Deconstructing debt supply shocks using Treasury auction announcements

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Abstract

Although public debt in the US is at a historical high, the economic effects of changes in public debt supply are unclear. There are two main reasons why. First, debt supply is jointly determined with the rest of the economy - the Treasury takes multiple economic factors into account while implementing debt management policy. Second, debt supply changes combine two distinct phenomena - a change in the total level of debt, and a change in issuance across maturities for a given level of debt. In this paper, I use a novel identification design to estimate shocks to the level and maturity structure of public debt supply in the US. Using high-frequency changes in Treasury futures prices around auction announcements, I first isolate exogenous changes in public debt supply. Next, I use narrative evidence to identify subsets of announcements that have high information on either debt level or maturity. Exploiting differences in the variance of level and maturity shocks across subsets, I estimate a factor model and separately identify the two shocks. I find that an increase in debt level and maturity leads to higher bond returns and yields. An increase in debt level leads to lower output and employment while an increase in debt maturity leads to higher output and employment.

JEL classification: C32, C36, C38, E43, E44, G12, G28

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1 Introduction

Governments issue public debt in order to fund fiscal deficits. In the US, the amount of public debt outstanding is at an all-time high of $33.51 trillion- a debt to GDP ratio of 123%.[1] Public indebtedness has also risen sharply in several other countries post Covid-19. The effects of public debt supply changes on the economy are, however, not obvious. There are two main reasons why. First, debt supply changes are jointly determined with the rest of the economy. The US Treasury fixes the total level of new debt issuance based on the fiscal deficit - a measure that responds to economic fluctuations. Second, public debt in the US is denominated in assets with different maturities. Debt supply changes are typically a combination of two distinct phenomena - a change in the overall level of debt, and a change in issuance across maturities for a given level of debt. Isolating the two is important as it is unclear ex-ante what their individual effects on the economy are.

In this paper, I study how exogenous changes in the two key components of public debt supply affect asset prices and the macroeconomy. To address this question, I use a novel identification approach to construct shocks to the level and maturity structure of public debt supply. First, I identify exogenous changes in debt supply by looking at high-frequency changes in Treasury futures prices in a narrow interval around Treasury auction announcements. Then, I separate these price changes into shocks to the debt level and to the maturity. I use narrative evidence to identify subsets of announcements that have high information on either debt level or maturity. Exploiting differences in the variance of level and maturity shocks across subsets, I estimate a factor model and separately identify the two shocks. I find that an exogenous increase in debt level leads to a rise in bond returns and yields and a consequent fall in output and employment. On the other hand, an increase in the maturity of debt issuance leads to a rise in bond returns and yields accompanied by an increase in output and employment.

The US Treasury issues new debt in the primary market by conducting periodic auctions. It typically takes into account a range of macroeconomic and financial indicators before fixing the supply of debt in these auctions. To elaborate, the level of new debt to be issued is based on the Treasury's estimates of the variables that determine the government's budget constraint - realized public expenditure and receipts, nominal interest rate, price level in the economy, and the amount of outstanding debt.[2] Each of these variables changes significantly over time owing to economic fluctuations.[3] Similarly, the US Treasury decides the distribution of new debt across maturities based on various economic indicators. For example, in case the yield curve is upward sloping at time t, there is an incentive for the Treasury to issue more short-term debt such that it could service the debt cheaply. On the other hand, if there

[1] Based on the most recent figures as of October 9, 2023. Source: Debt to the Penny (US Treasury), FRED (Federal Reserve Bank of St. Louis)

[2] In the case of a consolidated budget constraint that includes the central bank, there is an additional term due to seigniorage revenue.

[3] If the fiscal deficit pins down the level of debt, should we expect any surprises in the overall debt level? The US Treasury typically has more knowledge than private agents on the realized volume of public expenditure and receipts. Debt level shocks thus capture revisions to private agents' estimates of these two variables. Given that my identification strategy uses narrow time intervals around Treasury auction announcements, the shocks are unlikely to pick up major changes in other economic variables.

is a chance the nominal interest rate would increase in future FOMC meetings, there is an incentive for the Treasury to issue long-term debt such that it could lock in the existing yield and it is insured against refinancing the debt at the higher future short term rates.

In order to identify exogenous changes in public debt supply, I use auction announcements in the primary market for Treasury debt. A couple of days before an auction is to take place, the Treasury announces the volume of debt to be issued in the upcoming auction. I compile a list of such announcements from 1995 to 2021 that specify publicly for the first time, the amount of new debt to be issued at different maturities. I, then, look at changes in Treasury futures prices in a narrow time interval around these announcements. The identifying assumption is that these changes in prices only capture new information on Treasury debt supply. While the supply of debt is determined by several factors, these factors are all constant in a narrow interval around the auction announcements.

To separate the two components corresponding to the level and maturity structure of new debt issuance, I use a combination of narrative evidence and identification through heteroscedasticity. Specifically, I read through the text in the Treasury auction announcements to categorize the futures price changes into subsets that contain high information on either the level or the maturity structure of debt issuance. These announcements include ones where the Treasury explicitly uses words that either signal a change in stance on the quantity of new debt to be issued, or a change in stance on debt maturity management. Then, I exploit the fact that the variances of debt level and maturity shocks are different across these subsets. This restriction allows me to estimate a factor model and separately identify the two factors of interest. The debt level factor is a series of exogenous changes in prices if the Treasury were to, hypothetically, increase the level of debt issuance uniformly for all maturities. The debt maturity factor is a series of exogenous changes in prices if the Treasury were to, hypothetically, fund a given level of debt using more long-term bonds vis-à-vis short-term bonds.

I, then, estimate the effects of the two debt shocks on asset prices and on macroeconomic variables. In doing so, I test several key implications of the preferred habitat theory.[4] Previous literature has not attempted to separately identify the two shocks and thus, empirical evidence testing the predicted effects remains scarce. I find that in accordance with the theory, an increase in both debt level and maturity leads to a fall in Treasury bond prices and an increase in the corresponding returns and yields. Moreover as predicted, the increase in returns is larger for long-maturity bonds while the increase in yields is hump-shaped across bond maturities.

Next, I decompose the effect on nominal Treasury yields into real yields and breakeven inflation. I find that an increase in both the debt level and the maturity increases real yields significantly. The effect is largest in magnitude for short-maturity bonds and decreases monotonically with maturity. The significant increase in real yields suggests that there are non-trivial effects on the macroeconomy.

[4]The preferred habitat theory is a framework to understand how the term structure of interest rates is determined due to changes in demand/supply of public debt and other macroeconomic variables. See for example, Vayanos and Vila (2021), Greenwood and Vayanos (2014), Ray (2019), etc.

I do not find evidence that the factors contain significant information shocks on other economic variables. Given that the factors are price changes in response to debt supply shocks, a possible concern is that the factors pick up other shocks from debt supply announcements that also affect asset prices. I find no significant effects on equities, commodity prices, exchange rates, and uncertainty index - assets that typically react to a range of economic shocks. Importantly, I find a significant effect on corporate bond yields - an asset that is expected to react to public debt supply shocks. The effect on corporate bond yields provides suggestive evidence that public debt supply shocks transmit through the economy by affecting corporate debt issuance, similar to the gap-filling channel of transmission (Greenwood, Hanson and Stein, 2010).

In order to study how persistent are the effects of debt management policies, I estimate local projections and examine the effect of the shocks on asset prices over 60 days after an auction announcement. I find that the effect of the level shock on short-term and long-term Treasury yields peaks at 10 days and then fades away in around 20-30 days after impact. The maturity factor has a similar hump-shaped effect on yields. However, in this case, the effects dissipate much quicker - around 10 days after the announcement. Both level and maturity shocks to public debt supply have a smaller horizon of impact than monetary policy shocks, where the effects remain significant after two months (Swanson, 2021).

Next, I estimate impulse responses from an SVAR-IV specification to look at effects on macroeconomic variables. I use the estimated factors as instrumental variables for the unobserved structural shocks. I find that an increase in debt level leads to a fall in output and a rise in unemployment. The effects are consistent with the predictions of a framework embedding the preferred habitat setup in a standard New-Keynesian model (Ray, 2019). Contrary to the predictions of the framework, however, I find that an increase in debt maturity leads to an increase in output and a fall in unemployment. I suggest alternative channels through which debt maturity affects economic activity.

Finally, I use the shocks to study the effects of large-scale asset purchase programs conducted by the Federal Reserve in the aftermath of the financial crisis of 2008-09. Through the programs, the Fed bought public and private assets in the secondary market to bring down interest rates and stimulate the economy. To measure the effects, I first map the factors from the price space to the volume space (in dollars) using a measure of private demand elasticity in the primary market for Treasuries (Droste, Gorodnichenko and Ray, 2021). Next, I look at the effects of shocks equalling the volume of debt bought during LSAP 1,2,3 and the Maturity Extension Program. I find that LSAP 1,2 and 3 led to a significant decrease in the 10-year yield. This in turn led to a rise in output growth and a fall in the unemployment rate. The Maturity Extension Program led to a decrease in the 10-year yield accompanied by a fall in output growth and a rise in the unemployment rate.

Related literature

This paper contributes to the literature on the estimation of structural macroeconomic shocks and their dynamic causal effects.[5] I estimate two new series of shocks - to the level, and to

[5] See Ramey (2016) for a comprehensive review.

the maturity structure of public debt issuance. In doing so, I uniquely combine the use of three key identification methods used widely in this literature – high-frequency identification (Kuttner, 2001; Jarociński and Karadi, 2020; Känzig, 2021; Droste, Gorodnichenko and Ray, 2021, etc.), narrative methods (Romer and Romer, 2004; Mertens and Ravn, 2013; Aruoba and Drechsel, 2022, etc.), and identification through heteroscedasticity (Rigobon and Sack, 2003; Sentana and Fiorentini, 2001; Lewis, 2021; Brunnermeier, Palia, Sastry and Sims, 2021, etc.). While previous literature has used various ways to identify different volatility regimes, to the best of my knowledge this is the first paper to identify volatility regimes using narrative evidence. The identification strategy can be used more generally to separate other kinds of structural shocks from observed variable changes if the theory does not have a clear prediction of how the structural shocks should behave.

I use shocks to the level and maturity of debt issuance to test key predictions of the preferred habitat theory (Vayanos and Vila, 2021; Greenwood and Vayanos, 2014; Ray, 2019). Droste, Gorodnichenko and Ray (2021) estimate private demand shocks for US Treasuries in order to evaluate the theory. It looks at high-frequency price changes around the release time of Treasury auction results in order to isolate debt demand shocks. In contrast, I look at price changes around auction announcements to estimate shocks to debt supply.

Andreolli (2021) argues that the duration of marketable debt is decided by legislature and that it is independent of monetary policy. The focus is on the slow-moving variation in the duration of debt. Instead, I argue that the Treasury actively makes changes to the maturity of new debt as is evident from the Quarterly Refunding process. The maturity of debt fluctuates significantly as a result of these decisions. The focus of the paper is to estimate shocks to these fluctuations, rather than the slow-moving component over time.

Phillot (2021) uses daily movement in futures prices around US Treasury auction announcements to estimate debt supply shocks. Lengyel (2022) uses intraday movements in gilt futures prices around UK Debt Management Office announcements to estimate public debt supply shocks in the UK. This paper differs in three main dimensions – first, I separate the two distinct dimensions of debt supply that drive major changes in futures prices around the auction announcements. Second, different from Phillot (2021), I look at futures price changes around narrower intraday intervals vis-à-vis the daily change in futures prices. The usage of daily data contaminates debt supply shocks in the liquid Treasury futures market and leads to potentially weak identification, similar to the case for monetary policy shocks (Lewis, 2022). Finally, I look at institutional changes to remove redundant announcements that do not provide new information to private agents.

The rest of this paper proceeds as follows. In section 2, I discuss the data and institutional details around Treasury primary market announcements. In section 3, I construct changes in futures prices and estimate a factor model to separate the level and maturity factors. In section 4, I look at the effects on asset prices. In section 5, I use an SVAR-IV to look at the effects on the macroeconomy. I use my framework to study the effects of large-scale asset purchase programs of the Federal Reserve in section 6. Section 7 concludes.

2 Data and institutional details

In this section, I compile a list of US Treasury primary market announcements that specify the amount of new debt to be issued at each maturity in the next auction. Owing to changes in the institutional arrangement of Treasury auction announcements, not all announcements can be considered news. I discuss changes in the institutional arrangements of Treasury auction announcements and how I filter out announcements that contain redundant information. After I compile the list of announcements, I look at changes in futures prices in a narrow window around the announcement release times. Futures price changes in this interval capture new information about debt supply, exogenous to the information agents already have on the quantity of new debt to be issued at each maturity. In the next section, I use the futures price changes to estimate shocks to the level and maturity structure of debt supply.

The final sample consists of 331 announcements from August 1995 to December 2021. I obtain information on Treasury announcements from the website of the US Department of the Treasury and from TreasuryDirect.gov Futures prices at 1-minute bars are obtained from PortaraCQG.

2.1 Primary market for Treasuries

The US Treasury issues debt through periodic uniform price auctions. In each auction announcement, the Treasury specifies the total volume of debt to be issued at each maturity in the upcoming auction, which typically takes place around a week later. Each auction is only limited to debt at a particular maturity. The auctions are designed such that the Treasury always issues the total quantity of debt it announces.[6]

There are two kinds of announcements that contain information on the level of debt to be issued at each maturity during the next auction. At the end of the first month of each quarter, the Treasury discusses its debt management policy with primary dealers and members of the Treasury Borrowing Advisory Committee (TBAC). Following the meeting, it releases the Official Remarks on Quarterly Refunding. The Official Remarks, henceforth OFR, contain the quantity of debt to be issued for bonds of certain maturities. For example, a typical OFR may pin down the debt to be issued at the next auction for the 3-year note, 10-year note, and 30-year bond. In addition, it contains information on a change in the Treasury's stance on the issuance of new debt. In case the Treasury foresees an increase in the overall debt

[6] The Treasury issues marketable and non-marketable debt. Marketable debt can be traded in the secondary market. These include short-term bills, medium-term notes, and long-term bonds and makeup 77% of total debt as of October 2023. I only look at changes in marketable debt as they make up the bulk of public debt, and due to institutional differences in the way non-marketable debt is bought and redeemed. Marketable debt can be categorized into bills, notes, bonds, inflation-protected securities or TIPS, and floating rate notes or FRNs. I only look at nominal debt issued in notes and bonds, i.e. for maturities from 2 years to 30 years which make up around 71% of marketable debt. Other than the fact that they make up the bulk of marketable debt, I focus on these Treasuries as I look at changes in Treasury futures prices which are only available at the 2-year, 5-year, 10-year, and 30-year maturities. Moreover, bills, TIPS, and FRNs have different payoff structures than nominal notes and bonds.

level, or a need to change the maturity structure of issuances, it conveys this information in this announcement. Other sections contain information on on buybacks, changes in auction rules, changes in the auction calendar etc.[7]

Until 2003, the Treasury held a press conference and the remarks were made by the Assistant Secretary for Financial Markets. Since 2003, this information has been uploaded on the website of the US Treasury. At the same time at which the Official Remarks are made public, a one-page document for each maturity containing the volume of the auction to be issued along with the rules of the auction is uploaded to the Treasury Direct website - the arm of the US Treasury which deals with the primary market.

The OFR pins down the volume to be issued for certain auctions. For the rest of the auctions in the quarter, the Treasury releases the volume to be issued around a week before the auction is to take place. These announcements, henceforth intermediate announcements, are one-page documents containing the volume to be issued in the next auction, along with the auction rules. These are uploaded to the Treasury Direct website and resemble the Treasury Direct counterparts of the OFRs. The Treasury Direct website contains information on announcements from 1998. The US Treasury website contains information on announcements from 1985. The time of release, however, is only known for announcements from 1995.

From March 2000 until April 2002, the US Treasury conducted buyback operations which reduced the total debt in circulation by $67.5 billion and changed the average maturity of outstanding debt from 67 months to 65 months.[8] I take into account this information while constructing a series of debt supply shocks.[9]

The number of announcements containing new information on debt supply is less than the total number of OFRs and intermediate announcements in the sample period. All OFRs are news as they make public for the first time the total quantity of new debt to be issued during certain auctions. Until January 2010, these announcements did not mention anything about other auctions and thus all intermediate announcements from 1998 until 2010 are news as well. From February 2010, the OFRs contained a new section called *Projected Financing Needs*. If this section mentioned for example that,

"the Treasury foresees no more changes in the next quarter"

there would be no changes in auction sizes for the rest of the auctions in the quarter. These intermediate announcements thus contain no new information on US debt supply. On the other hand, often the section mentioned

"auction sizes may change".

In this case, intermediate announcements contain new information pinning down the auction volume. From January 2016, there was another change in this section. Whenever the

[7]The OFR is part of several documents that the Treasury releases as part of its Quarterly Refunding process. Appendix A.3 contains further details on these documents and on why the OFR is particularly relevant for me.

[8]This is the change in maturity of all outstanding debt. The weighted average maturity for the set of bonds I consider in this paper remained roughly steady at 84 months.

[9]Section A.2 contains additional details on buyback announcements.

Treasury mentioned that auction sizes may change, it explicitly started pinning down the volume to be issued at all maturities. Thus from January 2016, intermediate announcements effectively contain no new information on Treasury debt supply. After eliminating redundant announcements, I have a total of 348 announcements from August 1995 to December 2021 which contain new information on Treasury debt supply.

Additional institutional details of the Treasury primary market and a discussion on the relevance of the announcements I consider for debt supply shocks are in section A in the Appendix.

2.2 Treasury Futures series

I look at changes in Treasury futures prices around primary market announcements to identify shocks to debt level and maturity. The idea behind this identifying assumption is the following. The Treasury looks at a range of macroeconomic and financial variables before deciding the amount of debt to be issued at each maturity. Immediately after an announcement release, there is a revision to the agents' information set about debt supply, exogenous to everything else in the economy. Changes in Treasury futures prices in a narrow window around these announcements provide a market-based measure of this revision to the agents' information set.

Following the high-frequency identification (HFI) literature, I look at changes in the (log) price of 2-year, 5-year, 10-year, and 30-year Treasury futures and the 6-month Eurodollar around announcement days. Treasury futures are only available for the 2-year, 5-year, 10-year, and 30-maturities. I also use the futures on the 6-month Eurodollar as it offers a maturity point at the shorter end of the term structure. The aforementioned futures prices are likely to react the most when there is a debt supply shock. Moreover, the identification of two factors requires at least five variables, as determined by the Ledermann bound. Treasury futures trade in the Chicago Board of Trade (CBOT) exchange under the Chicago Mercantile Exchange (CME). The Treasury futures market is among the most liquid markets in the world. I obtain data on futures prices at 1-minute bars from PortaraCQG.

Futures prices are settled 4 times each year- in March, June, September, and December. I track the price of the contract that expires the soonest, until 21 days prior to expiry. These are the most traded contracts by volume. For example, if a contract expires on 25th March, I use the price of this contract until 4th March. From 5th March, I use the price of the contract that expires in June. I switch the contract 21 days prior as trading volume falls significantly for a contract in the month of expiry. The prices are adjusted to close the gap at each switching date and form a continuous series.[10]

The choice of the event window in HFI is crucial. A large event window would contaminate

[10]Each futures contract has a range of underlying securities that can be delivered upon expiry. For example, the 10-year futures allows Treasuries with remaining maturity between 6 years and 6 months, to 10 years. In reality, only one among the multiple securities would be the cheapest to deliver. The futures prices are thus a market-based proxy that tracks the price of this cheapest-to-deliver security.

the observed shocks while a small window would be unable to pick up the entire reaction of market participants to the news. Moreover, if a window contains other macroeconomic announcements, price changes would be contaminated by reactions to other news. I fix the event window based on the structure of the announcements. Intermediate announcements are short in length and typically contain little information. For these announcements, I look at changes in futures prices from 10 minutes before the announcement to 20 minutes after. Treasury futures markets are highly liquid and any new information is incorporated almost immediately after the release. The 30-minute interval is thus enough to capture all relevant information.

The release time for OFRs before 2001 is not publicly available. However, there is information on the time of the commencement of the press conference where the OFR is read out. Given that the flow of information was more gradual for these announcements, I look at the change in prices from 10 minutes before to 50 minutes after. For OFRs after October 1997, I look at prices from 10 minutes before to 45 minutes after. The window is different as post-October 1997, OFRs were released at 9 a.m. (EST) and the reports of the consumer confidence survey are released at 9:55 a.m. (EST). Post 2001, the exact time of release is known and I set the window as 10 minutes before to 20 minutes after the time of release.

It is important to rule out Treasury releases that clash with other major news releases. The Treasury futures market is elastic and futures prices react to a range of information. I exclude announcements that clash with other macroeconomic news announcements. This leaves 331 total announcements. Section A.5 in the appendix provides more details about how I obtain the final set of announcement dates and the choice of event window in each case.

