varepsilon_{t+1}, \tag{4}$$

where ρ is a persistence parameter, μ_z is the long-run mean of z_t, and ε_t are iid and follow a standard normal distribution.

Taxes, oil rents, and oil discoveries.—The government collects a fraction τ of household income as taxes. For simplicity, I assume τ is fixed, which is consistent with low-frequency changes in income tax rates. In addition to tax revenue, the government collects oil rents R_t^{oil} which can take two values

$$R_t^{\text{oil}} = \begin{cases} R_L^{\text{oil}} & \text{if } n_t \leq T_{\text{wait}} \\ R_H^{\text{oil}} & \text{if } n_t = T_{\text{wait}} + 1, \end{cases} \tag{5}$$

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

$$P = \begin{bmatrix} 1-\pi_{\text{disc}} & \pi_{\text{disc}} & 0 & \cdots & \cdots & 0 \\ 0 & 0 & 1 & 0 & \cdots & 0 \\ 0 & 0 & 0 & \ddots & 0 & 0 \\ 0 & 0 & 0 & \cdots & 1 & 0 \\ 0 & 0 & 0 & \cdots & 0 & 1 \\ \pi_{\text{ex}} & 0 & 0 & \cdots & 0 & 1-\pi_{\text{ex}} \end{bmatrix}, \tag{6}$$

where π_{disc} is the probability of discovery of a giant oil field and π_{ex} is the probability of exhaustion. This formulation allows the model to capture the delay between discovery and production that is observed in the data. I abstract from the details of oil production and FDI dynamics that follow discoveries. As discussed below, what is sufficient to explain the puzzling response of spreads is that oil rents accrued to the government constitute an additional source of income that may not be affected by potential default penalties.

Debt and default.—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:

$$b_{t+1} = (1-\gamma)\, b_t + i_{b,t} \tag{7}$$

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

$$g_t + \gamma b_t = \tau z_t + R_t^{\text{oil}} + q_t \left[b_{t+1} - (1-\gamma)\, b_t \right], \tag{8}$$

where q_t is the market price of government bonds defined below.[13] At the beginning of every period the government has the option to default. If the government defaults it gets excluded from international financial markets for a stochastic number of periods and gets re-admitted with prob-

[13] I assume that the government cannot make lump-sum transfers to the households. This assumption simplifies the government's problem, but is also important to have private consumption not increase after an oil discovery (as is the case in the data).

ability θ and zero debt. While in default, private income is

$$z_D(z_t) = \begin{cases} z_t & \text{if } z_t \leq \kappa\mu_z \\ \kappa\mu_z & \text{if } z_t > \kappa\mu_z. \end{cases} \tag{9}$$

This asymmetric default output cost was introduced by Arellano (2008) to capture the idea (consistent with empirical observations) that sovereign default disrupts the functioning of the domestic financial sector and contracts aggregate credit available in the economy. In later work Mendoza and Yue (2012), Bocola (2016), and Arellano, Bai, and Bocola (2017) further develop this idea and document evidence of the domestic financial channel. Moreover, it is this asymmetry that allows the baseline model to generate countercyclical default risk because the cost of defaulting is zero when income is low and increasing for high enough levels of income. The government's budget constraint in default is

$$g_t = \tau z_D(z_t) + R_t^{\text{oil}}. \tag{10}$$

Equation (10) presents the key assumption that allows the model to replicate the response of spreads to oil discoveries in the data: oil rents collected by the government are not affected by default.

Discussion.—This is the key assumption of the model and warrants some discussion. As mentioned above, I abstract from the details of oil production and on how the government collects oil rents. This assumption, however, is consistent with the two most common forms for these: fields exploited by foreign firms through FDI (see Toews and Vézina (2022) and Sheng and Zhao (2024)) and fields exploited directly by state-owned enterprises. In the first case, the assumption is consistent with foreign firms being insulated from the domestic disruption of credit that follows a sovereign default because they can access foreign financial markets. If oil production is not disrupted then the government can continue to collect oil rents from these firms regardless of its default standing. In the second case, the assumption is consistent with the observation that it is difficult for foreign private creditors to effectively seize sovereign assets (see the case of the attempted retention of the Argentinean frigate *Libertad* in 2012). If the government is directly exporting oil the assumption implies that it is difficult for foreign creditors to capture these exports or to effectively implement an oil embargo.

