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An explained extreme gradient boosting approach for identifying the time-varying determinants of sovereign risk

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ABSTRACT

We use a combination of Extreme Gradient Boosting and SHAP Additive Explanations to uncover the determinants of sovereign risk across a wide range of countries from 2002 to 2021. By considering numerous variables established in existing literature within a single framework, we identify year-by-year determinants of sovereign credit risk. To gauge the liquidity and solvency aspects of sovereign risk, we utilize 5- and 10-year yield spreads as proxies. Our findings show that the key variables driving sovereign risk have remained relatively stable over time and exhibit similarities in both liquidity and solvency components. Among the prominent variables, various macroeconomic fundamentals play a crucial role, including the current account, GDP growth, per capita GDP growth, and the real exchange rate. Prior to the Global Financial Crisis, macroeconomic variables, particularly the current account, held the highest importance in explaining sovereign risk. However, following the GFC, the relative importance of these variables diminished, giving way to institutional variables, especially the rule of law.

1. Introduction

Sovereign risk is a critical element in understanding international capital flows. Investors carefully consider the default risk they face when making short- and long-term investments in a foreign country, especially when dealing with emerging or low-income countries for which information is opaque and lending is subject to greater informational asymmetries. For this reason, determinants of sovereign risk have been widely studied before (e.g., Sy, 2002; Longstaff et al., 2005; Thuraiamy et al., 2008; Hilscher and Nosbusch, 2010; Comelli, 2012; Ordoñez-Callamand et al., 2017; Montes et al., 2022; Andrade et al., 2023). Several papers examine individual countries, while others adopt a multi-country approach. Some focus on emerging countries, while others investigate sovereign risk in advanced economies. However, a shared characteristic among these previous studies is the use of linear models to identify the primary drivers of country risk. While some have incorporated the nonlinear impact of specific variables or variable groups, assuming specific functional forms, the underlying models remain linear, failing to fully capture potential nonlinear relationships.

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Table A1
Description of the variables included in the empirical analysis.

Variable	Definition	Source
domestic_creditors	Gross Public Sector Debt, Central Gov., Domestic creditors,% of GDP	World Bank/IMF
external_debt	Gross Public Sector Debt, Central Gov., All maturities, All instruments, Nominal Value,% of GDP	World Bank/IMF
shorterm_debt	Gross Public Sector Debt, Central Gov., Short-term, as% of total debt	World Bank/IMF
rule_law	Rule of Law Index	World Bank
fiscal_rule	1 if the country has at least a rule of expenditure, debt o balance in place	IMF
corruption_index	International Country Risk Guide corruption index	ICRG/World Bank
current_account	Current Account Balance% GDP	WEO
real_grosscapitalformation	Real Gross Capital Formation%GDP	Own calculation IFS-IMF
nom_grosscapitalformation	Nominal Gross Capital Formation%GDP	Own calculation IFS-IMF
openness	(Exports+Imports)/GDP	Own calculation DoT-IMF/WEO
real_exchangerate	Real exchange rate, consumer price index calculation	IFS-IMF
reserve_ara	Adequacy reserves metric: Reserves/ARA Metric	ARA IMF
reserve_broadmoney	Adequacy reserves metric: Reserves/Broad Money	ARA IMF
res_imp_own	Adequacy reserves metric: Reserves/Imports	Own calculation
reserves_std	Adequacy reserves metric: Reserves/Short Term Debt	ARA IMF
reserves_GDP	Reserves/GDP	Own calculation IFS-IMF/WEO
nom_exchangerate	Nominal exchange rate USD/Domestic Currency	Bloomberg
5yr	5 yr government yield	Investing/Bloomberg
10yr	10 yr government yield	Investing/Bloomberg
20yr	20 yr government yield	Investing/CIQ
25yr	25 yr government yield	Investing
30yr	30 yr government yield	Investing/Bloomberg
stock_market_exchange	Stock Market Exchange Index	Bloomberg
sd_stock_market_exchange	24 months window stock exchange index standard deviation	Own calculation Bloomberg
sd_exchangerate	24 months window exchange rate estándar deviation	Own calculation Bloomberg
gdp_percapita_current	GDP per Capita (Current USD)	WEO
gdp_percapita_constant	GDP per Capita (PPP USD 2017)	WEO
consumption_usd	Consumption (Current USD, Millions))	Own Calculation IFS - IMF/ Bloomberg
consumption_gdp	Consumption (% GDP)	Own Calculation IFS - IMF
grosscapitalformation_usd	Gross Capital Formation (Current USD, Millions)	Own Calculation IFS - IMF/ Bloomberg
absortion_usd	Domestic Absortion (Current USD, Millions)	Own Calculation IFS - IMF/ Bloomberg
grosspublicdebt	Total Government Debt (% GDP)	WEO
totaldeficit	Total Net Borrowing/ Lending (% GDP)	WEO
primarydeficit	Primary Deficit (% GDP)	WEO
shorttermdebt	Gross Public Sector Debt, Central Gov., Short-term, Current USD (Millions)	World Bank/IMF
interest_expense_gdp	Interest Expense from the Central Government as% of GDP	Government Finance Statistics (GFS) - IMF
fdi	Foreign Direct Investment (Millions)	Balance of Payments - IMF
fdi_gdp	Foreign Direct Investment (% GDP)	IFS - IMF
consumption_domcurr	Consumption (Current domestic currency, Millions)	IFS - IMF
grosscapitalformation_domcurr	Gross Capital Formation (Current domestic currency, Millions)	IFS - IMF
totalspend_domcurr	Total Expenditure (Current domestic currency, Millions)	IFS
totalspend_usd	Total Expenditure (Current USD, Millions)	Own Calculation IFS - IMF/ Bloomberg
gdp_domcurr	Gross Domestic Product (Current domestic currency, Millions)	IFS
gdp_usd	Gross Domestic Product (Current USD, Millions)	Own Calculation IFS - IMF/ Bloomberg
cbie	CBIE (Central Bank Independence - Extended) Index proposed in the paper [0;1].	Romelli, D. (2022).
cbieboard	Degree of independence of the "Governor and central bank board" dimension of the CBIE Index [0;1].	Romelli, D. (2022).
cbiepolicy	Degree of independence of the "Monetary policy and conflicts resolution" dimension of the CBIE Index [0;1].	Romelli, D. (2022).
cbieobj	Degree of independence of the "Objectives" dimension of the CBIE Index [0;1].	Romelli, D. (2022).
cbielending	Degree of independence of the "Limitations on lending to the government" dimension of the CBIE Index [0;1].	Romelli, D. (2022).
cbiefinances	Degree of independence of the "Financial independence" dimension of the CBIE Index [0;1].	Romelli, D. (2022).
cbiereport	Degree of independence of the "Reporting and disclosure" dimension of the CBIE Index [0;1].	Romelli, D. (2022).
gmt	Grilli, Masciandaro and Tabellini (1991) Index of Central Bank Independence [0;1].	Romelli, D. (2022).
lvau	Cukierman et al. (1992) Unweighted Index of Central Bank Independence [0;1].	Romelli, D. (2022).
lvaw	Cukierman et al. (1992) Weighted Index of Central Bank Independence [0;1].	Romelli, D. (2022).
cwne	Jácome and Vázquez (2008) Index of Central Bank Independence [0;1].	Romelli, D. (2022).