I identify shocks as changes in log futures prices in a narrow window around announcements

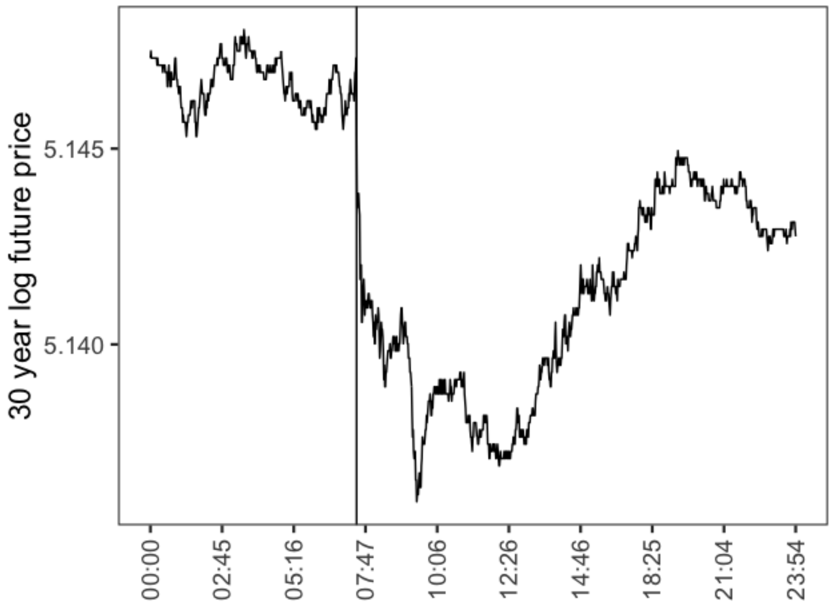
$$f_t^m = F_{t,post}^m - F_{t,pre}^m \tag{1}$$

To the extent that the risk premium in futures prices is constant around the event window, f_t^m captures exogenous changes in expectations from debt supply news.

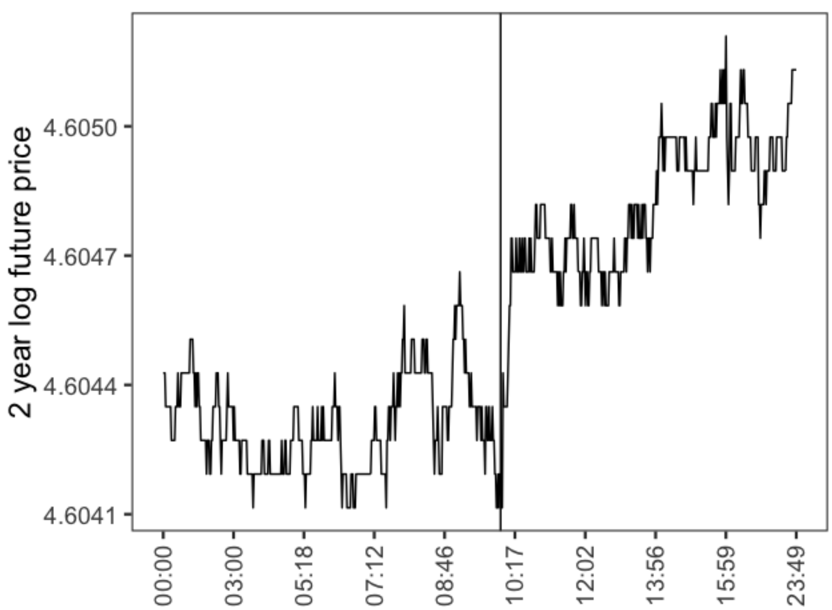
Figure 1(a) and 1(b) show intraday price movements for two announcements on 2020-05-06 and 2009-04-23. The announcement on 2020-05-06 was the first announcement after Covid-19 where the Treasury signaled a much larger issuance of debt than usual. Futures prices fell significantly following a larger-than-expected debt issuance.

Changes in debt supply at a particular maturity affect how agents substitute their holdings across maturities. I look at changes in prices of all futures for each announcement irrespective of the maturity being pinned down. For example, if an announcement pins down the volume of 2-year notes and 10-year notes, I look at the change in futures prices for all available maturities.

What exactly do these surprise movements in Treasury prices capture? Unlike the monetary policy literature where changes in Fed funds futures can be mapped to surprise changes in



(a) Announcement on 2020-05-06



(b) Announcement on 2009-04-23

Figure (1) Intraday movements in future prices. The x-axis is in CDT - the local time of the Chicago Mercantile Exchange (CME). y-axis is in log prices. In panel (a), price changes are on 2020-05-06. 30-year futures price jumped following an announcement at 7:30 a.m. (CDT). In panel B, price changes are on 2009-04-23. 2-year futures price jumped following an announcement at 10:00 am (CDT).

the policy rate, here the mapping is from a surprise in the volume space to a surprise in the price space. More specifically, if the Treasury announces $15 million of 2-year Treasury notes, this exercise cannot pin down what fraction of $15 million is expected and what fraction is a shock. The identifying assumption uses the fact that the unobservable shock in quantity leads to the observed movement in Treasury futures prices. The futures price changes are thus a market-based response to an exogenous change in debt supply.[11]

3 Quantifying shocks to debt supply

Futures price changes contain information on both shocks to the level of public debt and to its maturity structure. To separate the two components, corresponding to the level and maturity structure of new debt supply, I use narrative evidence to come up with a subset of announcements that contain particularly high information on the level and maturity of debt issuance. I exploit the differences in the variance of level and maturity shocks across these subsets to estimate a factor model and separate the two shocks.

This exercise allows me to construct a measure of exogenous changes in prices if the Treasury were to, hypothetically, conduct the following two exercises- fund a given debt level by issuing the same amount of debt at all maturities, and increase long-term debt issuance along with an equal decrease in short term debt issuance. Each of the shock series I construct has well-behaved properties, that is, it is not correlated with itself, it is not predictable by other macroeconomic variables, and it has no correlation with other proxies in the applied macroeconomics literature.

3.1 Summary statistics of asset price changes

Table 1 panel A reports summary statistics for the intraday price changes. The mean and median of the shocks are close to 0. Long-term futures tend to be more volatile than short-term futures. Price changes are highly correlated with each other. The correlations are highest for futures with closest maturities and decrease with difference in maturity.

In table 1 panel B, I look at the summary statistics for a set of randomly selected dates in the sample period. I look at price changes between 12:20 a.m. and 12:50 a.m. (EST) as it corresponds to a half-hour window with little possibility of a major macroeconomic news release.[12] I find that price changes around Treasury supply news have higher variance and lower kurtosis. Figure 2 plots the corresponding kernel densities for the 2-year and 5-year futures on announcement dates and time windows without announcements. Price changes

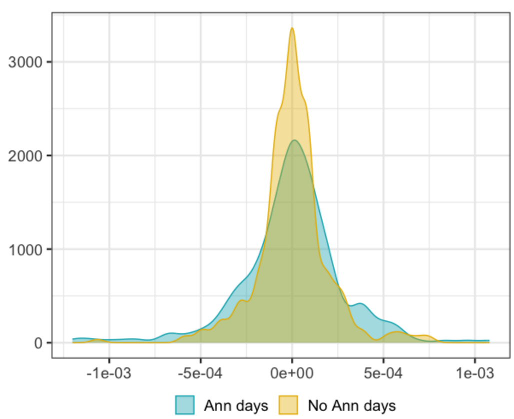
[11] An underlying assumption here is that the elasticities of the Treasury demand and supply curves do not change significantly around announcements. This is important to ensure that the observed futures price changes are comparable over time. The assumption is likely to hold as there have not been major changes in auction rules in the sample period I consider.

[12] I select the window based on the release times of major macroeconomic news reports according to Elenev, Law, Song and Yaron (2022) and Gilbert, Scotti, Strasser and Vega (2017).

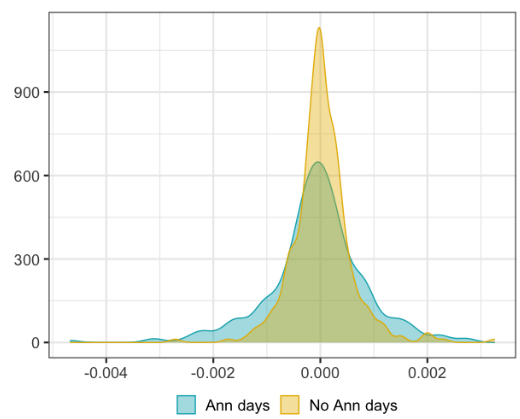
Futures price changes	Mean($\times 10^{-5}$)	Median	SD($\times 10^{-4}$)	Kurtosis	N	Correlations f_t^{6m}	f_t^{2Y}	f_t^{5Y}	f_t^{10Y}	f_t^{30Y}
Panel A: Ann days										
f_t^{6m}	0.6	0	0.8	3.19	331	1				
f_t^{2Y}	-0.2	0	2.8	3.24	331	0.42	1			
f_t^{5Y}	-6	0	9.1	2.72	331	0.4	0.84	1		
f_t^{10Y}	-17	0	19	3.92	331	0.34	0.72	0.89	1	
f_t^{30Y}	-22	0	33	4.96	331	0.28	0.53	0.67	0.81	1
Panel B: No ann days										
f_t^{6m}	-0.3	0	0.6	3.01	331	1				
f_t^{2Y}	0.2	0	1.9	4.33	331	0.30	1			
f_t^{5Y}	3	0	5.7	5.79	331	0.40	0.74	1		
f_t^{10Y}	3	0	12	4.96	331	0.31	0.67	0.89	1	
f_t^{30Y}	-1.5	0	22	4.67	331	0.29	0.61	0.81	0.89	1

Table (1) Summary statistics of all intraday asset price changes. Price changes are in log prices. Ann days are price changes around primary market announcement days which contain new information on debt supply. No ann days are price movements on a set of randomly chosen dates in the sample period.

around intervals with debt supply announcements contain fatter tails, driven by major jumps reacting to the news.



(a) 2 year futures



(b) 5 year futures

Figure (2) Kernel density of 2-year and 5-year futures price changes. Ann days correspond to price changes around Treasury primary market announcements which contain new information on debt supply at the maturity level. No Ann days correspond to price changes between 12:20 a.m. and 12:50 a.m. (EST) for a set of randomly chosen dates in the sample period. x-axis is in log prices

3.2 Testing for the number of factors

The high correlation among intraday prices in table 1 suggests that there are common factors driving changes in all futures prices. I collect the price changes in the five futures series in a 5×1 matrix D_t. To recover the underlying factors, I estimate the following factor model

$$D_t = \Lambda' F_t + \epsilon_t \tag{2}$$

where F_t is the $k \times 1$ vector of factors, Λ' is the $5 \times k$ matrix of factor loadings and ϵ_t is white noise.

I test for the number of underlying factors k using the Cragg and Donald (1997) statistic. Table 2 reports the results. The test rejects the null of 0 factors. It also rejects the null of 1 factor. This is key since the previous literature uses the first principal component of price changes around announcements as a proxy for exogenous changes in the supply of different assets and commodities.[13] For Treasury supply shocks, it is clear that the first factor is not enough to proxy for changes to debt supply. The test cannot reject the null of 2 factors. There is an additional dimension of debt supply that drives major changes in futures prices.

H_0 : No of factors =	Wald stat	χ^2 crit value	p-value	degree of freedom
0	103.35	18.31	0	10
1	19.11	11.07	0.002	5
2	**1.06**	**3.84**	**0.30**	**1**

Table (2) Cragg and Donald (1997) test for the number of factors underlying price changes around Treasury primary market announcements. $H_0 : k_0$ vs $H_1 : k > k_0$. The test searches over all possible factor models with the order k such that ϵ_t is as close to a white noise as possible. The distance between the residuals and the white noise is given by a Wald statistic.

3.3 Structural interpretation for the factors

In order to recover the two underlying factors, I estimate equation 2. As a first step, I estimate the first two principal components F_t.[14] Next, I orthogonally transform them using restrictions based on narrative evidence and heteroscedasticity to obtain the two factors of interest.

The factor model in equation 2 is identified up to a rotation

$$D_t = \Lambda' U U' F_t + \epsilon_t = \tilde{\Lambda}' \tilde{F}_t + \epsilon_t \tag{3}$$

where U is an orthogonal matrix $\begin{bmatrix} cos\theta & -sin\theta \\ sin\theta & cos\theta \end{bmatrix}$. $\tilde{F}_t$ contains the factors corresponding to changes in debt level and debt maturity. $\tilde{\Lambda}'$ is the loading matrix of the data on the factors of interest. The factors of interest are a linear transformation of the principal components given by

$$\tilde{F}_t = U' F_t \tag{4}$$

[13] Droste, Gorodnichenko and Ray (2021) use the first principal component as a proxy for Treasury demand shocks. Känzig (2021) uses the same as a proxy for news shocks to oil production.

[14] Appendix B contains information on the estimation of principal components

The orthogonal matrix U has one degree of freedom θ. In order to pin down U I provide a set of restrictions based on narrative evidence and heteroscedasticity.[15]

Equation 4 admits the following variance representation

$$V(\tilde{F_t}) = U'V(F_t)U \tag{5}$$

where $V(F_t)$ is the known covariance matrix of the first two principal components. Given that θ is the only unknown parameter required to pin down U, it suffices to restrict any one of the three unique elements in $V(\tilde{F_t})$ to estimate θ. This restriction would yield one equation in one unknown which, subject to regularity conditions, could be solved in order to obtain θ. However, to obtain the 'correct' θ – one that would yield the true factors of interest, the restrictions would have to be meaningful ones based on the properties of the factors in the sample. I impose the following restrictions based on the amount of information the announcements contain on either debt level or maturity.

Intermediate announcements are typically one page in length. These simply contain the total amount of debt offered at each maturity and some rules of the auction. These announcements contain similar information for both factors. Accordingly, I impose the following variance structure on this set of announcements which I label as subset *inter*.

$$V(\tilde{F}_{inter}) = U'V(F_{inter})U, \qquad V(\tilde{F}_{inter}) = \begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix} \tag{6}$$

Next, I read through the set of 95 OFRs. These announcements are more verbose and contain additional information on the Treasury's stance towards debt issuance. In case the announcement specifically discusses a reason behind a possible change in the overall level of debt issuance, I assign it to a subset *level*. Announcements in subset *level* contain more information on debt level and less information on maturity. The variances are thus allowed to be different from each other.

$$V(\tilde{F}_{level}) = U'V(F_{level})U, \qquad V(\tilde{F}_{level}) = \begin{bmatrix} \sigma^2_{1,level} & 0 \\ 0 & \sigma^2_{2,level} \end{bmatrix} \tag{7}$$

Announcements in this subset include releases that announce an overall change in the level of debt to be issued in the near future and buyback announcements with no information on the maturity of buying. The announcement on 2008-01-30, for example, contains information on the Treasury's stance about the future level of debt

[15]While searching over all possible rotations, I also consider solutions of the form $\bar{U} = \begin{bmatrix} cos\theta & sin\theta \\ sin\theta & -cos\theta \end{bmatrix}$ with $|U|$ = -1. However, the choice of the optimal matrix between the two sets of matrices is essentially a sign identification problem. I pin down the sign later in this section using restrictions from the Greenwood and Vayanos (2014) framework.

> "*The fiscal year 2008 outlook, even absent the enactment of a fiscal stimulus package,* ***potentially calls for a higher net marketable borrowing requirement*** *resulting from larger baseline deficit projections and potential reductions in the issuance of non-marketable securities to states and local municipalities. Consequently, in addition to expected increases in bill issuance,* ***Treasury may raise nominal coupon issuance in the coming months*** *to address these larger net marketable borrowing needs*"

Out of the 95 OFRs, 18 contain high information on total debt level and they are assigned to subset *level*. These include buyback announcements with no information on the maturity of Treasuries to be bought.

OFRs where the Treasury signals a change in issuance as they plan to change the maturity of outstanding debt are assigned to subset *mat*. Announcements in this subset contain higher information on the maturity factor compared to the level factor.

$$V(\tilde{F}_{mat}) = U'V(F_{mat})U, \qquad V(\tilde{F}_{mat}) = \begin{bmatrix} \sigma^2_{1,mat} & 0 \\ 0 & \sigma^2_{2,mat} \end{bmatrix} \tag{8}$$

A typical example is the announcement on 2000-02-02 where the Treasury explicitly addressed concerns related to debt maturity management

> " *Our first announcement concerns* ***reductions in the issuance sizes of longer-maturity debt****. This reduces our funding, takes into consideration the longer-term fiscal forecasts, and helps us* ***manage the average maturity of our debt****. In this regard, we plan to reduce the issuance of 5-year, 10-year, and 30-year debt, both fixed-rate and inflation-indexed securities. Consistent with the Committee's recommendations, we will maintain the regular monthly auctions of our two-year notes at the present time. We plan, however, to cut modestly the size of individual auctions of two-year notes.*"

Releases containing information about the introduction or discontinuity of maturity points are treated as subset *mat*. Moreover, the Treasury often changes the auction schedule, for example, increasing the frequency of auctions at a particular maturity, introducing re-openings for certain bonds, etc. These are usually done keeping in mind the maturity structure and are thus included in subset *mat*.

Among the 95 OFRs, there are releases with no significant information on either debt level or debt maturity. For example, the release on 2007-10-31 contains a section announcing the conversion to the TAAPS automatic system for its auctions, and another section mentioning a lowering of the minimum purchase amounts for Treasury auctions. Releases like these are assigned to subset *inter* as these do not contain significant information on either of the factors.[16]

Often the Treasury mentions that it sees no change in upcoming announcements. Post 2016 specifically after it started pinning down all auction volumes, often it announces no change in the volume of any auction in the quarter. I assign subset *inter* to these releases as there is no reason to believe one of the factors dominates in information relative to the other. The announcement on 2019-07-31 is a typical example

> "*Based on recent forecasts, Treasury is announcing* ***no increase*** *to nominal coupon and FRN auction sizes over the upcoming quarter and currently anticipates no further changes in issuance sizes for nominal coupon and FRNs for the remainder of the 2019 calendar year. Treasury plans to address any seasonal or unexpected variations in borrowing needs over the next quarter through changes in regular bill auction sizes and/or cash management bills.*"

In the restrictions above, the off-diagonal elements of the variance matrix of the factors are set to 0. This is necessary as by definition, the factors I want to estimate are orthogonal to each other. One of the factors is a change in price stemming from a shock to the overall level of debt. The other factor is a change in price stemming from a change in the maturity structure of debt keeping the overall level of debt constant. To the extent the prices are linear in quantities, it is important that the price changes are orthogonal to each other. Transforming the principal components provides a natural framework in this case as the principal components are orthogonal to begin with.

Two features of the identification strategy are worth explaining in more detail. First, while the subsets are defined based on the differential variances of the factors, I do not impose an inequality restriction between the variances of the two factors across each subset. For example, while it is known ex-ante that the maturity factor has a higher variance in subset *maturity*, I do not impose an inequality of the form $\sigma^2_{2,mat} > \sigma^2_{1,mat}$ during estimation. This is motivated by the fact that the factors are not identified up to ordering. There is no reason to believe the second factor is the maturity factor and hence, should have a higher variance in subset *maturity*. The only restriction is that the variances are different from each other in the subset. As explained below, the identification strategy will allow me to pin down the ordering based on the estimated variances.

Second, the subsets should not be interpreted as *only* containing information on the level of debt and the maturity structure. For example, the text of the announcement on 2000-02-02 quoted above contains information on both debt level and maturity. However, the amount of information on the maturity structure of issuance is higher, as a result of which it is allocated to subset *maturity*. Indeed, part of the challenge in identification is that the Treasury does not issue debt in a manner where it is possible to observe announcements that

[16]It is important to note that OFRs contain subsections providing information on the issuance of TIPS/bills/CMBs etc. Other sections contain information on changes in institutional rules of auctions. I do not take into account the information in all these sections when I assign each release to a regime. I assign them only based on the section discussing the issuance of nominal coupon notes and bonds.

only contain information on level or maturity. Identification using heteroscedasticity allows for a feasible way to get around this problem. While all announcements contain information on both factors, some announcements contain more information on one of the factors. This simple restriction allows me to separately identify the two factors of interest.[17]

Although pinning down U requires restrictions on 1 parameter θ, the restrictions imposed to give the factors an economic meaning impose 9 restrictions on 5 free parameters. This can be written as a system of overidentified non-linear GMM of the form

$$\mathbb{E}[g(Y_l, \theta_0)] = 0, \qquad l \in \{inter, level, mat\} \tag{9}$$

For each of the subsets $l \in \{inter, level, mat\}$, the moment $g(Y_l, \theta_0)$ is of the form

$$\left[vech(V(\tilde{F}_l)) - vech(U'V(F_l)U)\right] \tag{10}$$

where $vech$ is the vector-half operator, $V(F_l)$ depends on the sample Y_l and $\theta_0 \in \{\theta, \sigma_{1,level}, \sigma_{2,level}, \sigma_{1,mat}, \sigma_{2,mat}\}$

Table 3 reports the results from the GMM estimation. From the J-test, I cannot reject the null that the estimated model is the true model. The final U matrix is given by

$$U = \begin{bmatrix} 0.88 & -0.47 \\ 0.47 & 0.88 \end{bmatrix} \tag{11}$$

The factors estimated are only identified up to ordering and sign. I pin down the ordering in the following way. From table 3, it is the case that $\frac{\sigma^2_{1,mat}}{\sigma^2_{2,mat}} > \frac{\sigma^2_{1,level}}{\sigma^2_{2,level}}$. Given that the subsets are decided based on narrative evidence, it is known apriori that subset mat has a higher maturity shock than a level shock. This implies that the first factor has to be the maturity factor as subset mat has more information on the first factor compared to the second factor. The second factor is the debt level factor.