3.2 Recursive formulation and equilibrium

The state of the economy is the stock of debt b, the private income shock z, and the indicator function that determines current government income from oil rents n. The value of the government at the beginning of the period is

$$V(b,z,n) = \max_{d\in\{0,1\}} \left\{ dV^D(z,n) + (1-d)V^P(b,z,n) \right\}, \tag{11}$$

where $d=1$ is the choice to default. The value in repayment $d=0$ is

$$\begin{aligned} V^P(b,z,n) &= \max_{c,g,b'} \left\{ u(c,g) + \beta \mathbb{E}\left[V\left(b',z',n'\right)\right]\right\} \\ s.t. \qquad c &= (1-\tau) z \\ g + \gamma b &= \tau z + R^{\text{oil}}(n) + q\left(b',z,n\right)\left[b' - (1-\gamma) b\right], \end{aligned} \tag{12}$$

and the value of default is

$$\begin{aligned} V^D(z,n) &= \max_{c,g} \left\{ u(c,g) + \beta\theta \mathbb{E}\left[V\left(0,z',n'\right)\right] + \beta(1-\theta)\mathbb{E}\left[V^D\left(z',n'\right)\right]\right\} \\ c &= (1-\tau) z_D(z) \\ g &= \tau z_D(z) + R^{\text{oil}}(n). \end{aligned} \tag{13}$$

Equilibrium.—A Markov equilibrium is value functions $V(b,z,n)$, $V^P(b,z,n)$, and $V^D(z,n)$; policy functions in repayment $d(b,z,n)$, $b^P(b,z,n)$, $c^P(b,z,n)$, $g^P(b,z,n)$ and in default $c^D(z,n)$, $g^D(z,n)$; and a price schedule $q(b',z,n)$ such that: (i) given the price schedule, the value and policy functions solve equations (11), (12), and (13); and (ii) the price schedule satisfies

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

where r^* is the international risk-free rate and $b'' = b^P(b',z',n')$.

4 Quantitative analysis

The objective of the quantitative analysis is twofold. First, to show how the above model can replicate the puzzling increase in spreads following an oil discovery and the role of the assumption that government income from oil rents is not affected by default. Second, to evaluate the welfare implications of policies that could dampen this increase in spreads.

4.1 Calibration

I calibrate the model to the Mexican economy. There are two reasons why Mexico is an ideal example for the purposes of this paper. The first is that 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)). In addition, 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. The second desirable property is that Mexico did not have any giant oil field discoveries during the period of study, so the parameters of the model are disciplined with business cycle data that do not include endogenous variation induced by giant oil discoveries.

A period in the model is one year. Unless specified otherwise, all data are annual for the years 1993 to 2012, which are the sample years in the empirical section. There are two sets of parameters: the first (summarized in Table 1) is calibrated directly and the second (summarized in Table 2) is chosen so that moments generated by model simulations match their data counterparts. 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. For the persistence ρ and volatility of private income σ_z I estimate

$$\log y_t = \rho \log y_{t-1} + \sigma_z \varepsilon_t,$$

where y_t is Mexican GDP measured in local currency units and linearly detrended. This estimation yields the values $\rho = 0.7783$ and $\sigma_z = 0.034$. I normalize the mean of the private income shock to be $\mu_z = 1$. I set the probability of re-entry to financial markets to $\theta = 0.40$, so that the average duration of exclusion is 2.5 years, following Aguiar and Gopinath (2006). The bond maturity rate is $\gamma = 0.14$ so that the average duration of bonds is 7 years, as documented for Mexico by Broner, Lorenzoni, and Schmukler (2013). Tax revenue in Mexico is 15 percent of GDP on average, so $\tau = 0.15$.

Table 1: Parameters calibrated directly from the data

Parameter		Value	Parameter		Value
CRRA	$\sigma = \sigma_G$	2.00	risk free rate	r^*	0.04
bonds maturity rate	γ	0.14	probability of reentry	θ	0.40
persistence of output	ρ_z	0.7783	volatility of output	σ_z	0.034
probability of discovery	π_{disc}	0.01	probability of exhaustion	π_{ex}	0.02
size of small oil field	R_L^{oil}	0.037	size of large oil field	n_H	0.063

Average oil rents in Mexico are 3.6 percent of GDP, so I set $R_L^{\text{oil}} = 0.037$ (note that GDP in the model is $GDP_t = z_t + R_t^{\text{oil}}$). 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 oil production capacity.[14] Thus, I set $R_H^{\text{oil}} = 1.69 * R_L^{\text{oil}} = 0.063$. The probability of a discovery is $\pi_{\text{disc}} = 0.01$, which is the probability of new discoveries observed in the data. The probability of exhaustion is $\pi_{\text{ex}} = 0.02$ for an average field life of 50 years.

Table 2: Parameters calibrated simulating the model

Parameter		Value
default cost	κ	0.769
discount factor	β	0.842
Moment	**Data**	**Model**
$Av\,(r - r^*)$	2.9	2.9
$Av\left(\frac{b}{gdp}\right)$	0.15	0.15

Moments are computed by simulating 10,000 economies in their ergodic state without any oil discoveries and that are in good financial standing in the initial period.

Finally, I jointly set the parameter governing the cost of default $\kappa = 0.769$ and the discount factor $\beta = 0.842$ so that average spreads and debt-to-GDP ratios in the model are 2.9 and 0.15, respectively. These correspond to Mexico's average EMBI spread and the average of public and publicly guaranteed external debt stocks (see The World Bank (2021)). To be consistent with the data, the model samples used to compute these moments do not include oil discoveries.