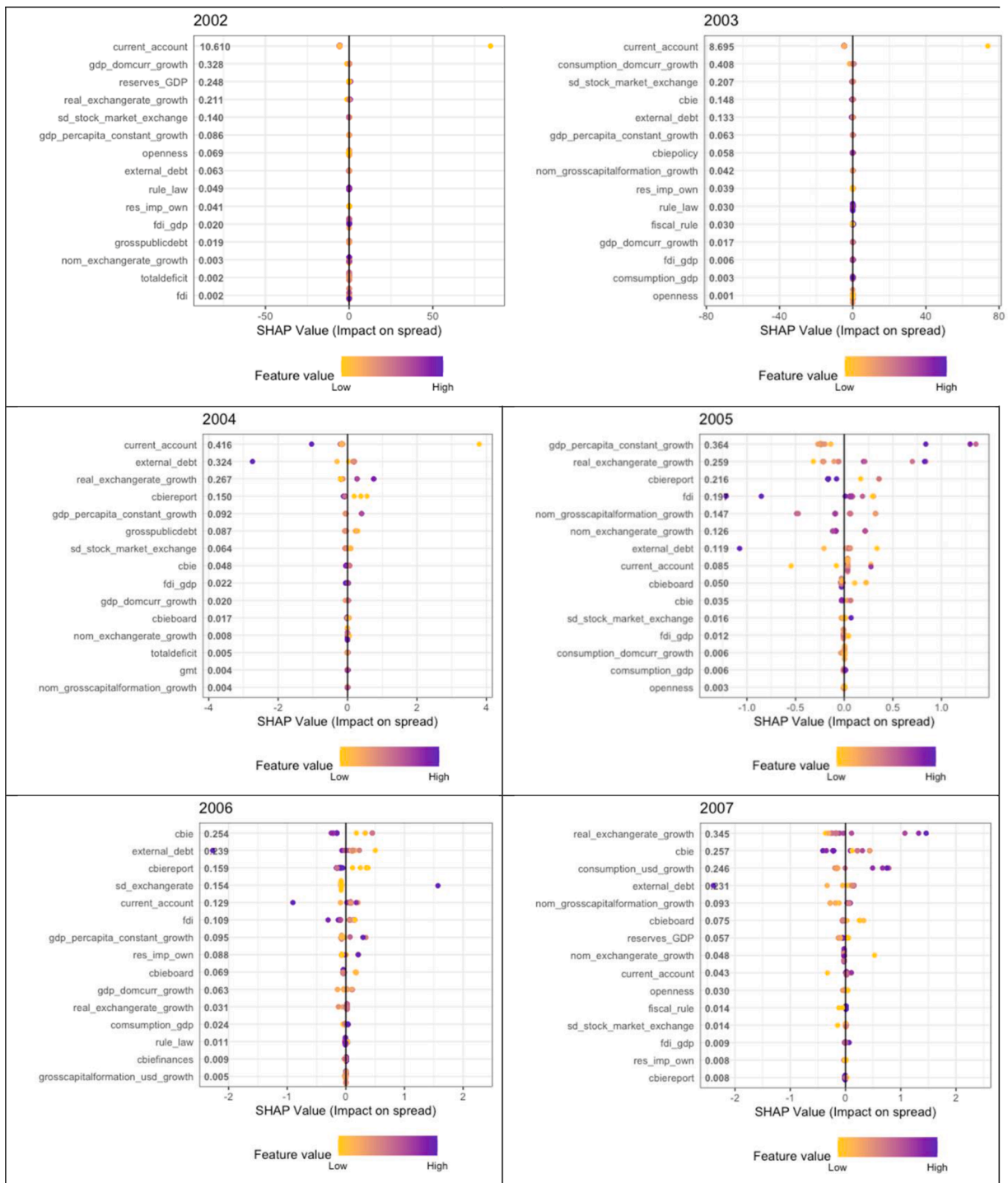


Fig. 1. SHAP values for 15 main determinants of 5-year yield spreads, 2002–07.

This paper contributes by studying the determinants of sovereign risk, measured by government-bond yield spreads, using Extreme Gradient Boosting (XGBoost). XGBoost allows considering a large set of explanatory variables, even with relatively low number of observations, alongside unspecified nonlinearities in the estimated effects. In addition, aiming to incorporate explainability into the framework, we use SHAP Additive Explanations (Shap-Values). SHAP values are one of the most popular tools in computer science to conduct Explainable Artificial Intelligence. It is technique used to measure the contribution of each input variable on the prediction of a machine learning model. SHAP values allow identifying the determinants of country risk associated with its liquidity (i.e., 5 years)