Table 4 reports the matrix of factor loadings $\tilde{\Lambda}'$. In order to pin down the sign for each factor, I look at the predicted effect of quantity shocks on prices through the lens of a simple preferred habitat model in the spirit of Greenwood and Vayanos (2014).[18] Bonds are risky in this setup as their prices are subject to fluctuations due to monetary policy and debt supply shocks. From table 4, an increase in the level factor leads to an increase in all futures prices.

[17] A related concern one might have is why should the two factors be labeled as debt level and debt maturity and not, for example, forward guidance on the part of the Treasury. The labeling of the factors boils down to the manner in which they are estimated. Given that the factor model is only identified up to an orthogonal transformation, one can come up with infinitely many factors that correspond to the data. The manner in which I use information on debt level and maturity issuance to estimate θ allows me to pin down the factors that can only correspond to these two features of debt supply.

[18] Appendix D contains the model and the expected effect on prices/yields/returns for each of the two kinds of quantity shocks.

	Estimates	Std Errors
θ	28.31	9.97
$\sigma_{1,inter}$	1	–
$\sigma_{2,inter}$	1	–
$\sigma_{1,level}$	0.72	0.20
$\sigma_{2,level}$	0.73	0.15
$\sigma_{1,mat}$	1.42	0.23
$\sigma_{2,mat}$	0.80	0.12
$\sigma^2_{1,level}/\sigma^2_{2,level}$	0.97	
$\sigma^2_{1,mat}/\sigma^2_{2,mat}$	3.12	
J-test stat	1.64	
p-value	0.80	
Degrees of freedom	4	

Table (3) Estimates from two-step GMM. J-test is the Sargan-Hansen J-statistic for testing the null of $E[g(Y_l, \theta_0)] = 0$, that is, the data implies the model is valid. The null is rejected at 5% level of significance if the p-value is less than 0.05

This is consistent with a smaller-than-expected shock to the overall quantity of debt. A negative debt level shock implies agents have to hold fewer bonds and thus demand a lower risk premium, or a higher price for assets.

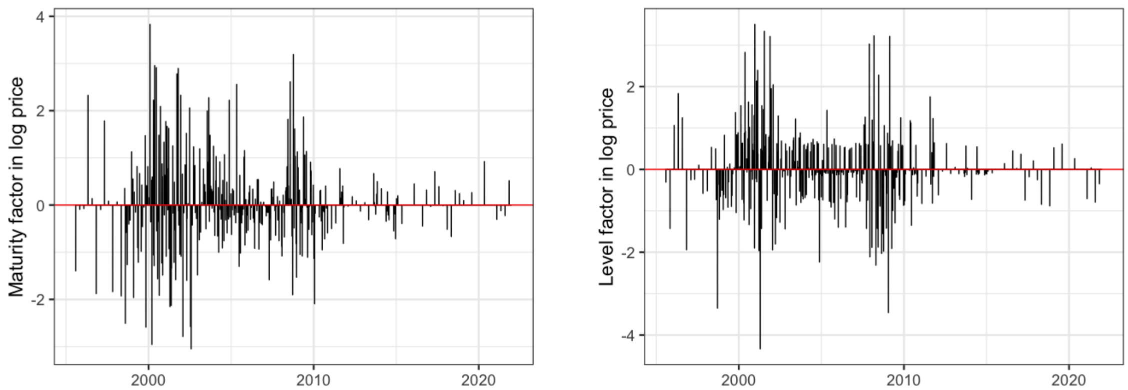
	6-mth	2-yr	5-yr	10-yr	30-yr
Maturity factor	-0.07	-0.72	-0.87	-0.92	-0.85
Level factor	0.98	0.47	0.38	0.27	0.14

Table (4) Matrix of factor loadings $\tilde{\Lambda}'$. The rows correspond to the two factors of interest. Columns correspond to the 6-month eurodollar futures, and the 2-year, 5-year, 10-year, 30-year Treasury futures prices.

Table 4 reports that an increase in the maturity factor leads to a decrease in all futures prices. This is consistent with an increase in the maturity of debt issuance. Intuitively, long-term bonds are more sensitive to risk than short-term bonds. An increase in maturity implies agents hold more long-term bonds and give up an equivalent amount of short-term bonds. This exchange increases risk in their portfolio and they demand a higher premium or a lower price. In the next subsection, I discuss the relative magnitude of factor loadings across bond maturities.

3.4 Diagnostics of the estimated factors

Figure 3 plots the factors over time. It is clear that there are fewer shocks towards the end of the sample. This pattern holds mechanically as from 2016, the Treasury started pinning down the supply of debt for all auctions in the next quarter as discussed in section 2. The period after 2016 corresponds to a time when all intermediate announcements are redundant and do not provide new information. Table 5 reports the summary statistics for the factors. Both factors are centered around 0 due to normalization. The variance restriction applied during estimation implies both factors have a variance of 1 and are uncorrelated with each other. This holds across the entire sample, even though the factors have different variances in the subsets defined in the previous section.



(a) Maturity factor

(b) Level factor

Figure (3) Maturity and level factors. y-axis is in log prices (standardized)

In order to look at the effects on macroeconomic variables in the SVAR-IV in section 5, I temporally aggregate the factors to the monthly frequency by summing across factors for each month. In case a month does not have an observation, the month is assigned a value of 0. As there were fewer releases registered as news in the latter part of the sample after 2016, this part of the sample mechanically has very few observations. Figure E.4 and table E.5 in the Appendix plot the monthly series and contain the respective summary statistics.

Factors	Mean	Median	SD	N	Correlations	
					$s_{M,t}$	$s_{L,t}$
Maturity factor $s_{M,t}$	0	-0.05	1	331	1	
Level factor $s_{L,t}$	0	-0.06	1	331	0	1

Table (5) Summary statistics of factors

The monthly aggregation allows me to conduct a range of diagnostic checks on the factors. I find the factors are not autocorrelated, are not predictable by other macroeconomic variables, and have no correlation with other proxies in the applied macroeconomics literature. Appendix E contains details on diagnostic checks.

4 Effects on asset prices

In this section, I use an event-study design to look at the effects of both factors on the prices of different assets. I first look at the effect of the factors on futures and spot prices for

Treasury bonds. Next, I look at the effects on the corresponding returns and yields. The effects on spot bond prices, yields, and returns are tested against the predicted effects in Greenwood and Vayanos (2014). Next, I decompose the effect of nominal yields into real yields and breakeven inflation. This is key since transmission to the macroeconomy takes place through the agent's consumption decision due to changes in real yields. To analyze if information shocks are largely present, I look at the effects on other asset prices. Finally, I use local projections to see the persistence of the shocks over time.

4.1 Effect on bond prices

In order to look at the effect on asset prices, I estimate

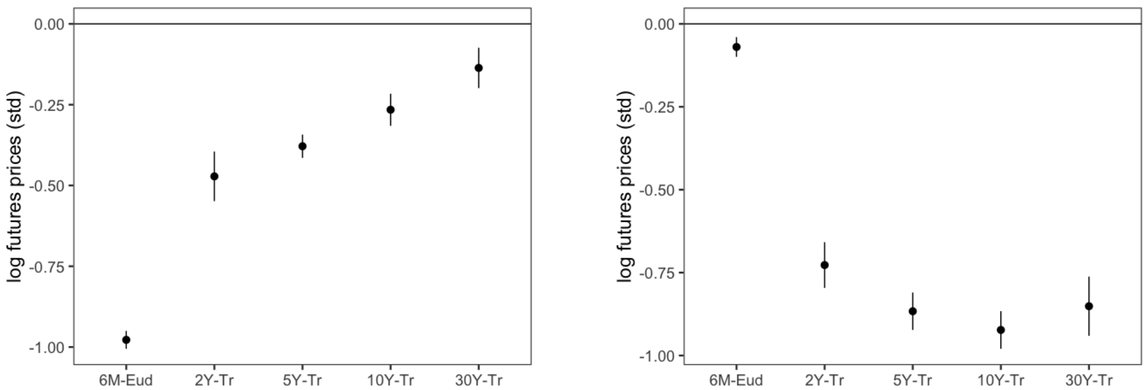
$$\Delta y_t = \alpha + \beta_1 s_{L,t} + \beta_2 s_{M,t} + \epsilon_t \tag{12}$$

where each t is an announcement day. Δy_t is constructed by taking the difference of the closing price between an announcement day t and the price of the last available date $(t-1)$. $s_{L,t}$ and $s_{M,t}$ correspond to the level and maturity factors estimated in the previous section. I normalize the factors such that $s_{L,t}$ corresponds to a surprise increase in debt level and $s_{M,t}$ corresponds to a surprise increase in debt maturity.

First, I look at the effect on futures prices for Treasuries. I estimate the above specification using the intraday futures price changes in the previous section as the dependent variable. Figure 4 plots the coefficients of interest β_1 and β_2 for maturities from 6 months to 30 years. The estimates for the maturity factor correspond to the factor loadings in table 4. The estimates for the level factor are the same as the loadings but with an opposite sign, due to the normalization above.[19]

From the previous section, the sign identification based on Greenwood and Vayanos (2014) pins down the effect of an increase in debt level and maturity shocks on futures prices. It does not place any restrictions on the relative effects across maturities. The estimates from figure 4 can, thus, be tested against the predicted effects of supply shocks in the Greenwood and Vayanos (2014) framework. The framework predicts that in response to an increase in both the level and maturity of debt issuance, the magnitude of the effects increases with bond maturity. In response to shocks in the economy, the equilibrium price of long-term bonds in the framework fluctuates more than the price of short-term bonds. Agents dislike volatility in consumption and the resulting high volatility in long-term bond prices makes long bonds riskier than short bonds.

[19]The mean estimates in figure 4 correspond exactly to the estimates in table 4 as the futures prices are used to construct the factors. Figure 4 additionally reports the 90% confidence intervals. Since the factors are generated regressors, there is additonal sampling uncertainty that the HAC standard errors do not capture. In Appendix figure G.18 I report the results using bootstrapped standard errors following the procedure in Swanson (2021). The results are very similar to the baseline case and hence, I report the results with HAC standard errors in the main text for the rest of the paper.



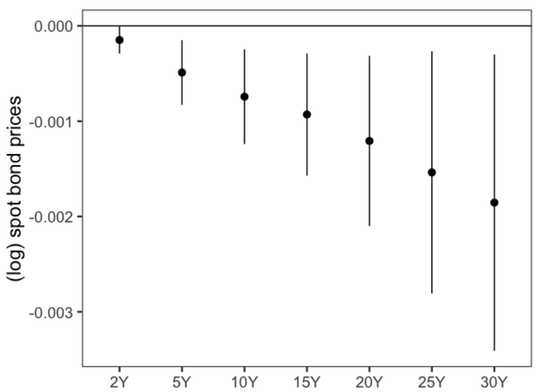
(a) Level factor (b) Maturity factor

Figure (4) Effect of an increase in level and maturity factors on log futures price changes f_t^τ, where τ goes from 6 months to 30 years. x-axis corresponds to the 6-month Eurodollar and the 2 to 30-year Treasury futures prices. y-axis is in log prices. Confidence intervals are based on Newey-West standard errors at 90% confidence level

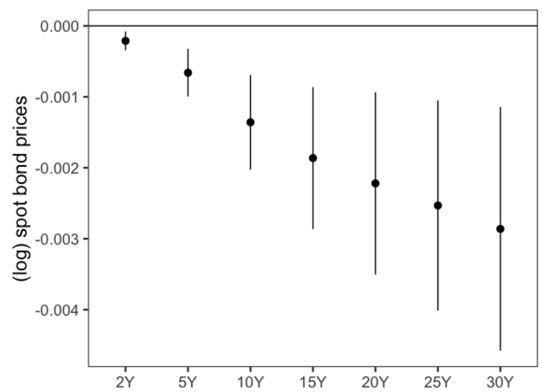
An increase in the debt level shock results in a uniform increase in bond holdings across maturities for agents. All bond prices fall as agents dislike holding more risk in their portfolios. A lower price is required to compensate the agents for the risk taken. The price of long-term bonds falls the most as long-term bonds are riskier than short-term bonds. An increase in the debt maturity shock results in agents holding more long-term bonds and giving up an equal amount of short-term bonds. The resulting portfolio is riskier than the one previously held. All bond prices fall as a result to compensate the agent for holding a riskier portfolio. Similar to the debt level shock, the price of long-term bonds falls the most as long-term bonds are riskier than short-term bonds. I find that in response to an increase in the maturity factor, the effect size increases with bond maturity, consistent with Greenwood and Vayanos (2014). The level factor effects are, however, inconsistent with the framework. Next, I show that the effects on spot prices are in line with the predicted effects.

I estimate equation 12 for the log prices of the 2-year, 5-year, 10-year, 15-year, 20-year, 25-year, and 30-year zero-coupon nominal bonds. I obtain daily data on zero coupon bond yields from Gürkaynak, Sack and Wright (2007). The log price of a τ maturity bond is defined as $p_t^\tau = -\tau(y_t^\tau)$, where y_t^τ is the corresponding yield. In order to obtain the response of spot prices most accurately, I need to look at the movement of prices around the same time window as the factors. However, since I do not have access to high-frequency data for spot prices, I look at the daily change in prices between the announcement day and the last available date.

Figure 5 plots the coefficients of interest β_1 and β_2 for maturities from 2 years to 30 years. An increase in the level and maturity factors have similar effects on asset prices, consistent with Greenwood and Vayanos (2014). Long-term bonds are riskier. The effect size increases



(a) Level factor



(b) Maturity factor

Figure (5) Effect of an increase in level and maturity factors on log spot price changes p_t^τ, where τ goes from 2 years to 30 years. x-axis is the maturity of the bonds. y-axis is in log prices (standardized). Confidence intervals are based on Newey-West standard errors at 90% confidence level

with maturity to compensate agents for holding riskier bonds.[20,21]

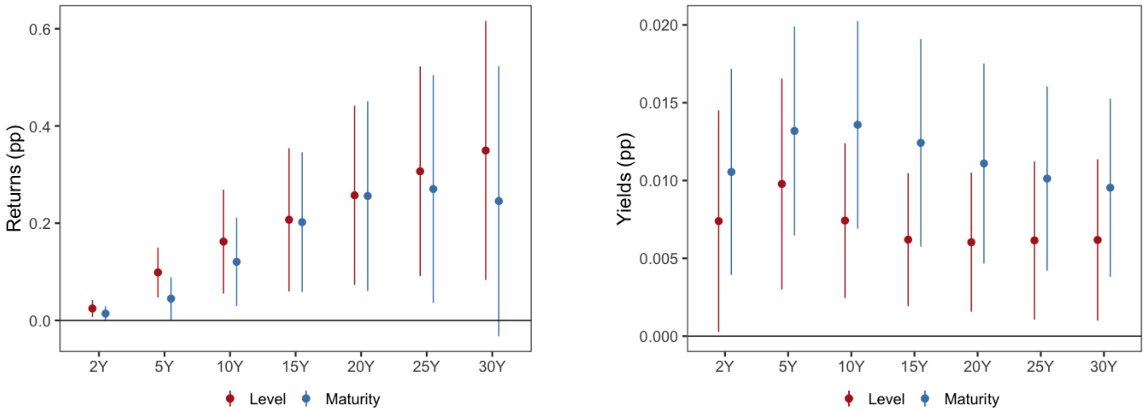
4.2 Effect on bond yields and returns

In order to look at the effects on bond yields and returns, I estimate equation 12 with nominal bond returns and yields as the dependent variable, reported in figures 6(a) and 6(b). The 1 year holding period return for a τ maturity bond is defined as $r_{t,t+1}^\tau = p_{t+1}^{\tau-1} - p_t^\tau$, where p_t^τ is the log price of τ maturity bond at time t. The yield $y_t^\tau = -p_t^\tau/\tau$ is the zero coupon bond yield from Gürkaynak, Sack and Wright (2007)

In figure 6(a), an increase in both debt level and maturity leads to a rise in returns. The magnitude of the effects increases monotonically with bond maturity. This is consistent with Greenwood and Vayanos (2014) as agents hold more risky bonds and demand a higher premium. The rise in premium is the largest for long-term bonds as they are the riskiest. Through the lens of a simple no-arbitrage model, the return on an asset must equal the asset's exposure to risk times the price of risk. The price of risk, which is the same for all assets, increases due to the agent holding a riskier portfolio. Long-term bonds are more exposed to

[20]Note that part of the monotonic increase in estimates and confidence bands in figure 5 stem from the fact that bond yields get scaled with maturities in order to obtain log prices. Maturities are large numbers in magnitude compared to the yields. In Appendix figure G.19 I report the estimates for prices in levels which show a similar pattern across maturities for both factors.

[21]Why do the futures and spot prices show a similar trend across maturities for the maturity factor but a different trend for the level factor? The evidence suggests that for futures prices, agents' perception of risk across maturities depends on the factor that affects their portfolio allocation. In response to a maturity shock, long bonds are perceived to be riskier consistent with Greenwood and Vayanos (2014). However, in response to a level shock, short bonds are perceived to be riskier. One possible explanation behind the latter is that a change in debt could be interpreted by agents as higher volatility in economic conditions, not currently but in the near future. As the central bank changes the nominal short rate to tackle economic indicators, short-term bonds are exposed to a higher refinance risk. This leads to short-term bonds being perceived as riskier.



(a) Returns

(b) Yields

Figure (6) Effect of an increase in level and maturity factors on the 1-year holding period return $r^{\tau}_{t,t+1}$ and the nominal zero coupon yield y^{τ}_{t} where τ goes from 2 years to 30 years. x-axis is the maturity of the bonds. y-axis is in percentage points. Confidence intervals are based on Newey-West standard errors at 90% confidence level

risk and thus, the compensation required to hold them is higher. The effects of both factors on returns are in line with proposition 1 in Greenwood and Vayanos (2014) outlined in section D in the Appendix.

The rise in yields in figure 6(b) is consistent with a larger demanded premium for holding a riskier portfolio. In contrast to the case for returns, the effect is hump-shaped across maturities. Moreover, the effects are smaller in magnitude for yields than for returns. An increase in the maturity factor leads to a 0.012 percentage point increase in the 15-year yield. The corresponding increase in returns is 0.2 percentage points.

In order to explain the differences with the case for returns, it is important to note that the yield of a bond equals the average of the 1-period returns over the life of the bond. The effect of the shock on 1-period returns dampens over time as the shock reverts back to its mean. The average effect of the 1-period returns thus tends to be smaller than the effect on current returns, explaining the difference in magnitudes. The mean reversion of the shock also explains the hump shape across maturities. If the shock mean reverts quickly, the effect on intermediate maturities tends to be higher than for long-term maturities. 1-period returns far into the future are less affected as the effect of the shock dampens quickly. Long-term yields which include these returns are thus lower than intermediate yields. The hump-shaped effect for yields is in line with proposition 2 in the model outlined in Appendix section D. The relative magnitude of the effects between returns and yields is in line with proposition 3.[22]

[22]An additional proposition in Greenwood and Vayanos (2014) that I do not directly test is the state dependence of the effect size on risk aversion of the agents. During periods of high risk aversion, agents demand a higher premium for holding risky assets. This results in a higher size of effects during high risk aversion periods. In my identification strategy, I do not observe shocks to debt supply (in dollars), but only the price responses to the corresponding supply shocks. Thus, it is not possible to test how the effect sizes change with risk aversion due to the same shock in supply. I report the effects on bond yields for subsamples

Overall, the effect of the level and maturity factors on bond prices, returns and yields are largely in line with the predicted effects of debt supply shocks in Greenwood and Vayanos (2014). This suggests that the estimated factors indeed capture shocks to the level and maturity structure of public debt supply.

4.3 Effect on real bond yields

In this section, I study how much of the effect on nominal yields translates into real yields. This is key since transmission to the macroeconomy takes place through the agent's consumption decision due to changes in real yields.

I use data on Treasury Inflation Protected Securities (TIPS), that is, real yields from Gürkaynak, Sack and Wright (2010) and use the following decomposition

$$y_t^\tau = \tilde{y}_t^\tau + \pi_t^{BE,\tau} \tag{13}$$

where y_t^τ, $\tilde{y}_t^\tau$ and $\pi_t^{BE,\tau}$ are the nominal and real yields, and the breakeven inflation at maturity τ respectively.[23] Data on TIPS yields is only available from 1999 as the US TIPS market came into effect then. The maximum maturity for TIPS bonds is 20 years.