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

4.2 Results

Business-cycle moments.—Table 3 compares untargeted business-cycle moments from the data with those from the model in samples without oil discoveries. The second row shows that the model performs well in replicating Mexican business-cycle regularities. The long-run default probability and volatility of spreads are close to their data counterparts. Consumption is slightly more volatile than GDP, as in the data, but the trade balance and current account are slightly more volatile in the model. This is because the model abstracts from other important sources of external imbalances like private borrowing.

Table 3: Business cycle moments

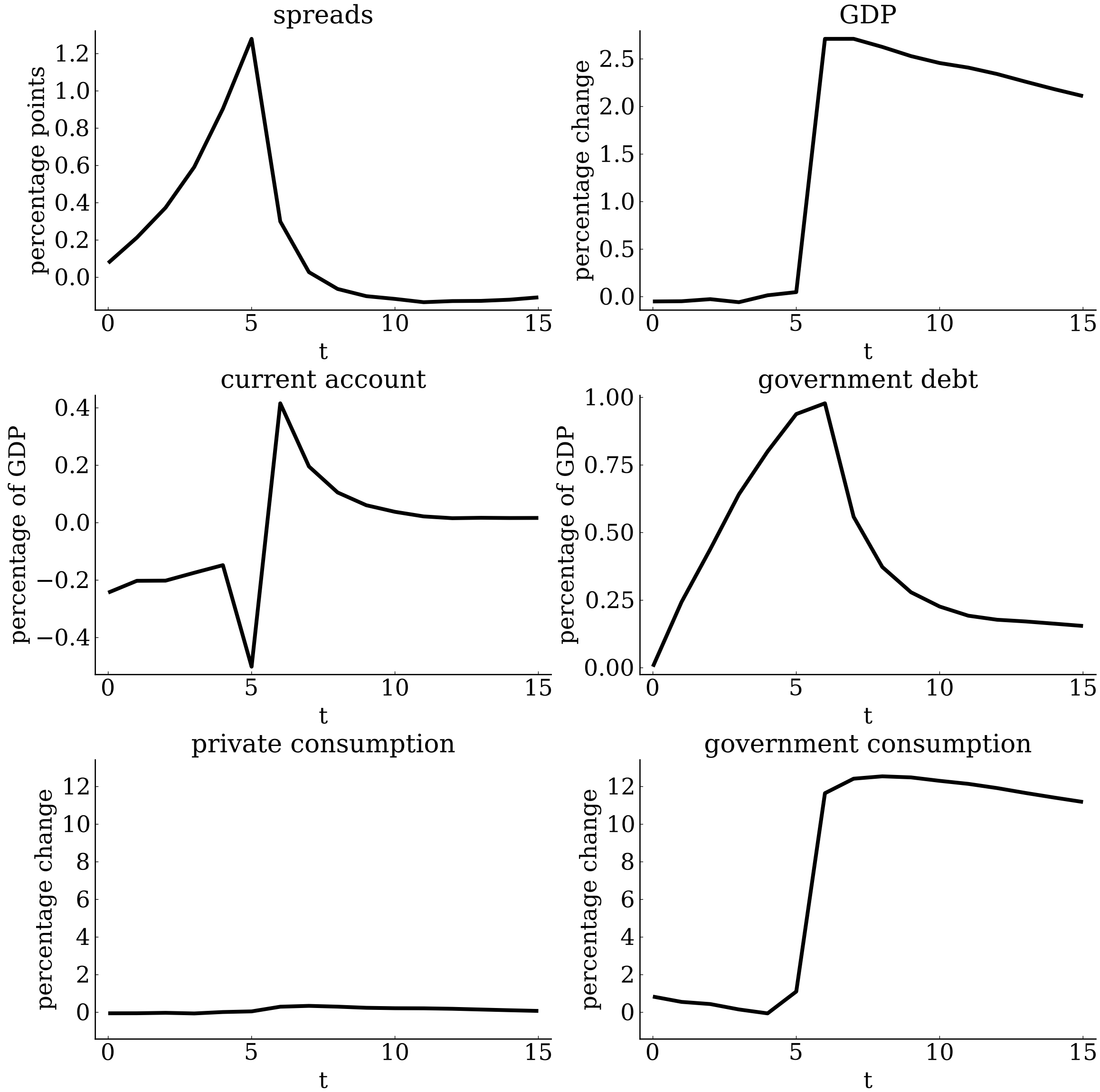
	$Pr(d=1)$	σ_{r-r^*}	$\frac{\sigma_c}{\sigma_y}$	σ_y	$\sigma_{\frac{tb}{y}}$	$\sigma_{\frac{ca}{y}}$	$\rho_{r-r^*,y}$	$\rho_{\frac{tb}{y},y}$	$\rho_{\frac{ca}{y},y}$
data	3.00	1.3	1.1	3.9	0.5	0.8	-0.2	-0.4	-0.1
model	2.30	0.9	1.1	4.5	1.9	2.6	-0.2	-0.1	-0.1

Moments are computed by simulating 10,000 economies in their ergodic state without any oil discoveries and that are in good financial standing in the initial period. Moments for GDP and consumption correspond to the cyclical component of linearly detrended real variables in local currency units.