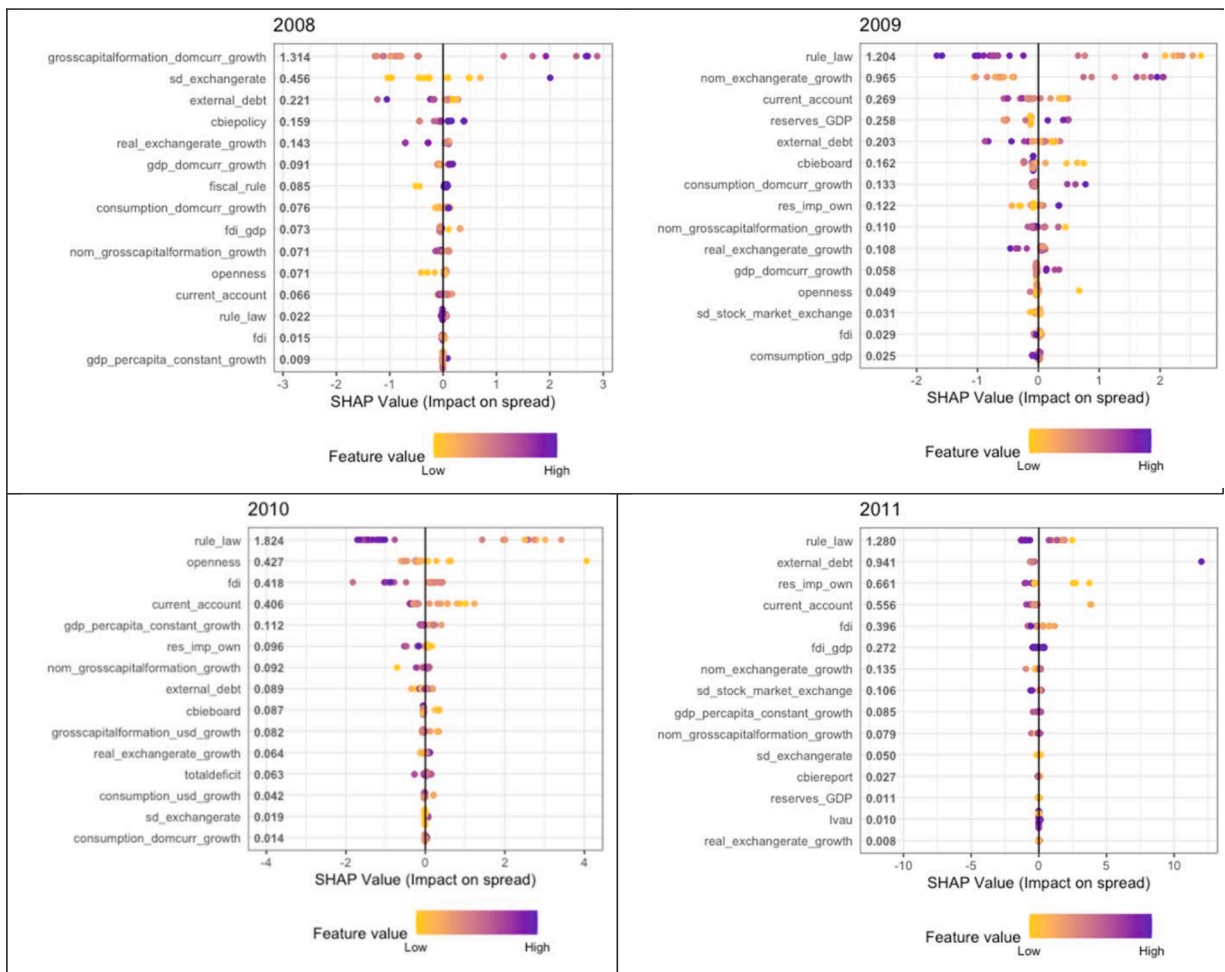


Fig. 2. SHAP values for 15 main determinants of 5-year yield spreads, 2008–11.

and solvency (i.e., 10 years) dimensions and to observe changes in the magnitude of the effects over time (e.g., normal years versus crisis years).

SHAP values offer a valuable approach for delving into the intricate dynamics of sovereign debt markets, surpassing the explanatory capacity of more conventional techniques commonly found in the literature. By providing global explanations, we gain insight into the contributions of various features to the model’s predictions. In our study, we utilize the average SHAP values of individual instances as a comprehensive measure of importance, which is discernible in the left columns of all figures.

Nevertheless, our summary plots go beyond global explanations, enabling us to visualize the specific impact of each variable on individual countries during a particular year. This empowers us to identify clusters based on the original levels of variables, wherein a particular feature exerts a more pronounced influence. This capacity allows us to transition towards local explanations tailored to specific countries and years. By considering the interplay of variables unique to each country, we can elucidate the observed sovereign yield patterns more effectively.

We include a considerably larger set of variables in our framework compared to the previous literature. Selected covariates reflect the governments’ debt situation, the state of the economy including external sector variables, international reserves, and institutional variables including the rule of law and indexes of central bank independence. Subsets of these determinants have been used in influential empirical papers like [Hilscher and Nosbusch \(2010\)](#), [Longstaff et al. \(2011\)](#), and [Eichler and Maltritz \(2013\)](#).

Our findings reveal that the relative effect of the various variables included in the model undergoes changes over time throughout the study period from 2002 to 2021. While only a limited number of variables emerge as consistent determinants across the entire period, they align with conventional indicators of sovereign risk. These variables are the current account, openness, output growth, foreign direct investment, and external debt.

Interestingly, the importance of international reserves, which played a substantial role in determining sovereign risk during the initial years of the sample, diminishes following the Global Financial Crisis (GFC). This outcome can be attributed to a couple of factors. Firstly, there has been a notable trend in the international monetary landscape characterized by a substantial increase in international reserves held by central banks of emerging economies. Notably, China has made a significant contribution to the