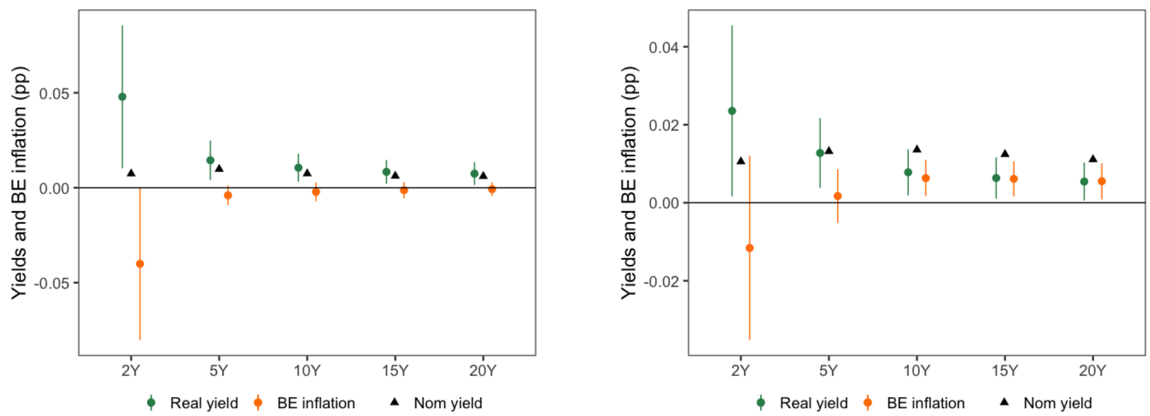
Figure 7 plots the effect of the factors on real yields and breakeven inflation.[24] Both factors have a significant effect on real yields. Like the nominal case, an increase in both debt level and maturity leads to a rise in real yields. This is evidence of the fact that the entire compensation that the agent demands to hold risky assets stems from a possible loss in the value of real wealth. The compensation required due to a change in prices or how prices move in tandem with real wealth, is negligible.

While the effects on breakeven inflation are not significantly different from zero, there is an increase across maturities. This leads to a monotonic decrease in real yields across maturities, unlike the hump-shaped effect for nominal yields. Long-term real bonds are, thus, perceived to be safer than short-term real bonds. For the maturity factor, an increase in long-term expected inflation can be explained through a representative agent's expectation of fiscal policy in the long run. In response to an increase in the maturity of debt issuance, it is feasible that the agent expects the government to increase inflation in the long run to decrease the real value of the debt. In the short run, on the other hand, there is an expected

with different risk aversion coefficients in Appendix figure G.20. While this should not be interpreted as a test of theory, it is informative to understand how the perception of risk changes for all bonds across high and low risk aversion periods. Figures G.21 and G.22 report the corresponding effects for log prices and returns.

[23] I first remove the liquidity premium from TIPS yields. This is necessary as the TIPS market is far less liquid than the market for nominal bonds. To model the liquidity premia, I regress the difference between the real and nominal yields on the volatility index and the noise measure of Hu, Pan and Wang (2013), following Andreasen, Christensen and Riddell (2021). The resulting liquidity premium series for the 10-year maturity is reported in the figure G.23 in the Appendix.

[24] Figures G.24 in the Appendix plots the effect of the factors on the liquidity premium. Figure G.25 reports the decomposition of nominal returns into real returns and expected inflation.



(a) Level factor (b) Maturity factor

Figure (7) Effect of an increase in level and maturity factors on the zero coupon real yield $\tilde{y}_t^{\tau}$ and breakeven inflation $\pi_t^{BE,\tau}$, where τ goes from 2 years to 20 years. x-axis is the maturity of the bonds. y-axis is in percentage points. Green lines indicate real yields, Orange lines indicate breakeven inflation, and triangles denote nominal yields. Confidence intervals are based on Newey-West standard errors at 90% confidence level

deflation. This can be explained by the potential effects on the macroeconomy as I explain below.

It is possible to hypothesize about the effects on the macroeconomy through the lens of a framework that embeds the preferred habitat setup in a standard New-Keynesian model (Ray, 2019).[25] A surprise increase in debt level leads to a rise in all bond yields through the preferred habitat block of the model. If the agent's consumption decision depends on a weighted average of the entire term structure, this implies an increase in the effective borrowing rate of the agent, an increase in savings, and a decrease in consumption and output. Through the Phillips curve, this implies a fall in short-term inflation. This effect is consistent with the mean effect of breakeven inflation in figure 7(a). A surprise increase in debt level thus leads to a recession.

An increase in the maturity of issuance increases all bond yields through the preferred habitat block of the framework. Through the same channel as above, this leads to a recession. The effect on short-term inflation is again consistent with the mean effect in figure 7(b). In section 5, I formally look at the effect of these shocks on macroeconomic variables.

4.4 Other asset prices

Given that the factors are equilibrium price responses to debt supply shocks, a possible concern is that the factors also pick up information shocks on other economic variables. For example, in case private agents interpret the announcements as new information on future economic activity, then Treasury futures prices would move significantly in response to such

[25] Appendix D.3 contains a formal setup of the framework.

news. In this subsection, I provide evidence to show that information shocks of such kind are largely absent in the factors that I construct. Following Droste, Gorodnichenko and Ray (2021), I look at the effect of change in the factors on other asset prices. I find no significant effects on equities, commodity prices, exchange rates, and an uncertainty index - assets that typically react to a range of economic shocks. Importantly, I find a significant effect on high-grade corporate bond yields - an asset that is expected to react to public debt supply shocks.[26]

From table 6, an increase in the maturity factor leads to a significant increase in Aaa and Baa-rated corporate bond yields. Both the sign and the magnitude of the effects are similar to the effect on Treasury yields in figure 6. There are no significant effects on C-rated bond yields. That high-grade corporate bond yields have similar effects as Treasury bond yields can be explained by the close substitutability between these two classes of assets. The effects provide suggestive evidence that public debt supply shocks transmit through the economy by affecting corporate debt issuance, similar to the gap-filling channel of transmission (Greenwood, Hanson and Stein, 2010). The result is similar to Droste, Gorodnichenko and Ray (2021) which finds evidence of pass-through of public debt demand shocks to the corporate debt market.

I find no significant response to the maturity factor on other asset prices. An increase in the level factor has a small and almost insignificant effect on the S&P 500, Russell 2000 and the CBOE Volatility VIX (log) indices. This implies that the constructed factors are largely free of information shocks or forward guidance shocks as usually found in the monetary policy literature (Nakamura and Steinsson, 2018; Jarociński and Karadi, 2020; Miranda-Agrippino and Ricco, 2021).[27] Overall, I conclude that information shocks are largely absent in the factors that I construct and that they truly capture exogenous shocks to public debt supply.

4.5 Persistence of effects

The previous subsections show the contemporaneous effect of factors on asset prices. In this subsection, I study how persistent are the effects of factors on short and long-term Treasury yields. This is important to understand the duration over which debt management policies have an effect on the economy. For this purpose, I use the local projection

$$y_{t+h} - y_{t-1} = \alpha_h + \beta_{1,h} s_{L,t} + \beta_{2,h} s_{M,t} + \epsilon_{t,h} \tag{14}$$

where h goes from 0 to 60 days. For $h = 0$, $\beta_{1,h}$ and $\beta_{2,h}$ correspond to the estimates in the

[26]While all asset prices likely react at a lower frequency due to general equilibrium effects of debt supply changes, these effects are unlikely to show up in high-frequency changes in prices immediately after the announcements.

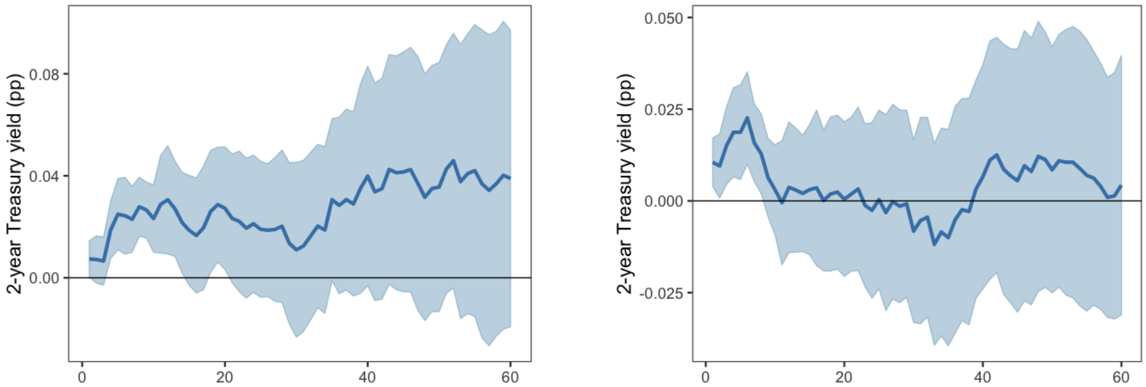
[27]No effect on the VIX also rules out the case that the factors pick up a mechanical fall in uncertainty following announcements. It is possible to be concerned that since the Treasury releases pin down the volume of debt, it clears speculation among private agents and asset prices are reflective of this fall in uncertainty. The results indicate that this is not a cause for concern.

		Panel A: Level factor	Panel B: Maturity factor	
		Estimate	Estimate	Sample
		(p-value)	(p-value)	
Corp bond yields				
	Aaa grade	0.001	0.01**	1995-2021
		(0.65)	(0.003)	
	Baa grade	0.004	0.01**	1995-2021
		(0.17)	(0.002)	
	C grade	-0.004	0.02	1996-2021
		(0.69)	(0.2)	
Equity				
	S&P 500	0.002*	-7e-4	1995-2021
		(0.07)	(0.44)	
	Russell 2000	0.002*	0.1e-4	1995-2021
		(0.09)	(0.99)	
Exchange rates				
	Dollar-Euro	0.003	5e-4	2003-2021
		(0.2)	(0.79)	
	Dollar-Yen	0.002	4e-4	1996-2021
		(0.12)	(0.61)	
Commodities				
	GSCI	-5.7e-4	0.14e-4	1995-2021
		(0.52)	(0.99)	
Uncertainty				
	VIX	-0.006*	-5e-4	1995-2021
		(0.09)	(0.88)	

Table (6) Effect of an increase in level and maturity factors on asset prices. All data is at a daily frequency. Corp bond yields are Moody's seasoned Aaa and Baa grade bonds, and BOfA C grade bonds (Source: FRED). Equity prices are given by log closing prices of the S&P500 and Russell 2000 indices (Source: Yahoo Finance). Exchange rates are given by the log daily closing rates of the Dollar-Eur and Dollar-Yen (Source: Yahoo Finance). Commodity price is given by the log daily closing price of the GSCI index which tracks the price of commodities (Source: Yahoo Finance). Uncertainty is given by the log CBOE Volatility Index (Source: FRED). Effects for Corp bond yields are in percentage points. All other effects are percent changes. p-values based on Newey West standard errors at 90% confidence level

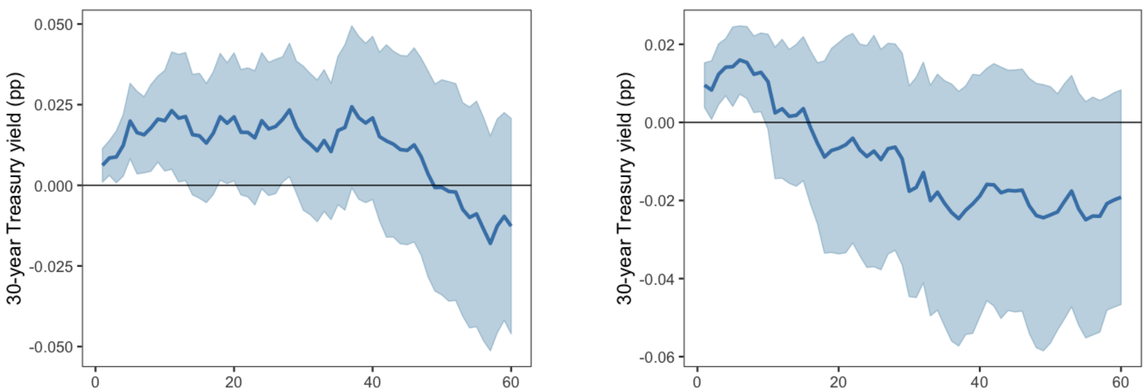
previous section. For h larger than 0, the regressions look at the effect of the shocks on asset price changes between day $t+h$ and the last business day $t-1$. The series of estimates $\beta_{1,h}$ and $\beta_{2,h}$ provide an idea of how far into the horizon the effects of these shocks last.[28] As time passes, bond yields are affected by various other shocks in the economy. The signal-to-noise ratio for any particular shock decreases with an increase in the horizon, resulting in larger standard errors over time.

[28]Swanson (2021) finds that monetary policy shocks are persistent even after 100 days. Droste, Gorodnichenko and Ray (2021) find the effects of asset demand shocks last for around 20 days.



(a) Level factor (b) Maturity factor

Figure (8) Estimated $\beta_{1,h}$ and $\beta_{2,h}$ from the regression $y_{t+h} - y_{t-1} = \alpha_h + \beta_{1,h} s_{L,t} + \beta_{2,h} s_{M,t} + \epsilon_{t,h}$ where h is the x-axis, $s_{L,t}$ is the level factor and $s_{M,t}$ is the maturity factor. The dependent variable is the change in nominal zero coupon yield at maturity $\tau = 2$ over h business days. y-axis is in percentage points. Blue shaded regions are confidence intervals based on Newey-West standard errors and a 90% level of confidence



(a) Level factor (b) Maturity factor

Figure (9) Estimated $\beta_{1,h}$ and $\beta_{2,h}$ from the regression $y_{t+h} - y_{t-1} = \alpha_h + \beta_{1,h} s_{L,t} + \beta_{2,h} s_{M,t} + \epsilon_{t,h}$ where h is the x-axis, $s_{L,t}$ is the level factor and $s_{M,t}$ is the maturity factor. The dependent variable is the change in nominal zero coupon yield at maturity $\tau = 30$ over h business days. y-axis is in percentage points. Blue shaded regions are confidence intervals based on Newey-West standard errors and a 90% level of confidence

Figures 8 and 9 report the estimated effect on nominal zero coupon bond yields at the 2-year and 30-year maturities.[29] I plot the estimates $\beta_{1,h}$ and $\beta_{2,h}$ across horizon h. The level factor has a significant effect on the 2-year yield up to 20 days. For the 30-year yield, the effects remain significant until after a month. For both cases, the effects peak after a few days and start falling towards zero. The hump-shaped effect on yields is consistent with the idea that the shock mean reverts over time and the premium charged on holding risky assets goes back

[29] Appendix figures G.26, G.27 and G.28 report the effects on the 2-year and 30-year Treasury returns and on Aaa corporate bond yields respectively.

to its steady-state value.

The maturity factor has a similar hump-shaped effect on both short-term and long-term yields. However, in this case, the effects dissipate much quicker - around 10 days after the announcement. The lower persistence of the effects suggests a higher mean-reversal rate for maturity shocks.

Given that the market for Treasury bonds is extremely liquid, it makes sense that the effects of debt supply shocks are not as persistent as monetary policy shocks. The liquidity of the US government debt market ensures that the yields move in response to a range of macroeconomic and financial news. The result has important implications for the next section, where I use a monthly SVAR-IV to look at the effects on macroeconomic variables.

5 Dynamic effect on the macroeconomy

In this section, I use an SVAR-IV specification to look at the dynamic effects on output, prices, and unemployment. The specification assumes that the true structural shock to debt level/maturity is a complex object and it is unobserved. The constructed factor is an imperfect proxy for the true structural shock. It is then possible to look at the dynamic effects of the structural shock on macroeconomic variables.

5.1 Specification

I use the SVAR-IV estimator (Mertens and Ravn, 2013) to look at the effects on macroeconomic variables. Under the conditions of

1. *Relevance.* $E(s_t \varepsilon_{1,t}) = \alpha \neq 0$
2. *Exogeneity.* $E(s_t \varepsilon_{j,t}) = 0, j \neq 1$

where $\varepsilon_{1,t}$ is a structural shock of interest - either debt level or maturity, s_t is the corresponding factor I construct, and $\varepsilon_{j,t}, j \neq 1$ are other structural shocks, the estimator allows me to look at the impulse responses - how the structural shock of interest affects variables over time. For inference, I use weak instrument robust confidence intervals, following Montiel Olea, Stock and Watson (2021).

The factors I construct in section 3 are likely to satisfy both the above assumptions. The relevance condition holds as the factors are constructed using information from debt supply announcements. Moreover, I look at price changes in a narrow window around the announcements. This implies that the factors are largely free of other structural shocks in the economy and the exogeneity condition is likely to hold.

I include 6 variables in the VAR - the nominal 1 year and 15 year yield, log of the personal consumption expenditure (PCE) and the index of industrial production (IIP), the unemployment rate, and the first principal component of the 134 variables in the FRED-MD database. The lag length is set to 12 as all variables are at a monthly frequency.

I discuss the full econometric specification, details of the data, and first-stage tests for the relevance condition in section C in the Appendix.

5.2 Impulse responses to debt supply shocks

Figure 10 reports the impulse responses to a surprise increase in the level of debt issuance that leads to a 1 basis point increase in the 15-year yield. The long-term yield remains elevated until around 16 months. In line with the results in section 4, the short-term yield rises by 0.9 basis points on impact. This is consistent with the idea that while all yields rise as agents require a higher premium to hold risky bonds, long-term yields rise more as long-term bonds are riskier than short-term bonds.

An increase in debt level leads to a fall in output and a rise in employment. Output falls on impact and the effects remain below zero for all horizons. The effects are statistically significant from around 15 months. Unemployment increases and peaks at around 2 years. The FRED-MD factor rises on impact and the effects remain significant until around 15 months. This is expected as the factor loads negatively on measures of economic growth, for example, non-farm employees. There are no statistically significant effects on prices.

The effects are in line with a model where the agent's consumption decision depends on a weighted average of the entire term structure, instead of simply the nominal short rate (Ray, 2019).[30] An increase in yields implies a fall in consumption, output and a rise in unemployment. Through the Phillips curve, this implies a fall in prices. The empirical evidence supports this channel of transmission for output and unemployment, but not for prices.

Figure 11 reports the impulse responses to a surprise increase in the maturity of issuance that leads to a 1 basis point increase in the 15-year yield. The long-term yield remains elevated for around 16 months. On impact, the short-term yield rises by 0.8 basis points, which is less than the effect on the long-term yield. This is in line with the effect on yields I find in section 4.

An increase in the maturity of issuance leads to an increase in output and a decrease in unemployment and the FRED-MD factor. There are no statistically significant effects on prices. An increase in yields accompanied by a rise in economic activity seems contradictory. The evidence indicates that the maturity of issuance affects economic activity through an alternative mechanism to the preferred habitat channel.

[30]Ray (2019) embeds the preferred habitat framework in a standard New Keynesian model. See Appendix section D for more details on this framework.

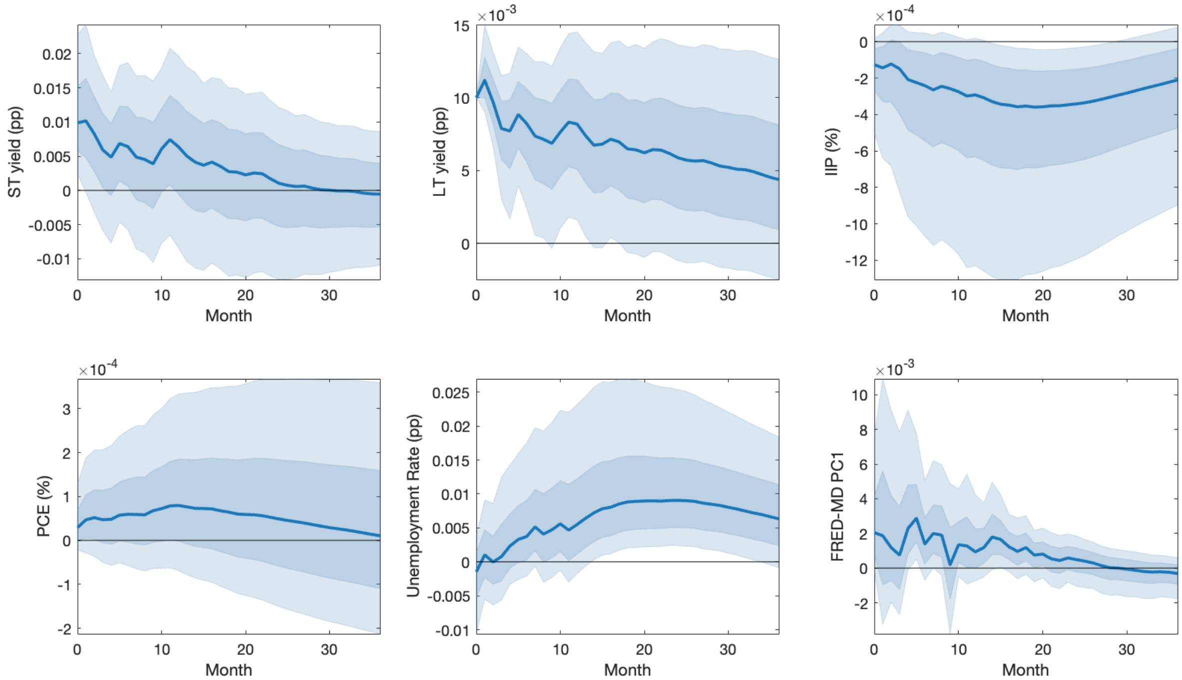


Figure (10) SVAR-IV impulse responses due to a surprise increase in the level of debt issuance, normalized to increase the long-term (15-year) yield by 1 basis point on impact. Solid line is the point estimate and the light and dark blue shaded regions are the Montiel Olea, Stock and Watson (2021) 68% and 90% confidence bands respectively.