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 in the data for Mexico, these model samples do not include oil discoveries. Figure 5 below shows how spreads in the model increase with GDP when higher GDP is driven by higher oil rents from a recently discovered giant oil field, which is the puzzling response documented in Section 2.

Responses to oil discoveries.—Figure 5 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 $R^{\text{oil}}_{-1}=R^{\text{oil}}_{L}$, without any oil discoveries in the past 50 periods, and that are in good financial standing throughout periods $t=-1,0,...,15$ (i.e. I drop the samples with a default event in Figure 5, Figure 7 presents the same exercise without dropping these paths).

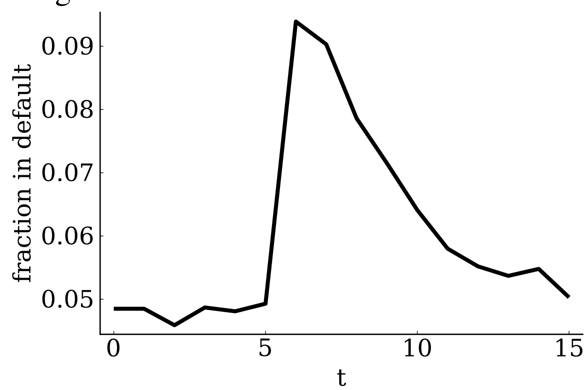
Figure 5: Model responses to a giant oil discovery, without defaults



Each time series considers 10,000 economies in their ergodic state without any oil discoveries since $t = -50$ and that are in good financial standing in all periods $t = -1, 0, ..., 15$. 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 $t = 5$ right before production in the new field starts in $t = 6$. All else equal, the government has higher incentives to default when $R_t^{\text{oil}} = R_H^{\text{oil}}$ because the fraction of government income that is not affected by the default penalty is now larger. In other words, the additional income from (not penalized) oil rents allows the governmet to "weather the storm" of lower tax revenue due to lower non-oil output in default. Since the debt is long-term, this higher default risk in $t = 6$ is priced-in in all preceding periods starting when the discovery happens in $t = 0$. To illustrate this, Figure 6 shows the fraction of economies that are in default before and after an oil discovery. Default events only spike once the government starts to receive larger oil rents from the field in $t = 6$, while spreads gradually increase as this higher risk becomes more imminent.

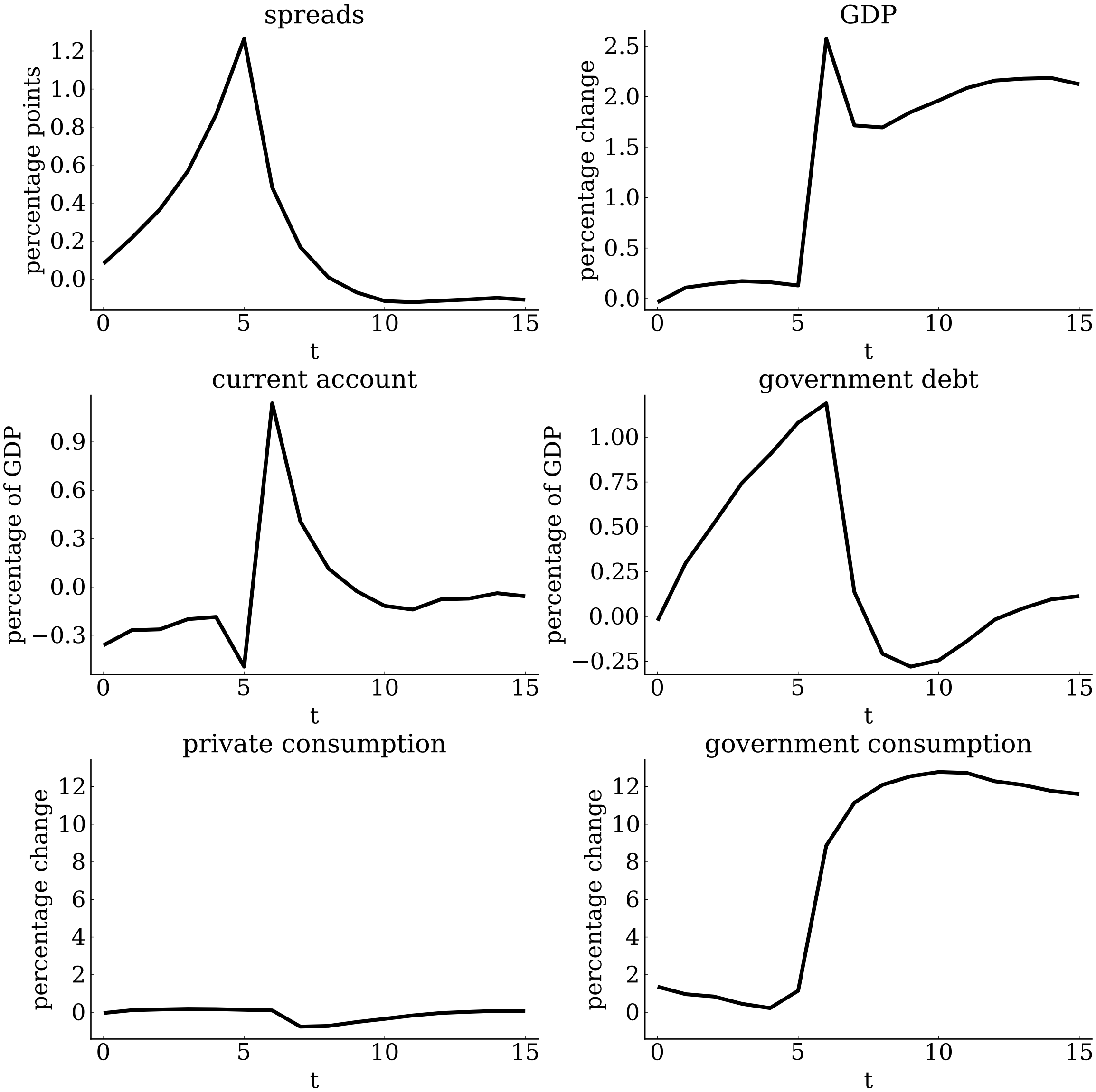
Figure 6: Fraction of economies in default