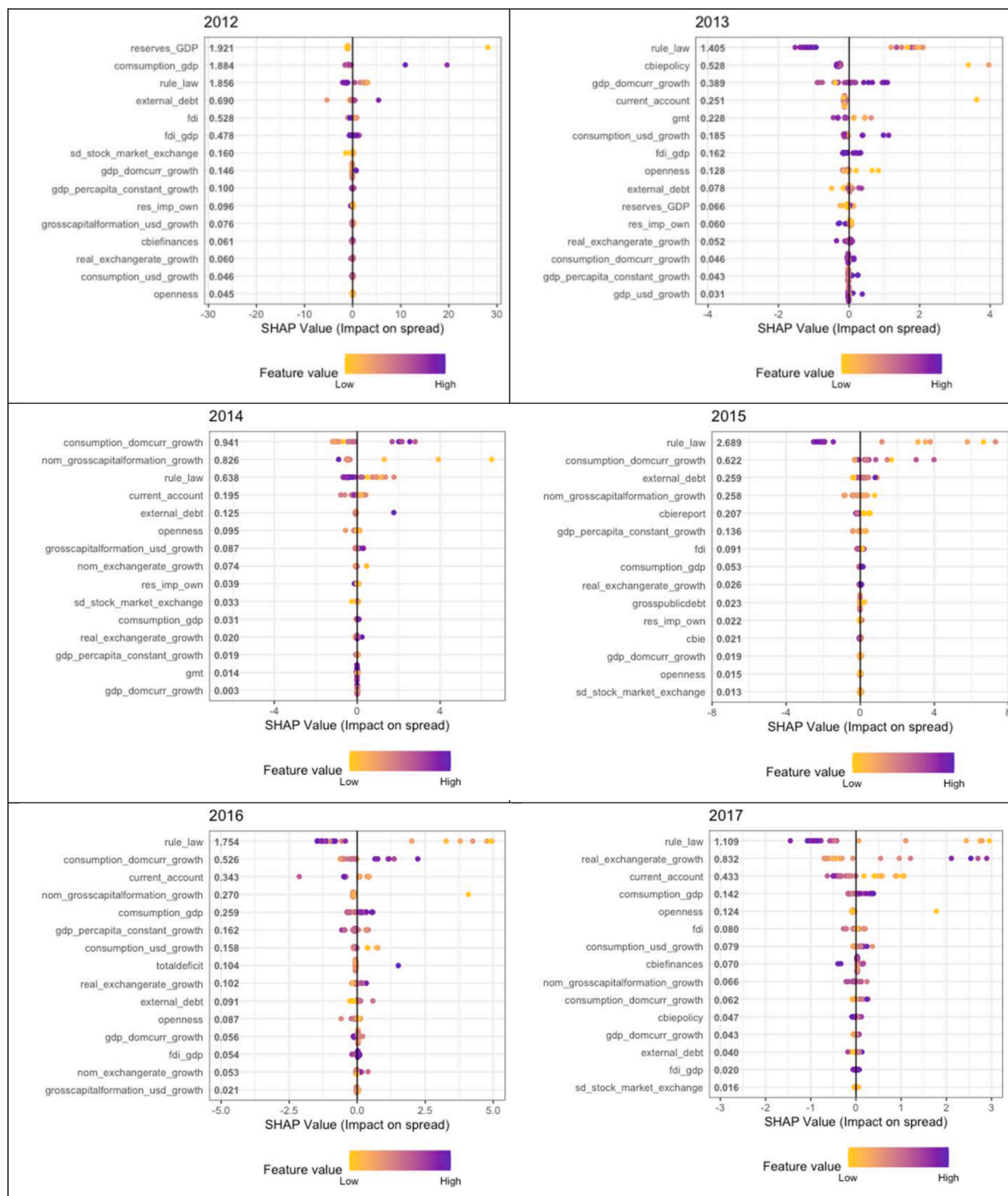


Fig. 3. SHAP values for 15 main determinants of 5-year yield spreads, 2012–21.

accumulation of reserves among emerging economies, although other countries have also played significant roles. As a result, the international reserves of emerging economies have surged from less than \$500 billion in the mid-1990s to nearly \$10 trillion in 2022. These reserves have reached a level sufficient to exceed the entirety of their public external debt. Consequently, while private sector borrowing has increased, governments have become net external creditors. Therefore, many countries have achieved an adequate level of international reserves, suggesting that further increases may be unnecessary to further mitigate sovereign risk.

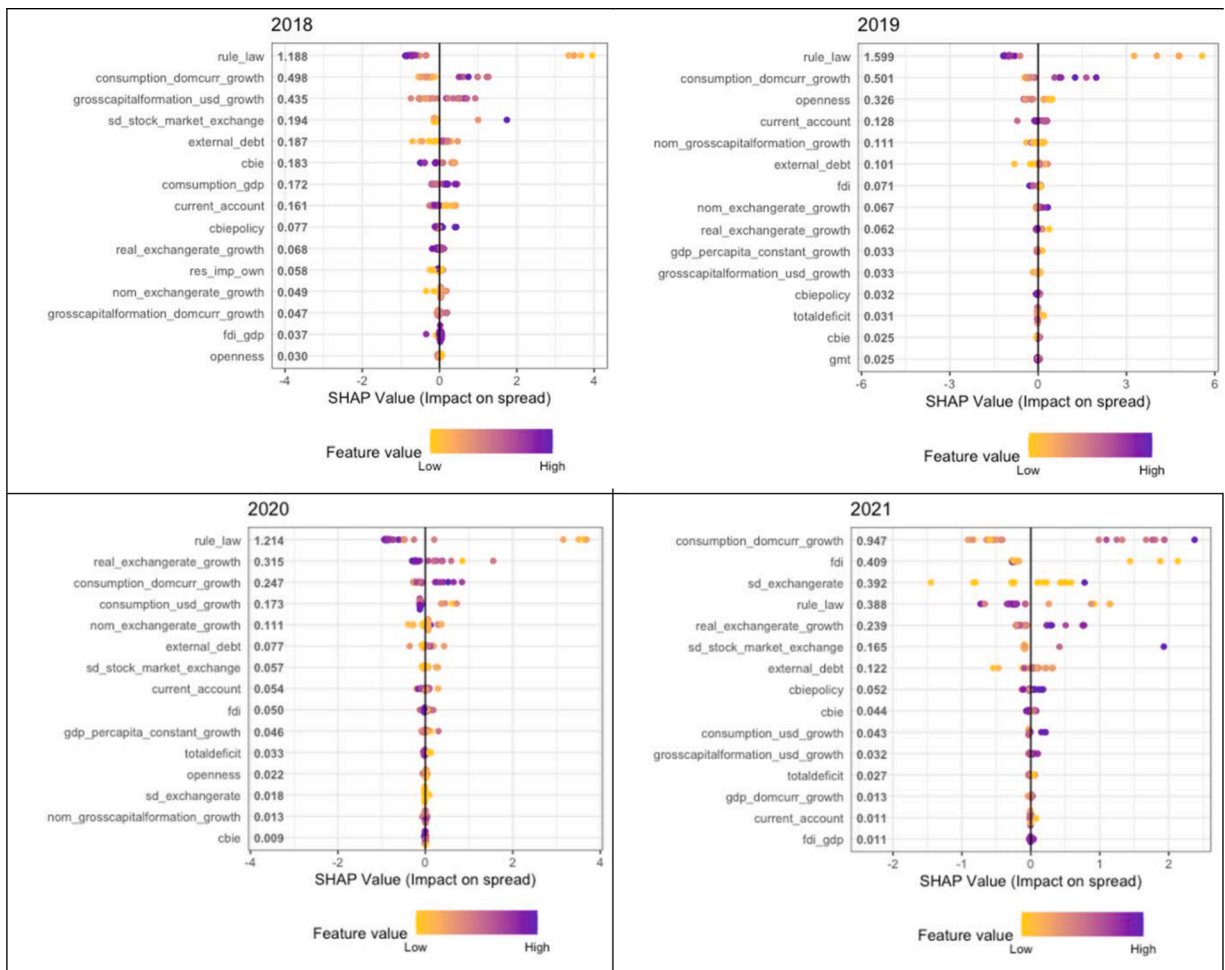


Fig. 3. (continued).