A potential alternative mechanism is through the government's budget constraint. If the government finances the debt using long-term bonds, it is insured against refinance risk if monetary policy rates increase in the near future. This allows the government to spend more and increase output (Andreolli, 2021). Another potential channel is through firms' liquidity constraints. Firms use long-term assets as collateral to borrow against their future income. In the face of a higher supply of long-term debt, firms substitute riskier long-term assets for long-term Treasuries as they provide a safer alternative. This eases the liquidity constraints of firms and allows for an increase in production (Woodford, 1990).

Overall, I conclude that the effects of debt level shocks on the macroeconomy are consistent with the predictions of the preferred habitat framework. The effects of debt maturity shocks, on the other hand, are inconsistent with the preferred habitat channel and leave room for alternative channels of transmission.

5.3 Robustness

I conduct multiple robustness tests by changing the lag order of the VAR, implementing a stationary VAR, using the factors as shocks in a local projection (LP), using them as

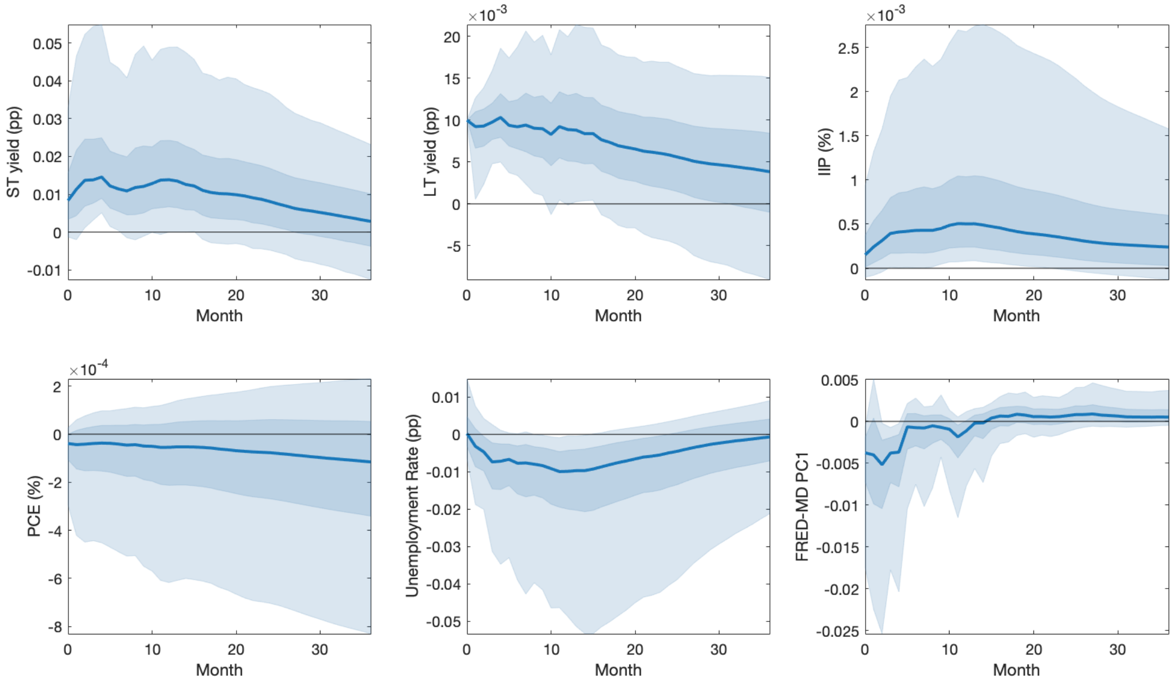


Figure (11) SVAR-IV impulse responses due to a surprise increase in maturity of debt issuance, normalized to increase the long-term (15-year) yield by 1 basis point on impact. Solid line is the point estimate and the light and dark blue shaded regions are the Montiel Olea, Stock and Watson (2021) 68% and 90% confidence bands respectively.

instruments in an LP-IV, and using wider event windows around announcements to construct the factors. For all cases, the results are qualitatively similar to the baseline case. I report the results in section F in the Appendix.

6 Effects of large scale asset purchase programs

From the previous section, it is clear that exogenous changes in debt supply have non-trivial effects on the macroeconomy. This implies the Federal Reserve's large-scale asset purchase programs (LSAPs) after the financial crisis of 2008-09 to decrease interest rates potentially had non-trivial effects. In this subsection, I use the debt level and maturity factors to look at the effects of LSAP programs. I map the constructed factors from the price space to the volume space (in dollars) using a measure of elasticity in the Treasury primary market (Droste, Gorodnichenko and Ray, 2021). I then study the effect of shocks equalling the volume of debt bought during LSAP 1,2,3 and the Maturity Extension Program (MEP).

6.1 Mapping to quantities

Droste, Gorodnichenko and Ray (2021) isolate shocks to private demand for Treasuries by looking at changes in Treasury yields in a narrow window around the publication time of auction results. The change in yields is regressed on the bid-to-cover ratio - an observable measure of excess demand for Treasuries.[31] For a typical offering amount in a 10-year Treasury auction of $25 billion, a surprise increase in demand for 10-year Treasuries by $10 billion decreases 10-year yields by 1.22 basis points.

From figure 6, a unit increase in the level factor corresponds to a 0.7 basis point increase in the 10-year yield. Through linearity, this equals a $5.74 billion surprise change in the Treasury debt level. Given that the factors I estimate are supply factors as opposed to demand factors, this corresponds to a rise in debt level by the specified amount. From figure 6, a unit increase in the maturity factor corresponds to a 1.4 basis point increase in the 10-year yield. This implies a $11.48 billion surprise increase in Treasury maturity, keeping the debt level constant.

6.2 Effects on the economy

I use the factors in the volume space from the previous section to look at the effects of LSAP 1,2,3 and the MEP. During these programs, the Fed bought a mix of Treasuries and private securities. I only look at the quantity of Treasuries bought in these programs as the factors I construct relate to Treasury debt.

	LSAP 1	LSAP 2	LSAP 3	MEP
Period	Mar '09 - Mar '10	Nov '10 - Jun '11	Sep '12 - Oct '14	Sep '11 - Dec '12
Amount ($ blns)	300	600	790	667
Effect on				
- 10 year yield (bp)	↓ 0.36	↓ 0.73	↓ 0.96	↓ 0.81
- IIP (%)	↑ 0.01	↑ 0.03	↑ 0.04	↓ 0.04
- Unempl rate (pp)	↓ 0.28	↓ 0.58	↓ 0.77	↑ 0.81

Table (7) Effects of large-scale asset purchase programs on the 10-year yield, output (IIP), and the unemployment rate.

Table 7 reports the effects of the programs on interest rates and economic activity. Through the MEP, the Fed bought $ 667 billion in long-term securities and sold an equivalent amount of short-term securities. I interpret this as a change in the maturity factor as the total amount of debt in the hands of the public remained roughly constant. If the entire amount was unexpected, it would have led to a fall in the 10-year yield by 0.81 basis points. Given that a fraction of the total volume was likely to be expected, the actual fall in the 10-year yield was lower. From the previous section, a rise in the maturity factor leads to an expansion. Correspondingly, a program that decreased the maturity of outstanding debt led to a fall in

[31] Specifically, the bid-to-cover ratio is the ratio of the amount of Treasuries tendered in an auction, as a fraction of the total offered Treasuries in the auction. A higher bid-to-cover ratio corresponds to higher demand for Treasuries in the auction.

output and a rise in the unemployment rate.

It is more challenging to look at the effects of LSAP 1-3 as they were a mix of both factors Each of the three LSAP programs decreased the amount of debt in the hands of the public and were concentrated in longer maturity bonds, in order to bring down long term bond yields in the face of a zero lower bound constraint of the Fed funds rate. The programs were thus a mix of the level and the maturity factor I estimate in section 3. The amount attributed as a shock to each of the factors remains unobserved. I make the simplifying assumption that the entire amount came as a shock only to the level factor as the programs significantly changed the level of outstanding debt. This implies that the programs led to a large drop in the 10-year yield and a rise in economic activity.

7 Concluding remarks

At a time when public debt in the US is at an all-time high, it is important to understand how changes in debt supply affect the economy. In this paper, I use high-frequency identification around Treasury auction announcements to isolate shocks to public debt supply. I then combine narrative evidence and heteroscedasticity to separate two key underlying dimensions of debt supply - a uniform increase in debt across maturities, and a shift in weight of issuance from low to high maturity keeping the level of debt constant.

I find that an increase in both the level and maturity of debt issuance leads to a fall in prices and an increase in bond returns and yields, in accordance with the preferred habitat framework. An increase in the level of debt leads to a fall in output and employment. Contrary to the preferred habitat framework, an increase in maturity of debt issuance leads to an increase in output and employment. I find LSAP 1,2 and 3 led to a significant decline in long-term yields and a rise in output growth and employment. The Maturity Extension Program led to a decline in long-term yields accompanied by a fall in output and employment.

This paper leaves open several potential areas of research. First, the effect of the maturity factor on the macroeconomy is not in line with the standard preferred habitat channel (Ray, 2019). This necessitates an alternative framework through which debt maturity affects the economy. Second, that debt maturity shocks affect corporate bond yields is in line with the gap-filling channel (Greenwood, Hanson and Stein, 2010). It is possible to use micro-data on corporate bond issuance at the maturity level and test the channel formally. Finally, I have used the simplest version of the preferred habitat framework to interpret the empirical results. It is worthwhile to look at the effects in more general versions of the framework (Vayanos and Vila, 2021; Kekre, Lenel and Mainardi, 2022, etc.).

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Appendix

A Institutional details

A.1 Auction details

There are two kinds of bidders at the auction- competitive and non-competitive. The Federal Reserve does not take part in the auctions. It specifies beforehand the amount of debt it requires as part of SOMA holdings and it is allocated the entire amount that it demands. Non-competitive bidders make up the minority of bidders. They submit bids typically limited to $5 million per bidder and they agree to pay the price that is decided in the auction. The clearing price in the auction is set by the competitive bidders who make up the majority of bidders.

Each competitive bidder submits their preferred price and quantity, not exceeding 35% of the total amount available in the auction, in the week between the announcement and the date of closure of the auction. The total debt to be issued to competitive bidders is obtained after subtracting the amount allocated to non-competitive bidders. Once all bids are submitted, the amounts are allocated to competitive bidders in the increasing order of yields submitted. The yield at which the entire amount is allocated is the cutoff yield and every auction participant pays the same yield. The results of the auction are released within minutes after the auction closes. Around 2-3 days later, the participants are issued the debt.

A.2 Buybacks

Successive years of fiscal surplus during the Clinton administration allowed the Treasury to buy back some of the debt it had initially floated. This was done with the intention of reducing the debt burden as buying back long-term debt at the existing price would be cheaper than servicing the debt until maturity at a higher yield

The announcements for buyback operations are similar in structure to debt supply announcements. OFRs at this time would signal possible maturities at which the Treasury would buy back the debt, without pinning down the final volume. A few days before the announcement, the Treasury would release a document on the Treasury Direct website containing the total amount of debt it planned to buy. I interpret the buyback operations as negative supply shocks and include them in the list of news to debt supply. The final set of shocks is the response of secondary market prices to changes in announcements. The prices thus move in a market-determined direction irrespective of whether the new information is for new debt issued or the amount of debt bought back.

A.3 Quarterly Refunding Process

At the beginning of each quarter, the Treasury decides its debt management policy for the rest of the quarter. As a part of this process, it releases several documents towards the end of the first month in the quarter that provide information on the final policy that is to be implemented. In this subsection, I go over all the documents that the Treasury releases in chronological order and argue why the OFRs are of primary importance to me. To provide an example of the chronological order, I specify key dates for the events of the first quarter of 2018 (2018:Q1) and dates of the official releases wherever publicly available.

Towards the middle of the first month of the quarter, the Treasury sends a questionnaire to primary dealers asking for their estimates of the volume of Treasuries to be issued in all the auctions in the current quarter. The questionnaire asks primary dealers to enter the estimates for the volume, a range for the same, and other questions concerning the state of the economy. Responses to the questionnaires are to be submitted towards the beginning of the last week of the first month of the quarter. In 2018:Q1, responses were to be sent by January 22nd. The meeting with the primary dealers takes place a few days later. For 2018:Q1, the meetings took place on January 25th-26th.

Note that the response to the questionnaire provides a measure of the expectation of the volume to be issued. However, while the questionnaire is made public as *Primary Dealer Meeting Agenda*, the responses to the questionnaire are not publicly available. From 2015, primary dealers are asked twice a year for their estimates on the total volume issued across auctions for each maturity for the next three fiscal years (including the current one). The release is made public as *Primary Dealer Auction Size Survey.* The responses are aggregated and are only available twice a year for a short sample period.

A few days after the meeting with primary dealers, the Treasury presents the Treasury

Borrowing Advisory Committee (TBAC) with a summary of the state of the economy and key issues concerning debt management policy. The TBAC is an advisory committee that meets the Treasury each quarter to offer feedback on the state of the US economy and provide recommendations on debt management policy. The statement made by the Treasury is made public in a press release labeled as *Office of Economic Policy Statements to TBAC*. In 2018:Q1, it was made public on January 29th, 2018. Accompanying discussion charts are made public as *Treasury Borrowing Advisory Committee Discussion Charts*.

A few days later, the TBAC meet members of the US Treasury. In 2018:Q1, the meeting took place on January 30th from 9:30 a.m. to 5:30 p.m. Minutes of the meeting are released as *Treasury Borrowing Advisory Committee Meeting Minutes*. In 2018:Q1, the minutes were released on January 31st. As part of the meeting, a report is made to the Treasury Secretary with the outlook and recommendations of the TBAC. For 2018:Q1 the report was made public on January 31st as *Treasury Borrowing Advisory Committee Report to the Secretary*. The recommendations are summarised in tables labeled *Treasury Borrowing Advisory Committee Recommended Financing Tables*. Before 2018:Q1, the tables were a part of the committee report. 2018:Q1 onwards, the tables are released separately.

Note that the tables contain the TBAC's recommended volume of debt to be issued at all the auctions in the quarter and could thus be a measure of expected volume. However, these recommendations are only taken as input to decide the final amount to be issued, and very often, the final amount is different than the recommended amount. Moreover, as the Treasury mentioned in the 2018:Q1 release, "Lastly, you will note that we have delinked the TBAC recommended refinancing tables from this letter. In the prior refunding in November, some market commentators focused on the tables for specific guidance about Treasury's expected issuance in the following quarter. It is a mistake to use the tables for precise predictions. It is this letter and the minutes of the TBAC meeting that should be the focus of attention for our recommendations. The refunding tables should be considered as illustrative examples rather than any kind of exact policy guidance."

Around this time, the Treasury releases its *Quarterly Financing Estimates* (QFE) - marketable borrowing estimates for the current quarter, for the next quarter, and the marketable amount borrowed in the previous quarter. While the release provides information on total debt, the amount is aggregated across maturities and thus contains very few maturity shocks by construction. In 2018:Q1, the press release was issued on January 29, 2018.

The final document to be released in the Quarterly Refunding Process is the Official Remarks on Quarterly Refunding (OFR), which I use to estimate debt supply shocks. The OFR provides the final volume for upcoming auctions and contains information on the Treasury's stance on the level and maturity structure of debt issuance. Note that the OFRs always take place in the form of a press conference. Until 2001:Q4, the time of commencement of the press conference is known from the QFE. For example, the QFE on October 29, 2001 mentions *"The Quarterly Refunding Press Conference* ***will be held at 9 a.m.*** *on Wednesday, October 31, 2001"*. The conference entails a reading out of the OFR, post which the Treasury is asked questions by the media. The time of release of the OFR takes place at some point during/after the press conference. The exact time is not known, as can be corroborated by looking at the

Treasury Direct release which mentions *"For release when authorized at press conference.* This motivates a larger window to look at the futures price shocks and thus I look at futures prices 50 minutes after the conference has started.

From 2002:Q1, the exact time of release of the OFR is known. For example, the QFE on January 28, 2002 mentions *"Additional financing details relating to Treasury's Quarterly Refunding* ***will be released at 9 am*** *on Wednesday, January 30, 2002"*. Moreover, the corresponding Treasury Direct Release mentions *"Embargoed until 9 a.m."*. Thus from 2002:Q1 onwards, the exact release time of the OFRs is available. This motivates a shorter window to look at futures price shocks and thus I look at 20 minutes after the release time. Video webcasts of the press conferences are available starting from the first quarter of 2013.

Information on the above announcements is available in the *Quarterly Refunding Archives* section under *Treasury Quarterly Refunding* on the website of the US Department of the Treasury.

A.4 Relevance of primary market announcements in identifying debt supply shocks

To what extent do the primary market announcements that I consider contain new information on the level and maturity of debt issuance? Let's first take the case for the level of new debt. Major policies related to government expenditures and receipts are decided in the US Congress and not the Treasury. It is perhaps then intuitive to think that after the budget for a fiscal year is set, there are no shocks left to debt supply. There are a few caveats to this line of thinking. Major events that take place throughout the fiscal year create changes to the government's expenditures and receipts. The level of debt to be issued thus changes over time from its planned amount at the beginning of the fiscal year. Each quarter, the Treasury specifies the final debt level in the QFE document released during the Quarterly Refunding process. Thus, while other announcements made throughout the year may provide information on the government's budget constraint, the final level of debt is only pinned down during the Quarterly Refunding Process.

Moreover, the supply of debt level at each maturity is only made known for the first time to private agents during the release of OFRs and intermediate announcements. The QFE contains news shocks to the debt level. However, the OFRs and intermediate announcements contain the maturity-wise distribution of debt supply - a mix of debt level and maturity. Moreover, it contains observations on the government's stance, as opposed to the QFE which is shorter in length and simply contains the figure of the estimated debt level for the quarter. Thus, OFRs contain enough information to revise the expectations of private agents significantly. This makes OFRs the ideal announcement to look at debt supply shocks. The presence of QFEs however dampens the level shocks I define in my paper- explaining the smaller variances in the level subset.

Once it is established that the OFRs and intermediate announcements contain a non-trivial amount of information on debt supply, it is important to understand what shocks these announcements provide. The government revises the debt level depending on realized outlays and receipts. OFRs and intermediate announcements thus provide information on the government's estimate of realized outlays and receipts for the current period.

To fix ideas, assume that in a rational expectations setup with no pre-existing debt, agents have full information on past economic conditions - outlays and receipts for the past quarter $t-1$. At the start of quarter t, the Treasury knows the total outlays G_t and total receipts T_t. It announces total nominal debt supply $DS_t = G_t - T_t$. The announcements thus provide new information to private agents on total debt supply $\varepsilon_t^{DS} = DS_t - E_{t-1}(DS_t)$. This implies a shock to agents' expectation of government outlays and receipts $\varepsilon_t^G = G_t - E_{t-1}(G_t)$ and $\varepsilon_t^T = T_t - E_{t-1}(T_t)$.

I do not analyze in this paper which shock is this more likely to be. From the OFRs, the Treasury revises debt levels based on news on both expected receipts and outlays. It is possible to include the corresponding fiscal variables in the SVAR-IV and analyze the impulse responses to answer this question. Note that in this case, the transmission takes place through the government's budget constraint. It is possible to argue that the effects of both ε_t^G and ε_t^T are expansionary making the recessionary impact of an increase in debt level puzzling. However, to the extent that an increase in government expenditure can crowd out private capital and lead to recessionary impacts, the effects are consistent with an increase in debt level. In the case I analyze, the results are in line with the transmission through prices in the preferred habitat framework where the shocks are simply shocks to the quantity of debt.

Unlike the case for debt levels, the Treasury has exclusive control over maturity management. The maturity structure of debt issuance is only known during the releases I consider. Note, that there is a higher possibility of information shocks in the maturity shocks that I estimate. I show in the main text that information shocks are largely absent relative to shocks to the maturity structure of debt issuance.