This time series averages the default state in each period t over 10,000 economies in their ergodic state without any oil discoveries since $t = -50$.

The responses of the other variables are in line with those in the data presented in Section 2. There is a current account deficit when the news arrives due to the increase in government debt. Once the field becomes productive in period $t = 6$ 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. Figure 7 presents the same average model responses without dropping paths with default events.

Figure 7: Model responses to a giant oil discovery, including defaults



Each time series considers 10,000 economies in their ergodic state without any oil discoveries since $t = -50$ and that are in good financial standing in the initial period $t = -1$, (one period before an oil discovery). The lines are the difference between the values in each period and the values in period t_{-1}.

The results are roughly the same. Average GDP mechanically drops in $t = 6$ because of the larger fraction of economies in default (which face the default penalty for non-oil income). For the same reason, the reversal in the current account is sharper since debt drops to zero in the defaulting economies and private consumption slightly drops (although its overall change is dwarfed by the response in government consumption, as in the data).

4.3 The role of the default penalty

As mentioned above, the assumption that oil rents collected by the government are immune to the default penalty is key to generating the response of spreads in the data. This assumption is consistent with giant oil fields being developed by foreign or government firms (insulated from the domestic disruption of private credit in default) and also consistent with private creditors having difficulty seizing sovereign assets (this includes the difficulty of effectively implementing an oil embargo). This section presents two alternative versions of the model that relax this assumption.

Field operated by domestic firms.—Suppose that the oil field is operated by the domestic private sector and that oil rents are taxed by the government at the same fixed rate τ. The realization of domestic private income in period t is now $y_t = z_t + R_t^{\text{oil}}$. When the government is in good financial standing, private income is y_t and the government collects τy_t in taxes. When the government is in default private income is

$$y_D(y_t) = \begin{cases} y_t & \text{if } y_t \leq \kappa\left(\mu_z + R_L^{\text{oil}}\right) \\ \kappa\left(\mu_z + R_L^{\text{oil}}\right) & \text{if } y_t > \kappa\left(\mu_z + R_L^{\text{oil}}\right), \end{cases} \tag{14}$$

where the dependence on R_L^{oil} implies that the function y_D treats $R_t^{\text{oil}} = R_L^{\text{oil}}$ as the average of oil rents in "normal" times (consistent with the calibration strategy). Oil rents are now affected by the same domestic credit disruptions that affect the rest of the economy when the government defaults. The government's budget constraint in repayment is

$$g_t + \gamma b_t = \tau y_t + q_t\left[b_{t+1} - (1-\gamma)b_t\right],$$

and in default it is $g_t = \tau y_D(y_t)$.

Oil embargo.—Suppose instead that the oil field continues to be operated by foreign investors, but now lenders can impose a partial oil embargo that reduces the government's oil rents in default. Specifically, when the government is in default rents are now