Second, in response to the GFC, major central banks worldwide implemented quantitative easing measures that significantly augmented global liquidity. Although these central banks have made efforts to taper these policies in recent years, many, particularly the Federal Reserve (Fed), have maintained an accommodative monetary stance, thus sustaining elevated levels of global liquidity. The ample liquidity in international financial markets has facilitated governments' access to abundant financing, even amidst the Covid-19 pandemic. As a result, the importance of international reserves appears to have diminished. In the same sense, their importance could increase in expectation of a reduction in US dollar global liquidity.

Interestingly, institutional variables like the rule of law and an index of central bank independence are also relevant during most of the sample period. Moreover, their relative importance has increased over the last decade. This may be since social unrest has lately risen, adding to risks for the global economy, according to the Reported Social Unrest Index calculated by the IMF (Barrett, 2022). Large and long-running anti-government protests have occurred in some advanced economies and in various emerging and low-income economies coups have sparked widespread protests.

2. Data and methods

Our study utilizes XGBoost by Chen and Guestrin (2016) as an efficient implementation of Gradient Tree Boosting (GTB), which is a variant of Gradient Boosting that employs decision trees as base learners (Friedman, 2001). GTB iteratively fits regression trees to the residuals of the previous trees, with the aim of reducing the loss function of the model. On its side, XGBoost works by iteratively building an ensemble of decision trees, where each new tree is trained to correct the prediction errors of the prior models. As it is based on decision trees, XGBoost is a natural option to handling datasets with many features, especially in relation with the number of observations. Models are fit using any arbitrary differentiable loss function, in our case a standard square loss, and gradient descent optimization algorithm.

To interpret the results of our models we use SHAP values by Lundberg and Lee (2017). SHAP values work by computing the contribution of each feature to the final prediction, considering the interactions between features (e.g., covariates) and the value



Fig. 4. SHAP values for 15 main determinants of 10-year yield spreads, 2002–07.

ranges of each feature. This can provide more accurate and intuitive explanations of how the model arrived at its prediction. Using SHAP values with XGBoost is especially helpful in cases where it's important to understand the factors driving the model's predictions, such as in understanding the determinants of sovereign debt markets. By understanding the SHAP values of each feature, we can identify which features have the most significant impact on the spread over time and how they are related to each other in the cross-section of markets.

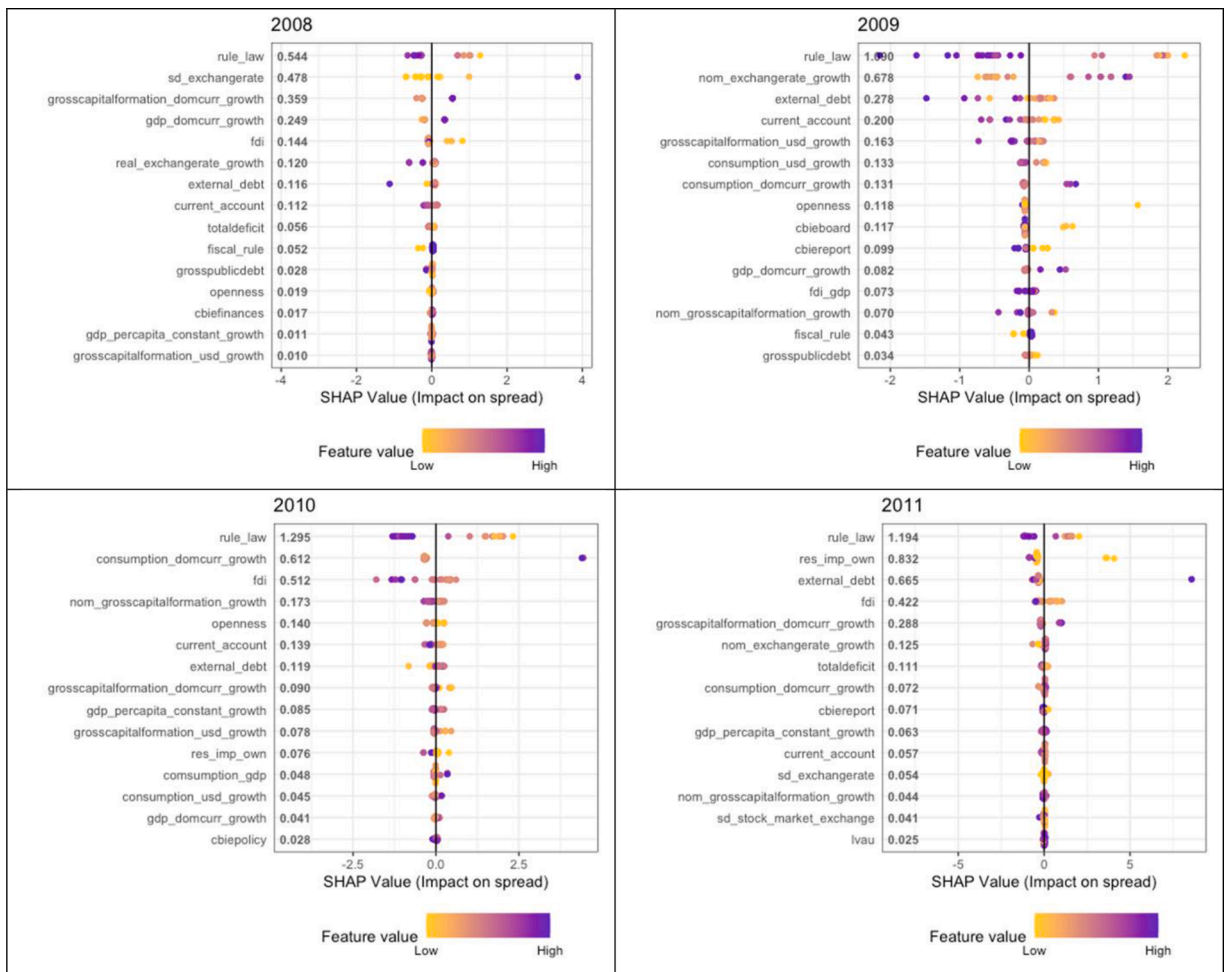


Fig. 5. SHAP values for 15 main determinants of 10-year yield spreads, 2008–11.