Overall I conclude that the set of announcements I consider are crucial to obtain debt supply shocks that contain information on debt level and debt maturity.

A.5 Event windows

The US Treasury futures market is extremely elastic and prices change in response to a range of macroeconomic news releases. As a result, it is important to find windows where Treasury announcements do not overlap with other macroeconomic announcements.

From 1995-08-02 to 1997-10-29, there only exists information on OFRs, that is, there is no information on intermediate announcements. During this period, releases were made at 1 p.m. EST. Since these are all press conferences with only the time of commencement known, I select a slightly larger window to observe intraday prices. I look at prices from 10 minutes before the announcement to 50 minutes. I do not go after 50 minutes as government budget deficit reports are sometimes released at 2 p.m. (Gilbert, Scotti, Strasser and Vega, 2017).

Post 1997-10-29, all OFRs are made at 9 a.m. (EST) and all intermediate announcements are made at 2:30 p.m. (EST). All intermediate announcements have a 30-minute window, from 10 minutes before the release to 20 minutes after. For the former, it is important to check with the FRB releases of i) Industrial Production and ii) Capacity Utilization as these releases also take place at 9:15 a.m. I remove two announcement dates - 2000-11-15 and 2001-08-15, which clash with these releases. On 2001-01-17, there was an official remark and a buyback announcement. The second clashed with the FRB release. Thus, I keep the date but do not look at changes in prices around buybacks.

For OFRs before 2002 which were press conferences with only the commencement time being known, the window is slightly longer- from 10 minutes before to 45 minutes after. I do not go after 45 minutes as often the UMich consumer confidence survey is released at 9:55 a.m. For announcements after 2001 when the exact time of the release is known, the window is set to 10 minutes before to 20 minutes after.

Intermediate announcements made at 2:30 p.m. do not clash with other macroeconomic news as most of these releases take place earlier in the day (Elenev, Law, Song and Yaron, 2022). However, monetary policy statements take place around this time and it is important to ensure they do not clash. I go through FOMC release dates from the FOMC website and check if they clash with these dates. I find that no overlap exists in dates.

Announcements made at 10:30 a.m., 10 a.m., and 9:30 a.m. do not clash with other macroeconomic news. The window for these announcements is always set to 10 minutes before to 20 minutes after.

On 2002-06-28, there was an intermediate announcement made at 8:15 a.m. This clashes with the BEA announcement on Personal Income at 8:30 a.m. To avoid clashing with the announcement I take a window from 10 minutes before to 10 minutes after.

Later announcements are made at 8:30 a.m. A lot of macroeconomic news gets released at this time. It is important to verify if there is any overlap with them. I look at BEA releases of GDP, personal income, and trade balance, and BLS releases of non-farm payrolls to see if there exist any clashes. I remove 11 announcements that have these clashes.

This leaves 335 announcements that contain macroeconomic news and do not clash with other releases. After defining windows and finding prices, I remove 3 observations for which the time of the news release was not available. I remove one observation for which there were no trades the day after the announcement. This makes up the final set of 331 news releases which I use for my analysis.

B Estimation of principal components

In equation 2, I normalize the price changes to have zero mean and unit variance in D_t. The principal components F_t are also normalized to have zero mean and unit variance[32]. Table 2 shows that there are mainly two underlying factors driving price changes. Table B.1 shows that the first two principal components explain a major share - 85%, of the total variance across all five series.

	PC1	PC2	PC3	PC4	PC5
Share of var explained	0.69	0.16	0.09	0.03	0.01
Cumulative share of var explained	0.69	0.85	0.95	0.99	1

Table (B.1) Share of variance explained by principal components (PCs). The variance share for each PC is given by the corresponding eigen value multiplied by a normalizing constant which sets the variance of each PC to be equal to 1

Table B.2 reports the matrix of factor loadings Λ'. The first factor affects Treasury futures prices fairly uniformly. There is a smaller effect by magnitude on the future with the shortest underlying maturity asset - the 6-month Eurodollar futures. The effects increase in magnitude from the 2-year Treasury future to the 5-year Treasury futures and then to the 10-year futures. The second factor has a smaller effect on prices at shorter maturities and the effect increases in magnitude with maturity.

	2-yr	5-yr	10-yr	30-yr	6-month Eud
PC1	-0.86	-0.94	-0.94	-0.81	-0.53
PC2	0.07	-0.08	-0.20	-0.28	0.83

Table (B.2) Matrix of factor loadings Λ'. PC1 and PC2 are the first two principal components. Columns correspond to the 2-year, 5-year, 10-year, 30-year Treasury futures prices and the 6-month eurodollar futures.

Given the nature of loadings, it is tempting to interpret the first factor as a level change and the second factor as a slope change in the term structure of asset prices. This follows the factor pricing argument in the term structure literature following Nelson and Siegel (1987). However, this is not the same as assigning the factors an interpretation linked to changes in debt supply. Changes in the level and slope of *quantity* of debt affect the level and slope of *prices* differently. An increase in the level of debt for all maturities increases both the level and the slope of the term structure. Similarly, a change in the maturity of debt issuance affects both the level and the slope.

[32]The normalization of unit variance for each component makes more economic sense than a normalization of unit norm for each component. A priori, there is no reason to believe one of the factors has more variance than the other in the population.

C Details on SVAR-IV framework

C.1 Econometric specification

Consider the following VAR(p) model

$$Y_t = A_1 Y_{t-1} + A_2 Y_{t-2} + ... + A_p Y_{t-p} + \eta_t, \quad Var(\eta_t) = \Sigma \tag{C.15}$$

where each Y_t is a $n \times 1$ vector. The vector of reduced form innovations η_t is related to the vector of structural shocks ε_t through $\eta_t = \Theta_0 \varepsilon_t$. The structural shocks are contemporaneously uncorrelated with each other, i.e. $V(\varepsilon_t) = diag(\sigma_1^2, \sigma_2^2, ..., \sigma_n^2)$. The objective is to find the effect of the structural shock to debt level and debt maturity on all the variables in Y_t. Without loss of generality, if I take the first structural shock to be the shock of interest, I need to impose restrictions to estimate $\Theta_{0,1}$, the first column of Θ_0.

The VAR(p) above admits the following MA representation in terms of the structural shocks

$$Y_t = \sum_{k=0}^{\infty} C_k(A) \Theta_0 \varepsilon_{t-k} \tag{C.16}$$

The impulse response to a variable i at horizon $t+k$ due to a unit change in $\varepsilon_{1,t}$ is given by $\lambda_{k,i} = \partial Y_{i,t+k} / \partial \varepsilon_{1,t} = e_i' C_k(A) \Theta_{0,1}$ where e_i is a zero vector of length n, with 1 at the $i'th$ place.

In the above formulation of the impulse responses, the parameters A and thus C can be estimated by OLS from the reduced form equation C.15. The vector $\Theta_{0,1}$ is, however, unknown. The external instruments method (Mertens and Ravn, 2013; Stock and Watson, 2018) imposes restrictions using the factors s_t computed in the section 3, to estimate $\Theta_{0,1}$. Under the assumptions of

1. *Relevance.* $E(s_t \varepsilon_{1,t}) = \alpha \neq 0$
2. *Exogeneity.* $E(s_t \varepsilon_{j,t}) = 0, j \neq 1$

the vector $\Theta_{0,1}$ is identified upto a normalising constant.

The factors s_t I estimate satisfy both these assumptions. The proxies are determined using information on debt supply announcements and thus, they are strongly related to structural shocks to debt level and maturity. The high-frequency identification ensures that the factors are not correlated with other structural shocks in the economy.

In order to estimate $\Theta_{0,1}$, I use the factor s_t to write

$$E(s_t\eta_t) = \alpha\Theta_{0,1}, \quad E(s_t\eta_{1,t}) = \alpha\Theta_{0,11} \tag{C.17}$$

Under the normalisation $\Theta_{0,11} = x$, $\Theta_{0,1} = [x; \tilde{\phi_0}.x]'$, where $\tilde{\phi_0} = \frac{E(s_t\eta_t)}{E(s_t\eta_{1,t})}$. All the parameters necessary to compute the structural impulse responses thus have a sample counterpart and it is possible to estimate them. Note that $\tilde{\phi_0}$ can be estimated using a regression of $\eta_{1,t}$ on η_t using s_t as an instrument for $\eta_{1,t}$. I normalize with respect to the long-term yield and set x to 0.01 from section 4. Thus I look at the effect of a structural shock that increases long-term yield by 1 basis point.

C.2 Data

I use 6 variables in the VAR. To look at the effect on asset prices I use the nominal 1-year and the 15-year yields in level percent terms. I use the 1-year yield as the short rate as in addition to being a yield at the short end of the term structure, it tracks the monetary policy rate. This saves the need for including the Fed funds rate, an additional variable, in the VAR. I use the 15-year yield as the long-term yield, instead of the 30 years, as the yield on the 15-year bond is available starting from earlier. This allows me to increase the sample size as much as possible. I use the PCE and IIP in log levels and the unemployment rate, in order to look at the effect of macroeconomic variables. The variables in the VAR are a mix of levels and rates with a maximum order of integration equal to 1. Data for all the variables are obtained from the FRED database of the Federal Reserve Bank of St. Louis.

As seen in section 4.5, debt supply shocks contribute only a small part of the monthly movement in variables. In order to control for other sources of variation, I use the first principal component of the 134 variables in the FRED-MD database. These variables are a set of monthly macroeconomic and financial indicators that summarise all sources of major fluctuations in the economy. The factors are used in dynamic factor models as a parsimonious way of controlling for a large number of variables (Stock and Watson, 2015). The first principal component of the entire set of variables co-moves negatively with the state of the economy. It loads negatively on economic activity, non-farm employees, etc. I obtain the FRED-MD database from the website of the Federal Reserve Bank of St. Louis.

I use a longer sample from 1971:M11 to 2021:M11 to estimate the VAR parameters A, Σ and C. Then, I use a shorter sample from 1995:M08 to 2021:M11 to find sample covariances $\mathbf{P}_t(s_t\eta_t)$ and $\mathbf{P}_t(s_t\eta_{1,t})$ and compute $\hat{\Theta}_{0,1} = [0.01; \frac{\mathbf{P}_t(s_t\eta_t)}{\mathbf{P}_t(s_t\eta_{1,t})} \times 0.01]'$. During estimation, I use only one of the factors at a time. As the factors are independent by definition, the effect would be the same as the effects obtained by jointly estimating a system with two instruments for two structural shocks. I, thus, implement the estimation twice- once to obtain the impulse responses for debt level shocks and again to obtain the responses for maturity shocks. For both cases, I use a lag length of 12 as the variables are at a monthly frequency.

During the estimation of $\hat{\Theta}_{0,1}$, I standardize both structural shocks to have an effect of 0.01 percent point or 1 basis point increase on the 15-year yield. The order of magnitude of the effect follows from the result in section 4. I standardize with the same effect in both cases such that the effects are comparable. The responses thus report the effect of an increase in debt maturity shock that increases the 15-year yield by 1 basis point and the effect of an increase in debt level shock that has the same effect on the 15-year yield. In terms of quantities, I am looking at the effect of a positive shock to the maturity of issuance and a positive shock to the level of debt, that leads to a 1 basis point increase in the 15-year yield.

C.3 First-stage tests for instrument relevance

Table C.3 reports results for first-stage tests of instrument relevance. The instruments do not pass the Olea and Pflueger (2013) threshold F-statistic of 23.1. Thus, the instruments are weak. While this is concerning, according to Ramey (2016), most instruments in the macroeconometrics literature fail to pass the threshold robust F-statistic. The order of magnitude in table C.3 is comparable to the case for widely used instruments for government spending shocks as noted in figure 4 of Ramey (2016). I use weak instrument robust confidence intervals (Montiel Olea, Stock and Watson, 2021) for inference of the impulse responses.

Test type	Test statistic		Critical value	
	Level	Maturity		
Robust F-test	2.72	1.70	$23.10\ (\alpha = 5\%, \tau = 10\%)$	
MSW Wald test	5.57	3.95	$0.99\ (\chi^2_{1,1-0.68})$	$2.71\ (\chi^2_{1,1-0.90})$

Table (C.3) Tests for instrument relevance. The null hypothesis for the robust F-test (Olea and Pflueger, 2013) is the Nagar bias exceeds $\tau = 10\%$ of a worst-case benchmark, which corresponds to the presence of weak instruments. The null is rejected at 5% level of significance if the test statistic is larger than the critical value. The test is robust to heteroscedasticity, serial correlation, and clustering. The critical value corresponds to the simplified case in Olea and Pflueger (2013). MSW Wald test (Montiel Olea, Stock and Watson, 2021) tests the null hypothesis that $E(s_t\eta_{1,t}) = 0$. This corresponds to the case where the instrument relevance condition does not hold.

As an additional test of instrument strength, I conduct the Montiel Olea, Stock and Watson (2021) Wald test. As x is normalised to 0.01, from equation C.17, $E(s_t\eta_{1,t}) = \alpha \times 0.01$. As $\sqrt{T}(\mathbf{P}(s_t\eta_{1,t}) - E(s_t\eta_{1,t})) \xrightarrow{d} N(0, V(\mathbf{P}(s_t\eta_{1,t}))$, the Wald statistic $T\mathbf{P}(s_t\eta_{1,t})/\hat{V}(\mathbf{P}(s_t\eta_{1,t}))$ is a measure of instrument strength. The null $E(s_t\eta_{1,t}) = 0$ corresponds to a test of $\alpha \times 0.01 = 0 \implies \alpha = 0$. From table C.3, I reject the null hypothesis at the 68% and 90% confidence level. This implies that the relevance condition holds.

The weak IV robust confidence intervals tend to be accurately large. It is common for the confidence intervals to span the entire real line for certain specifications. The Montiel Olea, Stock and Watson (2021) Wald test additionally has the feature that the test needs to reject the null in order to have finite confidence intervals of the impulse responses at all horizons for a given level of significance. The null that the instrument is not relevant is rejected for both factors at both the 68% and 90% level. The corresponding confidence intervals I report are thus finite sets at all horizons.

D A preferred habitat framework on debt management

I set up a simple version of the preferred habitat framework of Vayanos and Vila (2021), following Greenwood and Vayanos (2014). Different from Greenwood and Vayanos (2014), I calibrate the model to understand the predicted responses to debt level and debt maturity shocks on bond yields and returns. In order to understand the effects on the macroeconomy, I follow Ray (2019) and embed the preferred habitat block in a baseline New Keynesian model. The representative agent's consumption decision depends on a weighted average of the entire term structure of interest rates, instead of only the short rate. The term structure is priced in the preferred habitat block of the model.

D.1 Model setup

The model is set in continuous time. In the economy, there exist risk-averse arbitrageurs who maximise the following mean-variance preferences

$$\max_{x_t^\tau}[E_t(dW_t) - \frac{a}{2}Var_t(dW_t)] \tag{D.1}$$

subject to the budget constraint

$$dW_t = \int_0^T x_t^\tau \frac{dP_t^\tau}{P_t^\tau} d\tau + (W_t - \int_0^T x_t^\tau d\tau) r_t dt \tag{D.2}$$

where W_t is the total wealth of the arbitrageurs, $\{x_t^\tau\}_\tau$ are the porfolio holdings at different maturities and a is a risk aversion coefficient. Bond prices at maturity τ are given by P_t^τ and the corresponding zero coupon yield is given by $y_t^\tau = -\frac{lnP_t^\tau}{\tau}$. r_t, the short rate, is the limit of the zero coupon yield as τ goes to zero.

Following Vayanos and Vila (2021), I assume the net supply of bonds from the government and other investors in the economy is given by.

$$s_t^\tau = \zeta(\tau) + \theta(\tau)\beta_t \tag{D.3}$$

where the factor β_t has the following Ornstein-Uhlenbeck process

$$d\beta_t = -\kappa_\beta \beta_t dt + \sigma_\beta dB_{\beta,t} \tag{D.4}$$

where $\kappa_\beta, \sigma_\beta > 0$ are constants and $B_{\beta,t}$ is a Brownian motion. $\zeta(\tau)$ is the mean supply at maturity τ and $\theta(\tau)$ measures the sensitivity of supply to the stochastic factor β_t. The factor

β_t is a debt supply shock. The sensitivity $\theta(\tau)$ determines how the shock affects the different maturities. I assume that $\theta(\tau)$ has the following properties:

1. $\int_0^T \theta(\tau)d\tau \geq 0$
2. There exists $\tau* \in [0, T]$ such that $\theta(\tau) < 0$ for $\tau < \tau*$, and $\theta(\tau) > 0$ for $\tau > \tau*$

The first property ensures that an increase in β_t implies the total supply of bonds has not decreased. The arbitrageur absorbs this change in total supply. The second property ensures that an increase in β_t may lead to a case where arbitrageurs are supplied fewer bonds at short maturities and more bonds at long maturities. The two properties are useful as they allow for the following two polar cases of interest I study in this paper

1. *Debt level shock*, obtained by setting $\tau* = 0$ and $\theta(\tau) = k > 0, \forall t$
2. *Debt maturity shock*, obtained by setting $\int_0^T \theta(\tau)d\tau = 0$ and $\theta(\tau) = k'$, for at least one τ

The above two cases are of particular interest as they correspond to two dimensions of debt supply changes which are most commonly observed in practice. When new debt is issued, the supply at different maturities changes by different amounts. Thus, two distinct things happen. First, the total level of debt changes, and second, the maturity at which new debt is issued changes. Isolating these two channels is important as it is unclear ex-ante what are the effects of these changes. The functional form of $\theta(\tau)$ for the first case above corresponds to a debt supply change where the maturity of issuance does not change, but there is an increase in total debt supply. The second functional form corresponds to a case where total debt remains constant but there is a tilt in issuance from short to long maturities. I fix $\theta(\tau)$ corresponding to the two types of shocks while calibrating the model in section D.4.

To complete the setup in this partial equilibrium model, I assume the short rate follows an exogenous Ornstein-Uhlenbeck process

$$dr_t = \kappa_r(\bar{r} - r_t)d_t + \sigma_r dB_{r,t} \tag{D.5}$$

where $\kappa_r, \bar{r}, \sigma_r > 0$ are constants and $B_{r,t}$ is a Brownian motion. In the next subsection when I look at the general equilibrium effects on output and inflation, the short rate is set by the central bank following a Taylor rule.

To solve the model, I conjecture that equilibrium bond yields are affine in the risk factors β_t and r_t, that is,

$$P_t^\tau = e^{-[A_r(\tau)r_t + A_\beta(\tau)\beta_t + C(\tau)]} \tag{D.6}$$

Using, Ito's lemma and the processes for β_t and r_t, I find that the instantaneous return at maturity τ is given by

$$\frac{dP_t^\tau}{P_t^\tau} = \mu_t^\tau dt - A_r(\tau)\sigma_r dB_{r,t} - A_\beta(\tau)\sigma_\beta dB_{\beta,t} \tag{D.7}$$

where the instantaneous expected return is given by

$$\mu_t^\tau = A_r'(\tau)r_t + A_\beta'(\tau)\beta_t + C'(\tau) + A_r(\tau)\kappa_r(r_t - \bar{r}) + A_\beta(\tau)\kappa_\beta\beta_t + \frac{1}{2}A_r(\tau)^2\sigma_r^2 + \frac{1}{2}A_\beta(\tau)^2\sigma_\beta^2 \tag{D.8}$$

Substituting the above expression into the arbitrageur's budget constraint and solving the problem leads to the following no arbitrage condition at each maturity τ

$$\mu_t^\tau - r_t = A_r(\tau)\lambda_{r,t} + A_\beta(\tau)\lambda_{\beta,t} \tag{D.9}$$

where

$$\lambda_{i,t} = a\sigma_i^2 \int_0^T x_t^\tau A_i(\tau) d\tau \tag{D.10}$$

for $i = r, \beta$. The left-hand side of D.10 is the expected excess return of the bond. The right-hand side is the amount to be compensated for bearing an additional unit of risk from both factors. $A_i(\tau)$ measures the exposure to the source of risk and $\lambda_{i,t}$ is the price of the risk.

Next, I set the market clearing condition $x_t^\tau = s_t^\tau$, substitute to get an equation in r_t, β_t, and constant terms, and solve the ODEs obtained by setting the respective coefficients to 0. I get the following functional forms for $A_r(\tau)$ and $A_\beta(\tau)$

$$A_r(\tau) = \frac{1 - e^{-\kappa_r\tau}}{\kappa_r} \tag{D.11}$$

$$A_\beta(\tau) = \frac{Z}{\kappa_r}\left(\frac{1 - e^{-\hat{\kappa}_\beta\tau}}{\hat{\kappa}_\beta} - \frac{e^{-\kappa_r\tau} - e^{-\hat{\kappa}_\beta\tau}}{\hat{\kappa}_\beta - \kappa_r}\right) \tag{D.12}$$

where

$$Z = a\sigma_r^2 \int_0^T \frac{1 - e^{-\kappa_r\tau}}{\kappa_r}\theta(\tau) d\tau \tag{D.13}$$

and $\hat{\kappa}_\beta$ is the solution of

$$\hat{\kappa}_\beta = \kappa_\beta - a\sigma_\beta^2 \int_0^T A_\beta(\tau)\theta(\tau)d\tau \tag{D.14}$$

D.2 Implication for asset prices

The above setup implies the following four propositions on bond returns and yields due to a shock to the supply factor β_t. The propositions hold for general functional forms of $\theta(\tau)$ subject to the assumptions in the previous section. Formal proofs are detailed in Greenwood and Vayanos (2014).