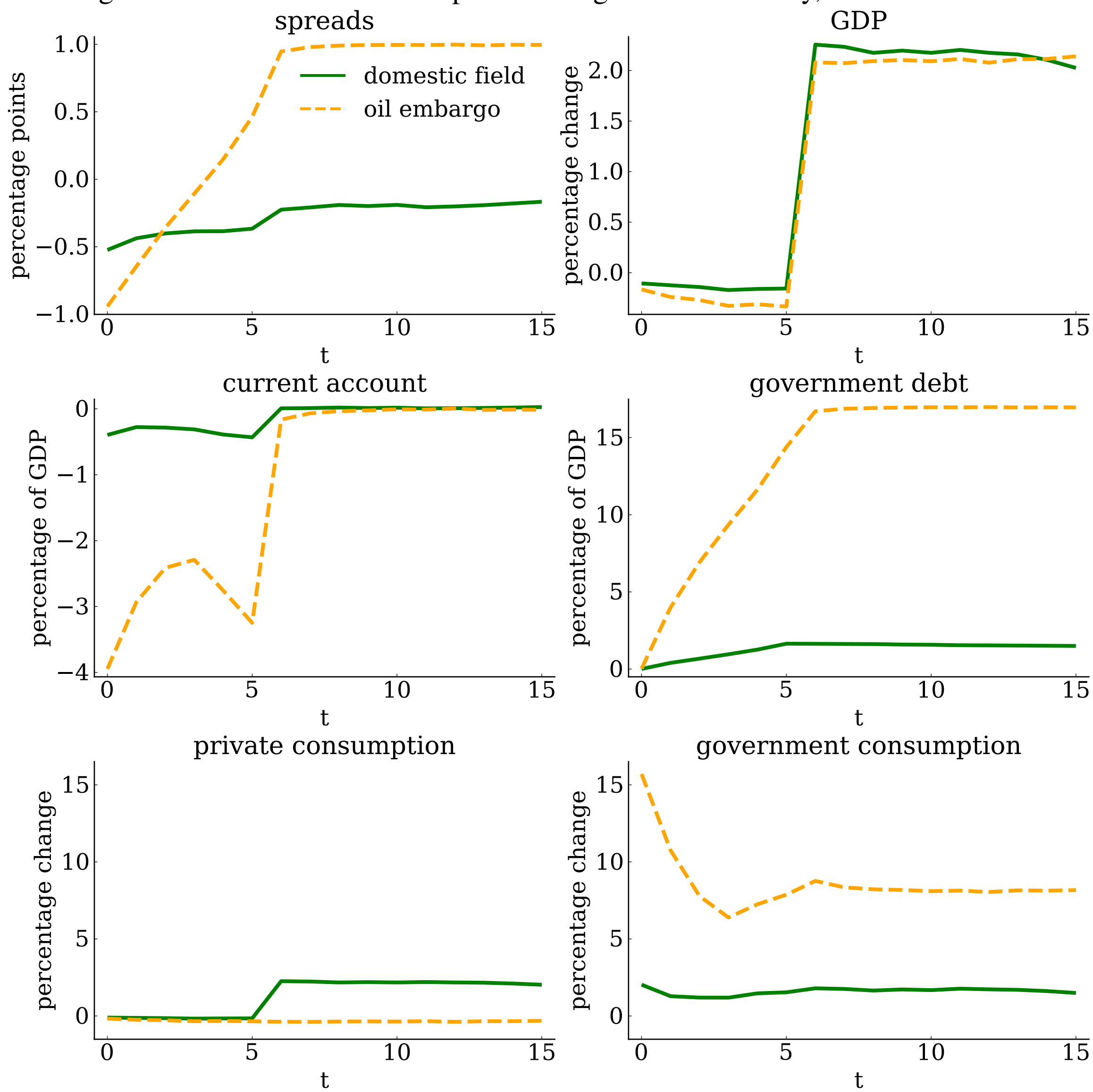
$$R_D^{\text{oil}}\left(R_t^{\text{oil}}\right) = \kappa_{\text{oil}} R_L^{\text{oil}}$$

where $\kappa_{oil} < 1$ implies that in default the government can only collect a fraction of the oil rents that it would without a giant oil field. The government's budget constraint in repayment is the same as in the benchmark model (equation (8)) and is

$$g_t = \tau z_D(z_t) + R_D^{\text{oil}}\left(R_t^{\text{oil}}\right)$$

in default.

Figure 8: Alternative model responses to a giant oil discovery, without defaults



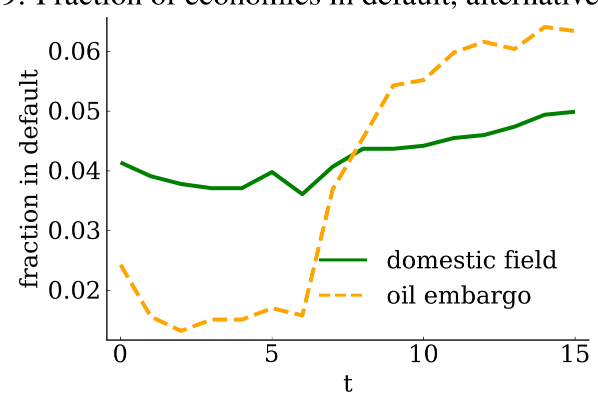
Each time series considers 10,000 economies in their ergodic state without any oil discoveries since $t = -50$ and that are in good financial standing in all periods $t = -1, 0, \ldots, 15$. The lines are the difference between the values in each period and the values in period t_{-1}.

Figure 8 presents the responses of macroeconomic aggregates to an oil discovery for both alternative models.[15] For clarity of the exposition, this Figure drops the paths with default events, but, as was the case with Figure 5, the responses that include all the sampled paths are similar.

First, note that the magnitudes of the responses are a lot smaller in the model where the field is operated by domestic firms. This is because the government has a limited ability to access the higher oil rents (τ is fixed), so the percentage increase in private and government consumption is similar. Also, note that the latter increases in $t = 0$, which shows that in this case the increase in government borrowing is mostly driven by a smoothing motive.