Our data come from a variety of sources. Spreads and other market variables come from Bloomberg, while macroeconomic and debt related variables come from the World Bank and International Monetary Fund web pages. Proxies for central bank independence come from Romelli (2022), given the virtually inexistent variability in time of these variables, we extend the original sample period, which concludes in 2017, to encompass data until 2022, aligning with the end of our own sample. A full description of the variables is shown in Table A1 in the Appendix.

3. Empirical results

We present our results for both 5-year and 10-year spreads on an annual basis. Our approach provides insights into the dynamics of risk determinants over time, while facilitates the evaluation of the relative significance of different variables associated with liquidity and solvency dimensions (see Ordoñez-Callamand, 2017 and others).

3.1. Main determinants of 5-year yield spreads

We divide the sample period into three, 2002 to 2007 (pre-GFC), 2008 to 2011 (GFC) and 2012 to 2021 (post-GFC and first pandemic year). Fig. 1 illustrates results for the first period. Several things are worth noting. First, the current account is among the main determinants of the 5-year spread and its effect on sovereign credit risk is as expected. Countries with a larger current account surplus tend to have lower spreads. This result is in line with recent literature that has shown that countries with more complex and diversified production and export structures tend to have lower risk of fiscal crises (Gomez-Gonzalez et al., 2023).

The real exchange rate also emerges as a significant factor influencing sovereign risk. Real depreciations are found to contribute to an increase in country risk. While the degree of economic openness has been among the main determinants for certain periods, it does not hold the same level of importance as other macroeconomic and institutional factors. This suggests that, when considering sovereign risk, the focus should extend beyond solely measuring the openness or closedness of an economy.



Fig. 6. SHAP values for 15 main determinants of 10-year yield spreads, 2012–21.

Real economic growth and per capita growth are also important and have the expected signs, indicating that higher product growth reduces the yield spread. International reserves, either measured in relation to GDP or in relation to imports, are also among the main determinants of country risk. Although in most years the dispersion between countries is low, the effect tends to be as expected,

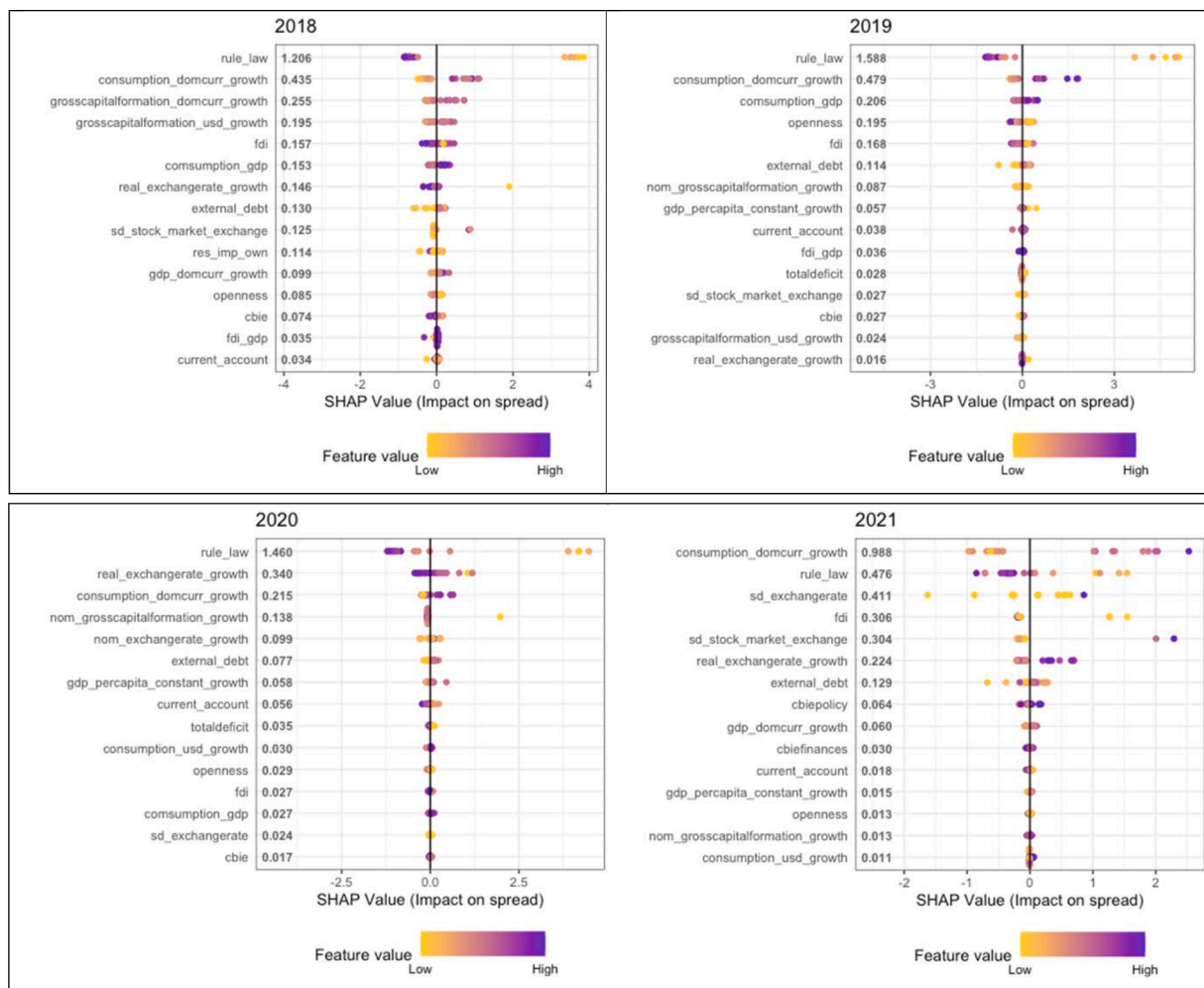


Fig. 6. (continued).

increases in international reserves tend to reduce the yield spread.