Proposition 1: A shock to the supply factor β_t moves the instantaneous expected returns of all bonds in the same direction as the shock. Moreover, the effect is increasing across maturities.

Proposition 2: A shock to the supply factor β_t moves the yields of all bonds in the same direction as the shock. Moreover, the effect is either increasing or hump-shaped across maturities.

Irrespective of how $\theta(\tau)$ is specified, an increase in β_t implies arbitrageurs have more long-term bonds in their portfolio. Long-term bonds are more sensitive to sources of risk than short-term bonds. This stems from the fact that $A_r(\tau)$ and $A_\beta(\tau)$ are both increasing in maturity τ. From the mean-variance preferences, arbitrageurs dislike large fluctuations in their wealth. Thus, an increase in the holding of long-term bonds implies a fall in prices and a larger expected return demanded by arbitrageurs to hold the additional risk in their portfolios.

The fall in prices implies that yields rise for all maturities. The effect on intermediate yields may be larger than long-term yields depending on how soon the shock mean reverts. As yields are equal to the average expected return over the life of the bond, a shock that dies down quickly implies a smaller effect on yields at larger maturities than for intermediate maturities.

Proposition 3: A shock to the supply factor β_t has a larger effect on instantaneous expected returns than on yields.

The intuition stems from the fact that the yield equals the average expected return over the life of the bond. The shock mean reverts over time and thus the average effect is smaller than the current expected return. Moreover, the average return includes returns on short-maturity bonds towards the end of the bond's life. The effect on short-maturity bonds is smaller as argued in Proposition 1, driving down the average return over the bond's life.

Proposition 4: The effect of the supply factor β_t on instantaneous expected returns is increasing in the arbitrageurs' risk aversion coefficient a.

The arbitrageur demands compensation for holding additional risk as it is averse to fluctuations in its portfolio. This stems from the variance component of their mean-variance preferences. The more risk-averse the arbitrageur is, the higher the compensation it demands for holding additional risk. The effect on returns and yields thus increases in magnitude with an increase in risk aversion of the arbitrageur.

D.3 Implication for the macroeconomy

Following Ray (2019), I embed the preferred habitat framework in a New Keynesian model. This entails an IS curve of the form

$$dx_t = \zeta^{-1}(\tilde{r}_t - \pi_t - \bar{r})dt \tag{D.15}$$

where x_t is the output gap, ζ^{-1} is the intertemporal elasticity of substitution, $\bar{r}$ is the real natural borrowing rate. Growth rate of output depends on a weighted average of the term structure given by $\tilde{r}_t = \int_0^T \eta(\tau) y_t^\tau d\tau$, where $\eta(\tau)$ is a positive weighting function and y_t^τ is the yield on a zero coupon nominal bond. This is as opposed to the standard case where the growth rate depends only on the nominal short rate. The term structure of interest rates y_t^τ is determined in the preferred habitat block of the model. The rest of the model is standard. The Phillips curve is given by

$$d\pi_t = (\rho\pi_t - \delta x_t)dt \tag{D.16}$$

where ρ is the discount rate and δ is an index of price stickiness. Instead of the stochastic process in the partial equilibrium case, the nominal short rate is determined by the central bank using a Taylor rule of the form

$$dr_t = -\kappa_r(r_t - \phi_\pi \pi_t - \phi_x x_t - r*)dt + \sigma_r dB_{r,t} \tag{D.17}$$

where $B_{r,t}$ is a standard Brownian motion and $r*$ is the central bank's target rate set to obtain zero output gap in a steady state.

Proposition 6 in Ray (2019) states that if arbitrageurs are not risk-neutral, any change in the arbitrageur's portfolio that leaves them holding more risky long-term bonds, will end up increasing all bond yields. This in turn leads to lower output and lower inflation as the effective borrowing rate for households $\tilde{r}_t$ rises.

It is important to point out that there are two key differences with respect to the framework in Ray (2019). In the latter, the net supply of government bonds at maturity τ depends on the yield at maturity τ following Vayanos and Vila (2021). Second, the debt supply shock β_t is a zero probability shock without the Brownian motion component. To the extent that debt supply shocks have more local effects if they are price-elastic, the global effects I observe in the data should be consistent with proposition 6 if supply is modeled to be price-inelastic. I, thus, conjecture that the proposition holds for the case I consider in the paper.

D.4 Calibration

The key parameters in Greenwood and Vayanos (2014) are $(\theta(\tau), \kappa_\beta, \kappa_r, \sigma_\beta, \sigma_r, \bar{r}, a)$. To estimate $\theta(\tau)$, Greenwood and Vayanos (2014) use the regression coefficient of debt supply at maturity τ on a measure of total debt supply. In order to look at debt level shocks, I use the definition of debt level shock in section D.1 and set $\theta(\tau) = k$, where k is the mean of $\theta(\tau)$ in Greenwood and Vayanos (2014), aggregated across maturities. An increase in β_t corresponds to a uniform increase in debt supply at all maturities. In order to look at debt maturity shocks, I follow the definition in section D.1 and set $\theta(\tau_{min}) = -k'$, $\theta(\tau_{max}) = k'$, and $\theta(\tau) = 0$ for $\tau \neq \{\tau_{min}, \tau_{max}\}$. I set k' to half the total value of the sensitivities $\theta(\tau)$ in Greenwood and Vayanos (2014). An increase in β_t in this case corresponds to a tilt in issuance from τ_{min} to τ_{max}, keeping the total level of debt constant. $\theta(\tau)$ for Greenwood and Vayanos (2014), level and maturity shocks are reported in figure D.1.

In order to estimate $(\kappa_\beta, \kappa_r, \sigma_\beta, \sigma_r, \bar{r})$, I first discretize the processes D.4 and D.5. This corresponds to the equations

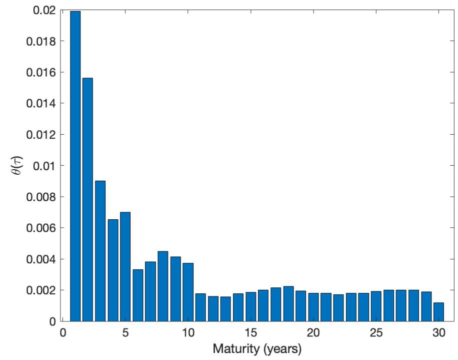
$$\beta_{t+\Delta t} = c_\beta \beta_t + \epsilon_{\beta,t+\Delta t} \tag{D.18}$$

$$r_{t+\Delta t} = c + c_r r_t + \epsilon_{r,t+\Delta t} \tag{D.19}$$

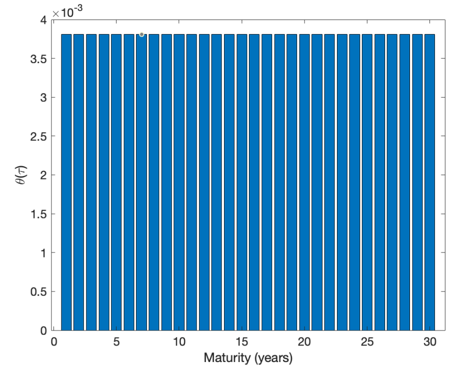
where $\kappa_i = \frac{(1-c_i)}{\Delta t}$, $\sigma_i^2 = \frac{Var(\epsilon_{i,t+\Delta t})}{\Delta t}$ for $i \in \{r, \beta\}$ and $\bar{r} = \frac{c}{\kappa_r \Delta t}$. I set $\Delta t = 1/12$ as the frequency of data is monthly and the model period is yearly. I estimate equation D.19 by using the yields on the nominal 1-year Treasury yield from Gürkaynak, Sack and Wright (2007). For equation D.18, I follow Greenwood and Vayanos (2014) and use the Maturity-Weighted-Debt-to-GDP in equation D.20 as a measure of supply. The Maturity-Weighted-Debt-to-GDP $(\frac{MWD}{GDP})_t$ is given by

$$(\frac{MWD}{GDP})_t = \frac{\sum_{0 \leq \tau \leq 30} D_t^\tau \tau}{GDP_t} \tag{D.20}$$

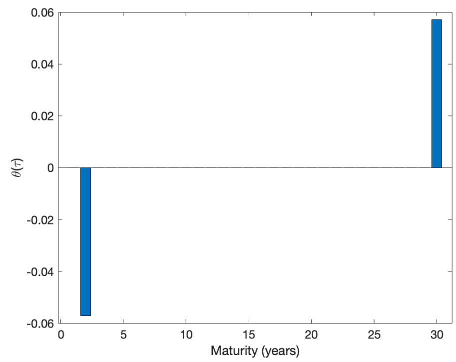
where D_t^τ is the amount of outstanding debt net of Fed holdings, at maturity τ in time t. In order to ensure that $c_\beta < 1$, I include a trend term in equation D.18. As the equation does not have an intercept, I estimate the OLS using the demeaned values of the variables. I do not use the constructed factors as they are price responses to the exogenous changes in supply and not the change in supply themselves. I use the sample for which the factors are constructed- 1995:M08 to 2021:M12 to estimate the parameters. The sample period is chosen



(a) $\theta(\tau)$ weights in Greenwood and Vayanos (2014)



(b) $\theta(\tau)$ weights for level shock



(c) $\theta(\tau)$ weights for maturity shock

Figure (D.1) Weights $\theta(\tau)$ in Greenwood and Vayanos (2014), for level shocks and for maturity shocks.

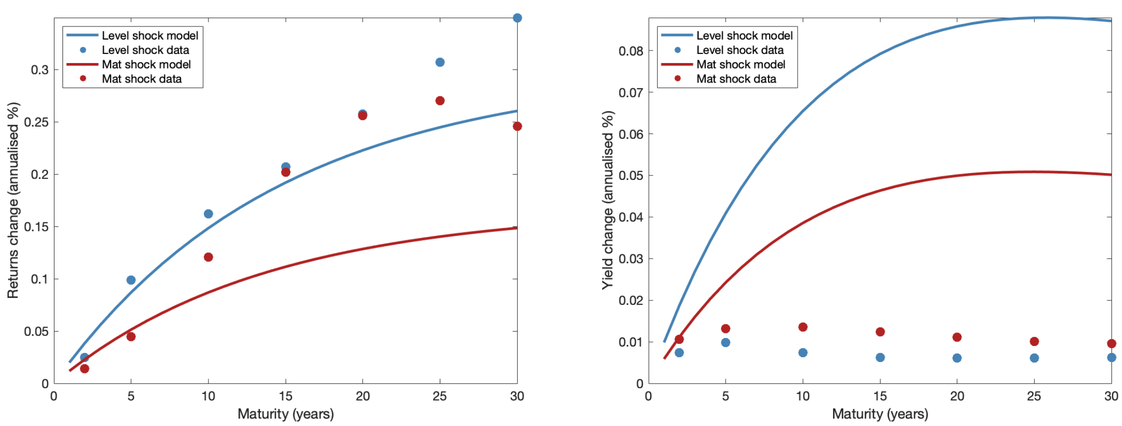
keeping in mind the sample for the data-driven moments in section 4. Figure D.4 reports the estimated parameter values.

I search across values of a to minimize the distance between the model and data implied average effect of supply shocks on returns/yields. As the effects are increasing in a, there is a unique value of a that minimizes the distance between the average effects in the model and the data. I find the value of a that minimizes the distance corresponds to a value of 5, which falls within the range of feasible values typically estimated in the macro-finance literature.

Figure D.2 plots the model and data implied effects of the debt supply factors. The returns required as compensation in the data are well approximated by the model. For yields, the fit is slightly worse. The model implies a much larger compensation for arbitrageurs than in the data. Moreover, the required compensation for a tilt in maturity of issuance in the data is larger than for an increase in overall supply. One way of bringing the model closer to the data is to define $\theta(\tau)$ for the level factor to have less weights towards longer maturities. Arbitrageurs would then require less compensation to hold a 'safer' portfolio containing fewer long-term bonds, driving the blue line below the red line.

	Parameter	Estimate	Std error
Panel A: AR(1)			
	c	-6.8e-6	1.6e-5
	c_r	0.99	5.1e-3
	$\sqrt{Var(\epsilon_{r,t})}$	0.002	
	c_β	0.99	3.5e-3
	$\sqrt{Var(\epsilon_{\beta,t})}$	0.35	
Panel B: OL			
	κ_r	0.08	
	$\bar{r}$	-0.001	
	σ_r	0.007	
	κ_β	0.07	
	σ_β	1.21	
Risk aversion			
	a	5	

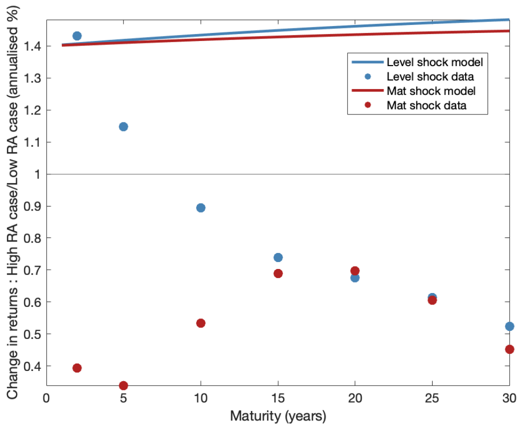
Table (D.4) Calibrated parameter values. Panel A reports the OLS coefficients and standard errors from equations D.18 and D.19. Panel B reports the coefficients for the Ornstein-Uhlenbeck processes D.4 and $D.5$ obtained by transforming the estimates in Panel A. Panel C reports the value of risk aversion a obtained by matching model and data implied effects of supply shocks on returns/yields.



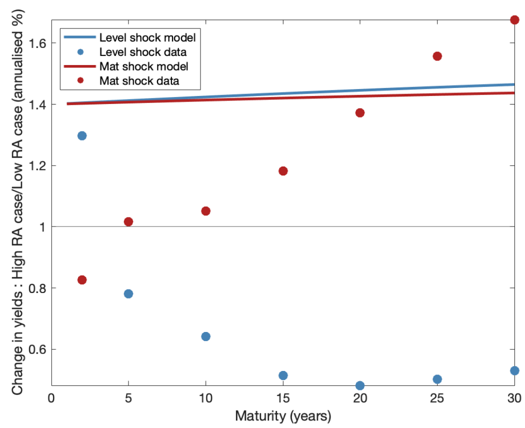
(a) Effect on returns

(b) Effect on yields

Figure (D.2) Effect of level and maturity factor on bond returns and yields. Blue lines/dots correspond to the level factor. Red lines/dots correspond to the maturity factor. Solid lines show the model-implied moments. These correspond to an increase in β_t in Greenwood and Vayanos (2014) with the corresponding $\theta(\tau)$. The model returns at maturity τ equal the instantaneous expected return μ_t^τ. Model yields correspond to zero coupon yield y_t^τ. Dots show the data-implied moments. The moments correspond to an increase in the maturity factor and a fall in the level factor estimated in section 3. Data returns correspond to a 1-year holding period return $r_{t,t+1}^\tau$. Data yields correspond to zero coupon yield y_t^τ.



(a) Effect on returns



(b) Effect on yields

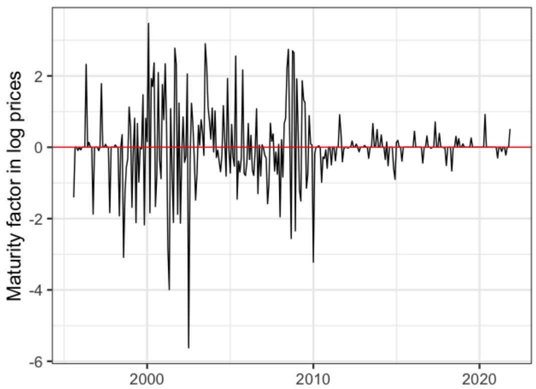
Figure (D.3) Relative effects of debt factors on returns/yields during high and low risk aversion (RA) periods. Blue lines/dots correspond to the level factor. Red lines/dots correspond to the maturity factor. Solid lines show the model-implied moments. These correspond to an increase in β_t in Greenwood and Vayanos (2014) with the corresponding $\theta(\tau)$. The model returns at maturity τ equal the instantaneous expected return μ_t^τ. Model yields correspond to zero coupon yield y_t^τ. Dots show the data-implied moments. These correspond to an increase in the maturity factor and a fall in the level factor estimated in section 3. Data returns correspond to a 1-year holding period return $r_{t,t+1}^\tau$. Data yields correspond to zero coupon yield y_t^τ. High and low RA periods in the data correspond to regimes in section 4. High RA in the model corresponds to baseline estimates. Low RA in the model corresponds to scaling a by 1.4, which equals the ratio of the median value of the absolute RA index in high RA periods and low RA periods.

I report the relative effects for high and low risk aversion in figure D.3. The data moments are taken from section 4. Model moments for high risk aversion correspond to baseline effects in figure D.2. Low risk aversion effects are obtained by scaling a with a factor (=1.4) which equals the average ratio of the absolute risk aversion coefficient in high and low regimes. The model-implied effects on returns are mostly above 1, implying a higher magnitude of effects during high risk aversion periods. This is in line with the idea that the more risk-averse the arbitrageur is, the higher the compensation required to hold risky long-term bonds. In the data, the shocks to supply are unobserved. The effects do not stem from a unit shock to supply. Instead, they stem from a change in supply that leads to a unit change in the factor which is the price response to the supply shock. The difference in trends between the model and data possibly arises as the origin of the shock is not comparable.

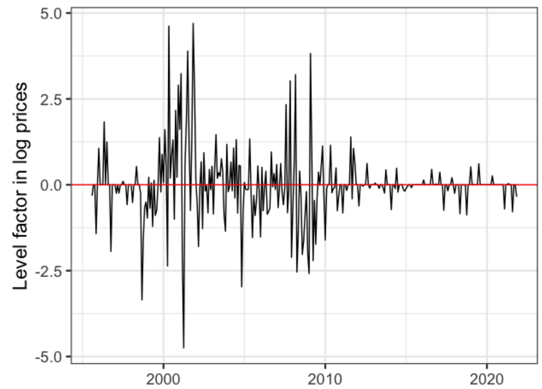
E Diagnostics of the estimated factors

I temporally aggregate the factors to the monthly frequency by summing across factors for each month. In case a month does not have an observation, the month is assigned a value of 0. As there were fewer releases registered as news in the latter part of the sample after 2016, this part of the sample mechanically has very few observations. Figure E.4 and table

E.5 plot the monthly series and contain the respective summary statistics. The properties of the factors after aggregation remain roughly similar to the daily shocks.



(a) Maturity factor



(b) Level factor

Figure (E.4) Maturity factor and level factor aggregated to monthly. y-axis is in log prices (standardized)

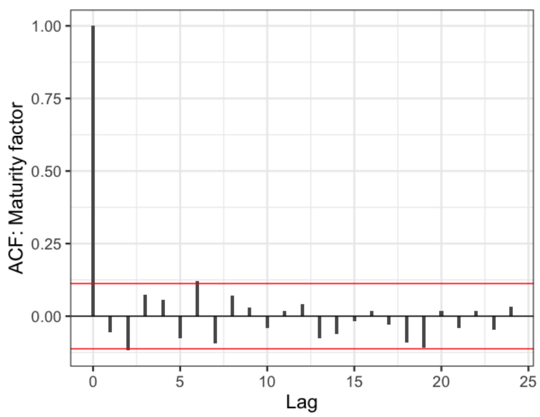
Factors	Mean	Median	SD	N	Correlations S_t^{mat}	Correlations S_t^{level}
Maturity factor S_t^{mat}	0	0	1.00	316	1	
Level factor S_t^{level}	0	0	1.01	316	0.09	1

Table (E.5) Summary statistics of monthly aggregated factors

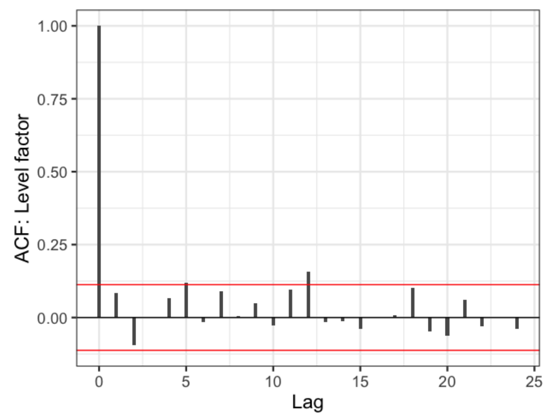
The monthly aggregation allows for a range of diagnostic checks on the factors. In figure E.5, I report the autocorrelation function for both factors. I find no evidence that either of the factors is serially correlated. The factors are, thus, not predictable by their past values. I also check if the factors are predicted by past values of other macroeconomic and financial variables. Table E.6 reports the results of a Granger-causality test by taking a bivariate VAR of order 12 with a factor and each of the listed variables. I find that except for the Fed funds rate, none of the other variables are useful to predict the factors.