Spreads drop on impact because, all else equal, the government has less incentives to default when $R_t^{\text{oil}} = R_H^{\text{oil}}$ in both cases—the total default penalty is now larger when the economy is operating a giant oil field. In the oil embargo case, however, the government has access to all the additional oil rents in repayment, which fuels a much larger increase in government debt. Once production on the field starts, the government takes advantage of the more favorable price schedule by sustaining a higher level of debt, albeit with slightly higher spreads. Figure 9 shows how the fraction of economies in default changes around an oil discovery in these alternative models.

Figure 9: Fraction of economies in default, alternative models



These time series average the default state in each period t over 10,000 economies in their ergodic state without any oil discoveries since $t = -50$.

In the case in which the field is operated by domestic firms, the fraction of economies in default remains virtually unchanged for the same reason mentioned above: the government has less scope to change its behavior as a response to the oil discovery. In the oil embargo case defaults increase once the field becomes productive, but for different reasons than in the benchmark case. In the benchmark case higher default risk with $R_t^{\text{oil}} = R_H^{\text{oil}}$ is driven by higher default incentives due to a relatively lower default penalty, while in the oil embargo case it is driven by the government's

[15] Both use the benchmark calibration and the oil embargo case uses $\kappa_{\text{oil}} = \kappa$.

choice to substantially increase its outstanding debt.

4.4 Welfare analysis

The model above reconciles the puzzling findings from Section 2 by noting that the higher default risk may be driven by the nature of oil rents collected by the government. In particular, by the fact that oil production may be insulated from domestic credit disruptions and the fact that foreign creditors may have a limited ability to seize oil rents accrued to the government. 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 and government consumption, I define welfare gains of a discovery in t as χ_t such that

$$\mathbb{E}_t\left[\sum_{s=0}^{\infty}\beta^s u\left([1+\chi_t]\,c_{t+s}^{ND},[1+\chi_t]\,g_{t+s}^{ND}\right)\right]=\mathbb{E}_t\left[\sum_{s=0}^{\infty}\beta^s u\left(c_{t+s}^{D},g_{t+s}^{D}\right)\right],$$

where the superscripts ND and D indicate no discovery in t and discovery in t, respectively. 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 presents the average welfare gains of oil discoveries in four versions of the model. Column (1) corresponds to the benchmark model and shows that there are sizable welfare gains from oil discoveries, despite the increase in spreads. The gains of 3.4 percent, however, contrast with the average 12 percent increase in government consumption shown in Figure 5. 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. Columns (2) and (3) correspond to the two alternative versions of the model described in Subsection 4.3. Welfare gains from a discovery would double if private creditors were able to effectively implement a partial oil embargo in default. The economy would benefit both from higher income and lower default risk.[16]

Table 4: Welfare gains of oil discoveries

	benchmark (1)	domestic field (2)	oil embargo (3)	selling the field (4)
average welfare gains χ	3.4	1.4	7.3	10.4

Welfare gains are the average of 1,000 draws of $\chi(b,z) = 100 * \left[\left(\frac{V(b,z,-1)}{V(b,z,0)}\right)^{\frac{1}{1-\sigma}} - 1\right]$, where $V(b,z,0)$ and $V(b,z,-1)$ are, respectively, the value of discovering and not discovering an oil field given the state (b,z) drawn from the ergodic distribution.

Column (4) corresponds to a version of the benchmark model in which the government sells the giant oil field to foreign investors. Since I am abstracting from modeling the details of oil production, I assume that the government sells the rights to the stream of oil rents that it would receive from the field. The value of the field is then