Countries with more independent central banks have a lower yield spread. This result is consistent with the hypothesis that an independent central bank helps fiscal discipline and contributes to macroeconomic stability. Institutional factors are mainly fixed in time, and therefore are associated with idiosyncratic perceptions of countries by investors. Their inclusion helps us to control for such difficult to measure fixed effects.

Fig. 2 covers the years associated to the GFC. It is evident the increasing importance of the rule of law as a determinant of short-term risk. In fact, it has the highest SHAP value for all years except for 2008. This result suggests that during times of high uncertainty and turbulence in the financial sector, international investors pay more attention to the institutional strength of the countries they invest in than during normal times. In line with the above, variables related to central bank independence are also very relevant, especially during the most intense crisis moments experienced between 2008 and 2009. The current account is still among the main determinants, but its relative importance has decreased compared to the previous period, before the GFC.

International reserves are not as relevant as during the period prior to the crisis. This may be due to two factors that are not mutually exclusive. On the one hand, several emerging economies had accumulated a considerable level of reserves between 2002 and 2007, taking advantage of the depreciation of the dollar against the currencies of these countries. For this reason, many emerging economies entered the period of the GFC with adequate levels of international reserves, which is why higher increases in them would have less impact on sovereign risk. On the other hand, the enormous infusion of liquidity generated by the central banks of developed economies in response to the GFC led countries to have enough liquidity without the need to use their international reserves to fulfill foreign currency debt payments.

The other variables that were among the main determinants of the short-term spread in the previous period remain so in this one. The relationship between international reserves and imports stands out, as it occupies one of the top places according to SHAP values in 2010 and 2011.

Fig. 3 depicts 5-year yield spreads for the post-GFC period. This period is relatively long and when considering year-by-year

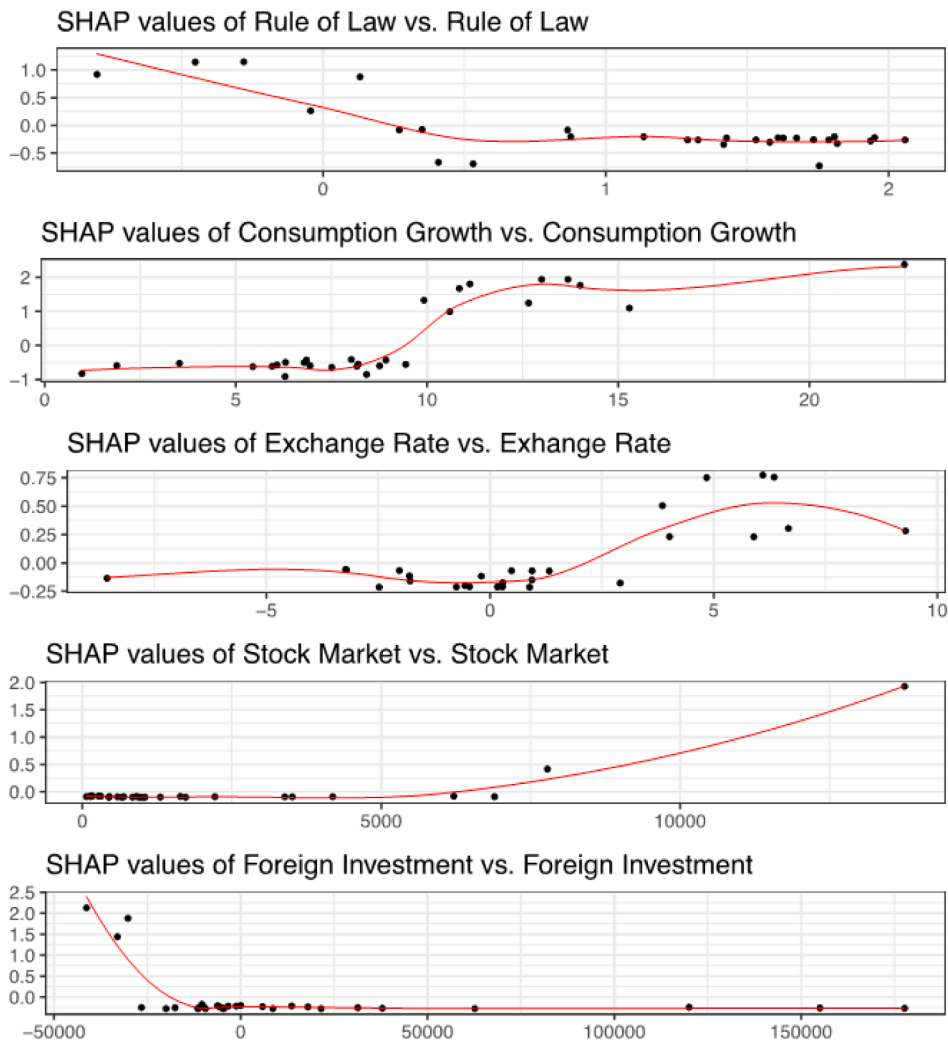


Fig. 7. Dependence plot for top-5 variables, 5 year yield spreads, in 2021.

information, the SHAP values of the main determinants exhibit considerable variation. However, even though the relative order changes from year to year, the main determinants of the 5-year spread remain relatively intact throughout the period. As during the GFC, the most important variable is the rule of law, which in several years occupies the first place according to the SHAP values. Countries with a higher index have a lower yield spread. The post-GFC period is also one of turbulence both in the economic (European debt crisis in 2012 and 2013) and in the political and social realms (increases in the IMF's social unrest index and the Covid-19 pandemic).

The variables related to central bank independence continue to be relevant, and only in two years (2012 and 2014) do not appear among the top fifteen. In fact, they become especially relevant between 2018 and 2021, a period in which several governments carried out considerable fiscal expansions. This shows the importance of the central bank acting independently of the government in times when the latter may have incentives to considerably increase public spending. Although the relative importance of the current account as a determinant of country risk has diminished compared to the pre-Global Financial Crisis (GFC) period, it still holds significance among the main factors. Similarly, other macroeconomic variables such as GDP growth and per capita GDP growth continue to exert influence on country risk, albeit to a lesser extent than before.