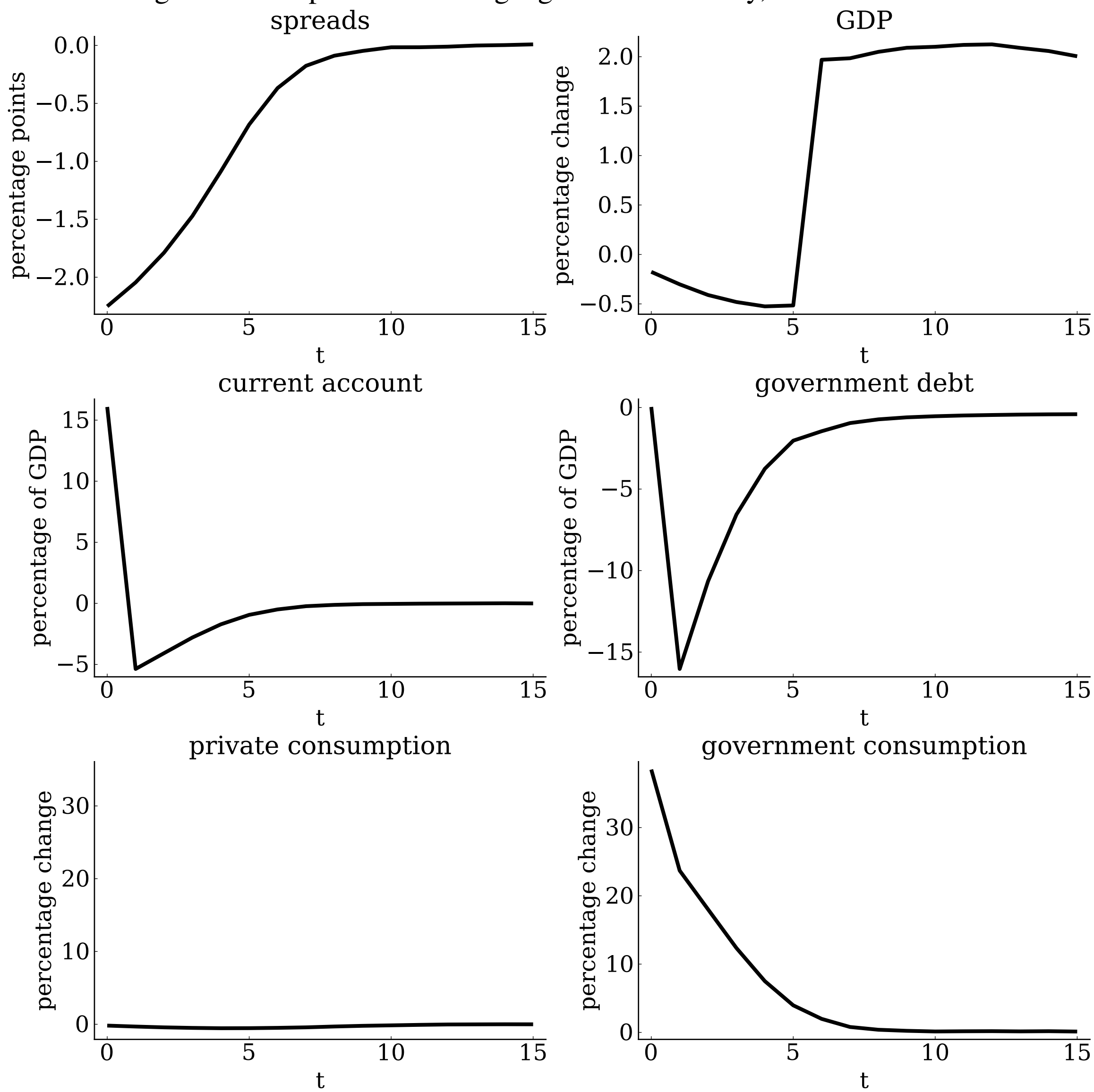
$$v = \left(\frac{1}{1+r}\right)^{\text{Twait}} \left(R_H^{\text{oil}} - R_L^{\text{oil}}\right) \frac{1+r}{r+\pi_{\text{ex}}} \tag{15}$$

where $\text{Twait} = 6$ is the time between discovery and production, π_{ex} is the probability of exhaustion, and $r = r^* + 2.9$ is the interest rate used to discount future flows of oil rents.[17] Selling the field yields even larger gains than those from facing an oil embargo in column (3). To understand why this is the case, Figure 10 plots the average model responses to an oil discovery for this alternative model.

[16]Welfare gains in the economy where the field is operated by domestic firms (column (2)) are more modest, but still positive. It is important to note that this model is not as comparable to the benchmark as the others because besides oil income no longer being immune to default the model imposes a different composition of c and g on average.

[17]I add the target of spreads to the risk-free rate to be consistent with the treatment of discovery data in Arezki, Ramey, and Sheng (2017). The welfare calculation is conservative because discounting using only r^* would yield a higher valuation.

Figure 10: Responses to selling a giant oil discovery, without defaults



Each time series considers 10,000 economies in their ergodic state without any oil discoveries since $t = -50$ and that are in good financial standing in all periods $t = -1, 0, ..., 15$. The lines are the difference between the values in each period and the values in period t_{-1}.

The government receives a large windfall in period $t = 0$ from selling the field, which fuels a large increase in government consumption and a significant reduction in government debt. The government chooses to payoff a large fraction of its debt to smooth the increase in government consumption, This last several periods during which the government accumulates debt again and spreads return to their original level.

5 Conclusion

In this paper, I documented a puzzling response of sovereign spreads to giant oil field discoveries: spreads increase sizably 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 my findings with existing theory I developed a model in which oil rents accrued to the government are not affected by a sovereign default, but tax revenue is. This is consistent with the fact that oil output is not distorted by credit disruptions from default when it is carried out by foreign firms or by state-owned enterprises.

Despite the increase in default risk that they generate, there are significant welfare gains from oil discoveries. These gains, however, would more than triple if the government sold the field to foreign investors upon discovery. There are two reasons for this significant increase in welfare. First, the economy would immediately receive a large resource windfall equal to the present value of the rents from the field, which the government would use mostly to pay outstanding debt. Second, selling the field would reduce default incentives for future governments, who would otherwise receive higher oil rents that are immune to the costs of defaulting. Removing this temptation turns out to be very valuable.

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