3.2. Main determinants of 10-year yield spreads

The Figs. 4, 5, and 6 show the main determinants of 10-year spreads year by year according to SHAP values. It is interesting to contrast these results with those of the previous subsection to analyze solvency and liquidity dimensions of sovereign risk. As seen in the graphs, the variables that are relevant to explain the 5-year spread are also relevant to explain the 10-year spread. While at the beginning of the sample, macroeconomic variables and especially the current account occupied the top spots, from the GFC onwards the most relevant spots are occupied by institutional variables. In fact, the rule of law and central bank independence variables become

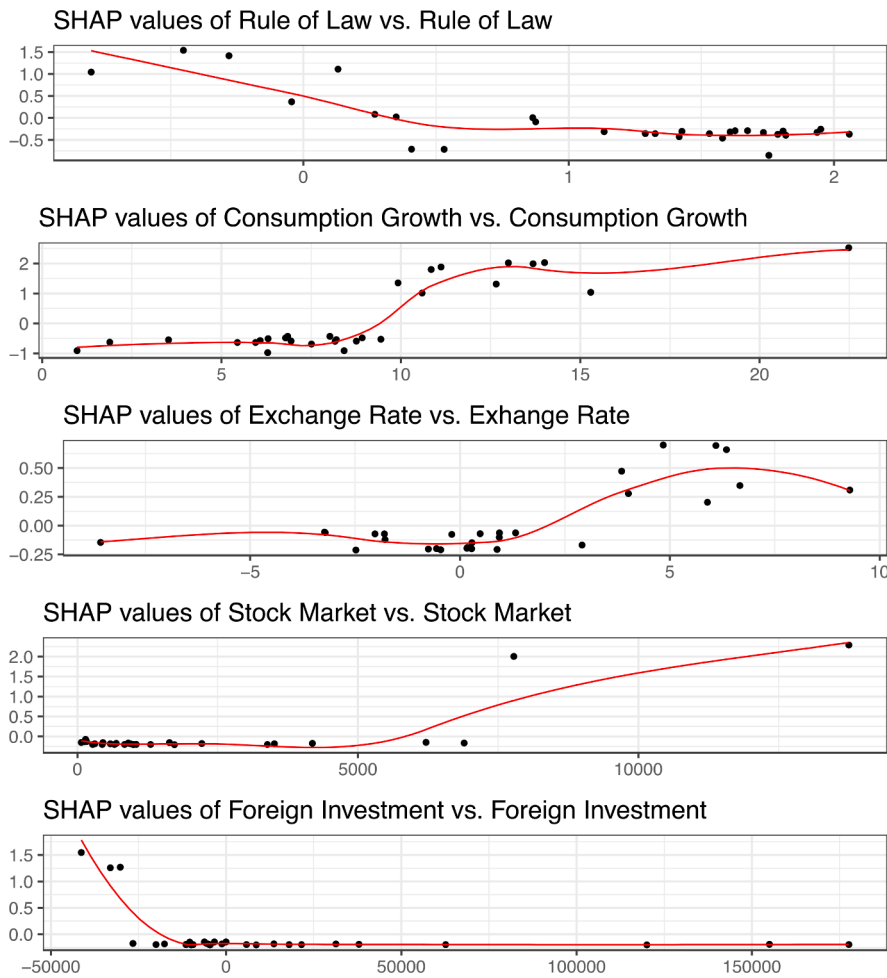


Fig. 8. Dependence plot for top-5 variables, 10 year yield spreads, in 2021.

more relevant after the GFC. The rule of law occupies the first place according to SHAP values. These results indicate that the longer the yield spread period, the more relevant institutional variables become as its determinants. This is justified by the fact that when taking positions in longer-term assets, investors are more careful in considering the institutional structure of countries. On the other hand, as financial markets integration and asset volatility in global markets increase, the importance of these fundamental factors for the long-term stability of countries has become more relevant.

Slightly more pronounced than in the case of the 5-year spread, the relative importance of international reserves has decreased since the GFC. However, this does not mean that maintaining an adequate level of international reserves is no longer important. In fact, they will likely regain relevance as central banks of advanced economies continue to normalize their monetary policy stance. For example, as shown in the graphs of this subsection, when the taper tantrum occurred in 2013, international reserves reappeared as one of the main determinants of sovereign risk.

Figs. 7 and 8 present the dependence plots showcasing the influence of the five most relevant variables on the prediction of 5-year and 10-year yields for the final year of our sample. They clearly illustrate that the impact of these variables is non-linear, in accordance with our initial expectations. Specifically, the rule of law variable demonstrates a significantly high effect for values below 0.5. However, beyond this threshold, its influence remains relatively stable, exhibiting lower variance for values ranging between 1 and 2. On the other hand, domestic consumption growth becomes increasingly important for values exceeding 10, while exchange rate growth shows a significant impact after reaching the 5 mark. In contrast, both stock market growth and foreign direct investment exhibit their effects driven by extreme values. The former is influenced by extreme values in the right tail of the distribution, whereas the latter is impacted by extreme values in the left tail of the distribution. These dependence plots provide compelling evidence that supports our approach and underscores its advantages over traditional linear models in the investigation of sovereign debt markets.

4. Conclusions

We use recent tools from explainable AI known as SHAP Values, for analyzing predictions of a sequence of XGBoost models of year-

by-year determinants of sovereign debt markets. Doing this we can observe the variation in their fundamental determinants over time, emphasizing the GFC as a turning point. Our results show that the set of variables that matter in explaining the behavior of sovereign risk are relatively stable over time and similar for the liquidity and solvency components. Among the most relevant variables are several macroeconomic fundamentals, such as the current account, GDP growth and per capita GDP growth, and the real exchange rate. International reserves and institutional variables such as central bank independence and the rule of law are also found to be relevant.

Both in the case of the 5-year yield spread and the 10-year yield spread, before the GFC, macroeconomic variables were the most important, especially the current account. However, the relative importance of these variables decreased after the GFC, giving way to institutional variables, especially the rule of law. This effect is more pronounced in long-term spreads than in short-term spreads. This result may indicate that as the international environment has become more volatile and political unrest has increased in countries, international investors have become more cautious and pay closer attention to institutional variables when making investment decisions in countries.

Author statement

The authors declare they do not have conflict of interest.
All authors contributed equally in this study.

Data availability

Data will be made available on request.

Appendix

Table A1

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