Given that there is high co-movement between the effective Fed funds rate and the Treasury futures prices, the result makes sense. To the extent that the co-movement stems from the reaction of the Fed funds rate to debt supply shocks, the result is not evidence of the fact that the factors are contaminated by shocks to the monetary policy rate.

Next, I check if the factors are correlated with other well-known proxies in the applied macroeconomics literature. From table E.7, I find that for most factors I cannot reject the null that the correlation is 0. There is, however, a significant correlation of both factors with monetary policy shocks and the level factor with information shocks. It is important to note that the correlation is reported at a monthly frequency while the results in section 4 and 4.5 hold for daily changes in asset prices due to the factors.



(a) Maturity factor



(b) Level factor

Figure (E.5) Auto-correlation function for maturity and level factor. Red lines are critical values at 5% level of significance given by $\pm 2/\sqrt{N}$

Variable (X)	p-value	
	Level	Maturity
Output growth	0.99	0.70
PCE inflation	0.44	0.27
Unemployment rate	0.99	0.99
Fed Funds rate	**0.01**	**0.008**
S&P 500 diff	0.19	0.87

Table (E.6) Granger causality test (lag order=12, differenced wherever needed to make the series stationary). The null is that lagged values of X are **not** useful to predict shocks

Shock	Source	Level		Maturity	
		ρ	p-value	ρ	p-value
Monetary policy	JK (2020)	**0.14**	**0.02**	**0.17**	**0.01**
Information	JK (2021)	**0.12**	**0.07**	-0.04	0.52
Oil supply	Kanzig (2021)	0.001	0.98	0.04	0.47
Oil supply news	Kanzig (2021)	-0.05	0.40	-0.05	0.35
Uncertainty	Baker, Bloom and Davies (2016)	0.07	0.21	0.04	0.43
Govt exp	Ramey (2011)	0.03	0.81	-0.14	0.22
Productivity news	Barsky and Sims (2011)	0.14	0.32	-0.11	0.46

Table (E.7) Pearson correlation coefficient ρ with other proxies. For proxies that are available at a quarterly frequency, I aggregate the estimated factors into quarterly by summing across months

F Robustness checks for SVAR-IV results

In order to check if the SVAR-IV estimates are robust, I repeat the exercise with alternative specifications. First, I look at the local projection (LP) and local projection-IV (LP-IV) estimates. Next, I transform the variables in the VAR into their stationary counterparts.

Finally, I set the lag length of the VAR corresponding to the optimal information criterion. For all cases, the results are qualitatively similar to the baseline case.

F.1 Local projections

A strong assumption that the SVAR framework makes is that the structural shocks can be obtained as a linear combination of the reduced form innovations. This assumption, also known as invertibility, is particularly strong as it implies that even if a researcher suddenly possesses a high volume of information on the state of the economy, they would not use this information in their forecasting equations.

In this subsection, I compute impulse responses using the following LP specification

$$y_{i,t+h} = \alpha_h^i + \beta_{1,h}^i \hat{\varepsilon}_{f,t} + \epsilon_{t,h}^i \tag{F.1}$$

where $y_{i,t+h}$ are the variables in the VAR taken one at a time, $\hat{\varepsilon}_{f,t}$, $f \in \{L, M\}$ correspond to the structural shocks obtained from the SVAR-IV and $\beta_{1,h}^i$ correspond to the response to the supply shock of variable i at horizon h.

For the treatment variable, I use the shocks estimated from the SVAR-IV, which are the sample estimates of $\varepsilon_{f,t} = (\frac{\Theta_{0,1}'\Sigma^{-1}}{\Theta_{0,1}'\Sigma^{-1}\Theta_{0,1}})\eta_t$. I use the structural shocks and not the factors that I construct for two reasons. First, the estimated structural shocks are observed at regular intervals and are available for a longer sample period, thus increasing statistical power. Second, at $h = 0$ the estimates correspond exactly to the estimates from the SVAR-IV. For $h > 0$, the estimates from the SVAR-IV stem from parameter restrictions in the framework. There are no such restrictions in the LP as the sample period changes over time. The estimates thus allow me to check how restrictive the parameter constraints are for the dynamic effects, given the same estimate at $h = 0$.[33]

From figures F.6 and F.7, I conclude that the parameter restrictions do not drive the results. At horizons lower than the lag length, the estimates are very similar. The effects start to diverge for horizons above the lag length. At longer horizons, the sample is very different from the one used to estimate the SVAR-IV, potentially giving rise to different estimates.

[33]Note that an LP with the estimated factors used directly assumes that I observe the structural shocks perfectly. The SVAR counterpart of this would be doing a Cholesky decomposition with the factor ordered first and coefficients of the lagged variables in the VAR set to 0. This is a different framework than the SVAR-IV and while it is a case of interest, I do not include it here as part of the robustness checks for the SVAR-IV specification.

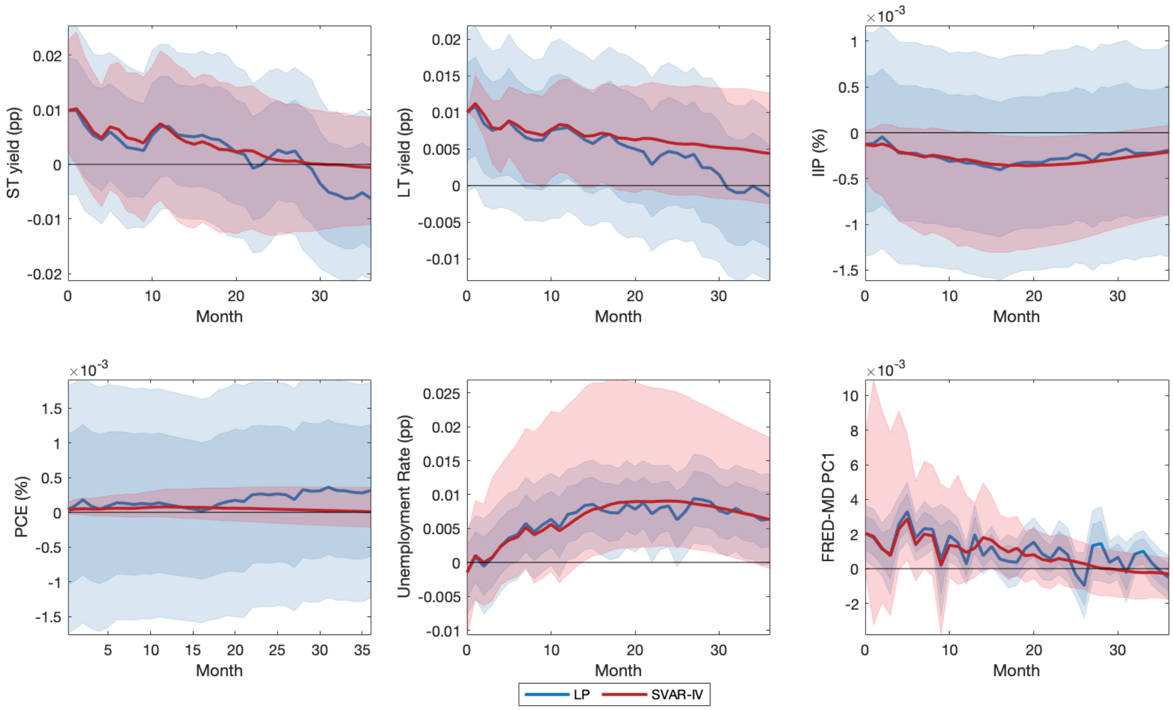


Figure (F.6) Solid blue line is the point estimate of LP impulse responses due to a surprise increase in the level of debt issuance. Light and dark blue shaded regions are Newey-West 68% and 90% confidence bands respectively. Red line is the point estimate of SVAR-IV impulse responses due to a surprise increase in the level of debt issuance, normalized to increase the long-term (15-year) yield by 1 basis point on impact. Red shaded region is the Montiel Olea, Stock and Watson (2021) 90% confidence band.

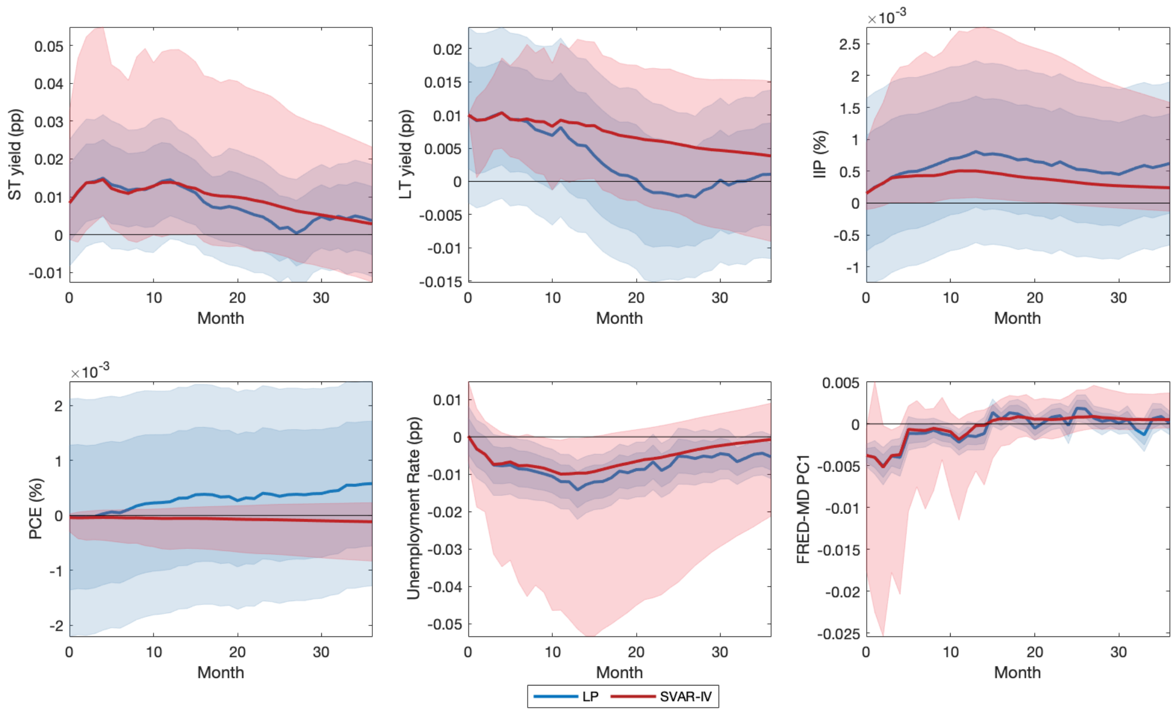


Figure (F.7) Solid blue line is the point estimate of LP impulse responses due to a surprise increase in maturity of debt issuance. Light and dark blue shaded regions are 68% and 90% confidence bands respectively. Red line is the point estimate of SVAR-IV impulse responses due to a surprise increase in maturity of debt issuance, normalized to increase the long-term (15-year) yield by 1 basis point on impact. Red shaded region is the 90% confidence band.

F.2 Local projections-IV

In this subsection, I compute the impulse responses by using the factors as instruments in the following LP-IV

$$y_{i,t+h} = \alpha_h^i + \beta_{1,h}^i y_{LT,t} + \beta_h(L)'\mathbf{x}_t + \epsilon_{t,h}^i \tag{F.2}$$

where $y_{i,t+h}$ are the variables in the VAR taken one at a time, $y_{LT,t}$ is the yield on the 15-year bond which I instrument using the factor $s_{f,t}$, $f \in \{L, M\}$ that I construct. The controls $\mathbf{x}_t$ correspond to 12 lags of the variables used in the VAR. $\beta_{1,h}^i$ corresponds to the response to the debt supply shock of variable i at horizon h.

Unlike the SVAR-IV, the LP-IV does not require the invertibility assumption. However, the instrument in this case needs to satisfy an additional lead-lag exogeneity condition given by

$$E(s_{f,t}\varepsilon_{t+j}) = 0, j \neq 0 \tag{F.3}$$

As controls, I include 12 lags of all the variables in the VAR. There are two main reasons to include controls in the LP-IV (Stock and Watson, 2018). First, the controls reduce the residual variance leading to higher statistical power of estimates. Second, the controls could be potentially necessary for the lead-lag exogeneity condition to hold. It is important to note, however, if all 12 lags are necessary for the condition to hold, this is the same as assuming invertibility in the VAR and the researcher is better off doing the SVAR-IV as the estimator is more efficient. In order to bypass the assumption of invertibility, I assume here that not all 12 lags are necessary for the lead-lag exogeneity condition. If invertibility fails, the SVAR-IV estimator is not consistent and in this case, the researcher should use the LP-IV estimator.

I estimate $\beta_{1,h}^i$ by projecting all the variables in y_i on the controls, using the full sample. Next, I use the smaller sample for which the factor is available and estimate the following parameter

$$\beta_{1,h}^i = \frac{E(y_{i,t+h}^p Z_t)}{E(y_{1,t}^p Z_t)} \tag{F.4}$$

where variables with the p superscript denote the residual after projecting the variable on controls. Given the controls are 12 lags of all the variables used in the VAR, at $h = 0$, the LP-IV estimate and the SVAR-IV estimate are exactly the same. At $h > 0$, the dynamics in the SVAR-IV are driven by parameter restrictions. There are no restrictions tying the estimates from the individual regressions in the LP-IV. Given that the instrument is weak, I use the Anderson and Rubin (1949) confidence intervals for inference.

Figure F.8 reports the responses to an increase in debt level that increases the long-term

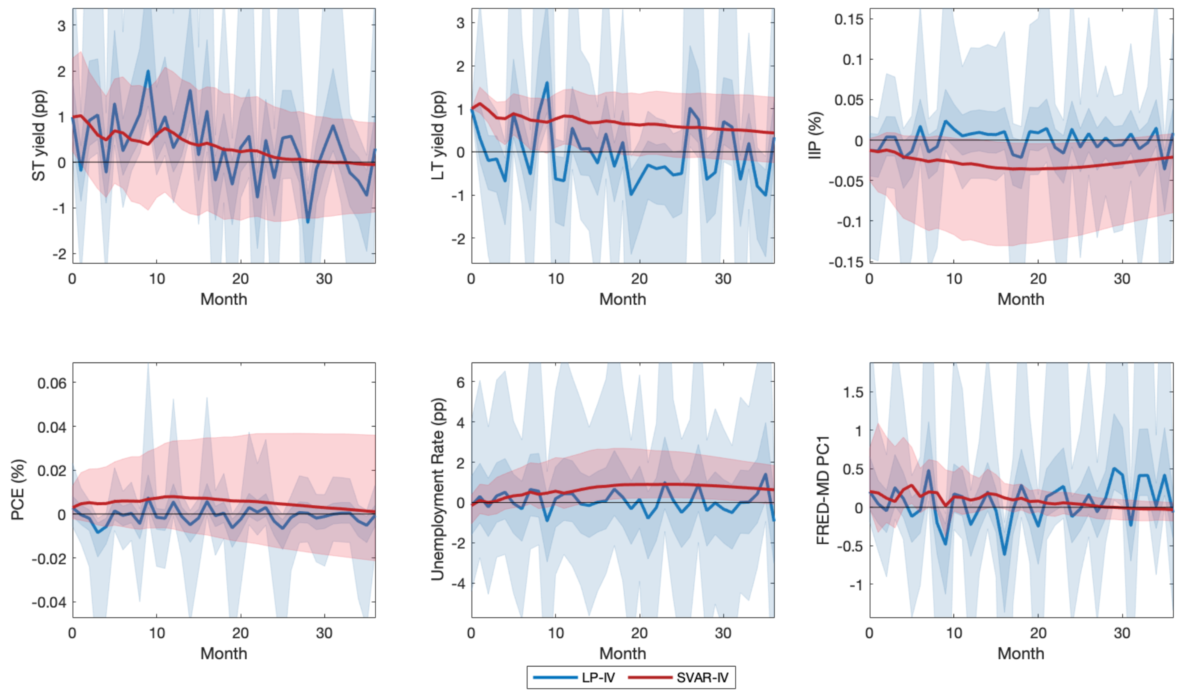


Figure (F.8) Solid blue line is the point estimate of LP-IV impulse responses due to a surprise increase in the level of debt issuance, normalized to increase the long-term (15-year) yield by 1 percentage point on impact. Light and dark blue shaded regions are Anderson-Rubin 68% and 90% confidence bands respectively. Red line is the point estimate of SVAR-IV impulse responses due to a surprise increase in the level of debt issuance, normalized to increase the long-term (15-year) yield by 1 percentage point on impact. Red shaded region is the 90% confidence band.

yield on impact by 1 percentage point. The LP-IV estimates are not as smooth as the SVAR-IV estimates and are less precisely estimated. Nevertheless, for most horizons, the interest rates have a positive and significant effect. For the macroeconomic variables, the effects are less similar. While there is a dip in IIP and a jump in unemployment for the LP-IV at horizon 18, which corresponds to the trough and peak in IIP and unemployment respectively in the SVAR-IV, the effects are insignificant. Figure F.9 reports similar responses due to the maturity factor. For most horizons, the interest rates are positive. While the effects on IIP and unemployment are insignificant at all horizons in the LP-IV, the largest effects in magnitude have the same sign as the SVAR-IV estimates.

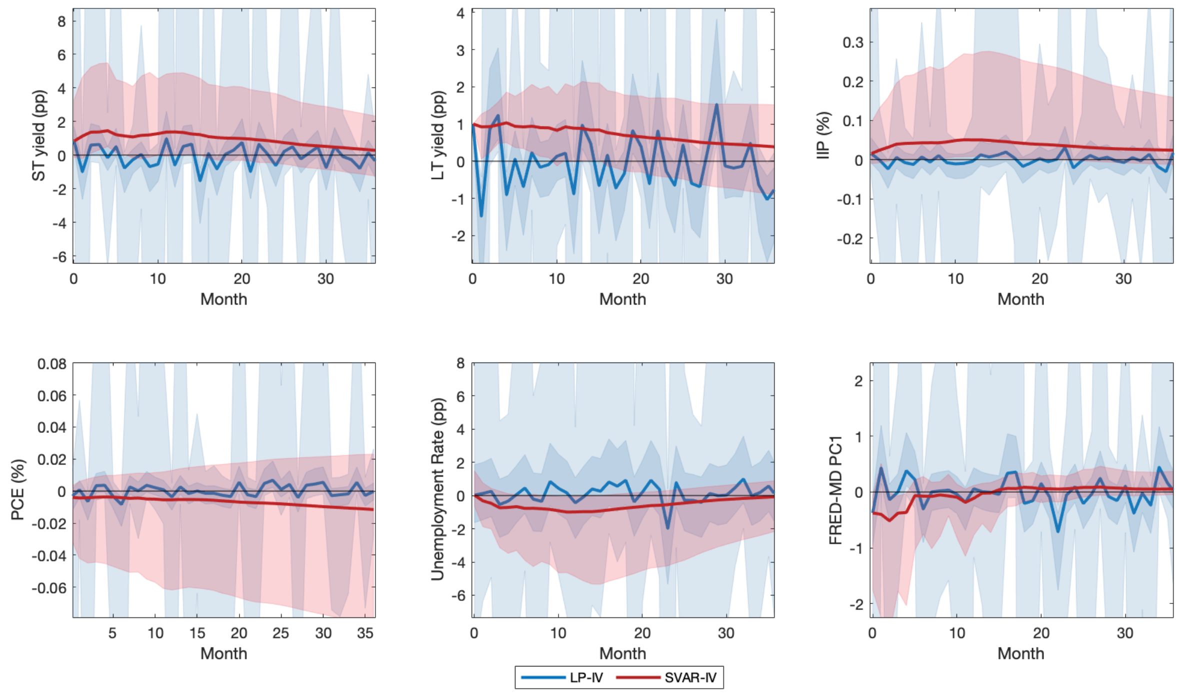


Figure (F.9) Solid blue line is the point estimate of LP-IV impulse responses due to a surprise increase in maturity of debt issuance, normalized to increase the long-term (15-year) yield by 1 percentage point on impact. Light and dark blue shaded regions are Anderson-Rubin 68% and 90% confidence bands respectively. Red line is the point estimate of SVAR-IV impulse responses due to a surprise increase in maturity of debt issuance, normalized to increase the long-term (15-year) yield by 1 percentage point on impact. Red shaded region is the 90% confidence band.

F.3 Lag length from information criteria

In the baseline specification, I set the lag length to 12 as the data is observed at a monthly frequency. I check for the optimal number of lags in the VAR using the Akaike information criterion, which equals 7. I report the results in figure F.10 and F.11 using the lag length of 7 in the VAR. All the effects are extremely similar to the baseline case.

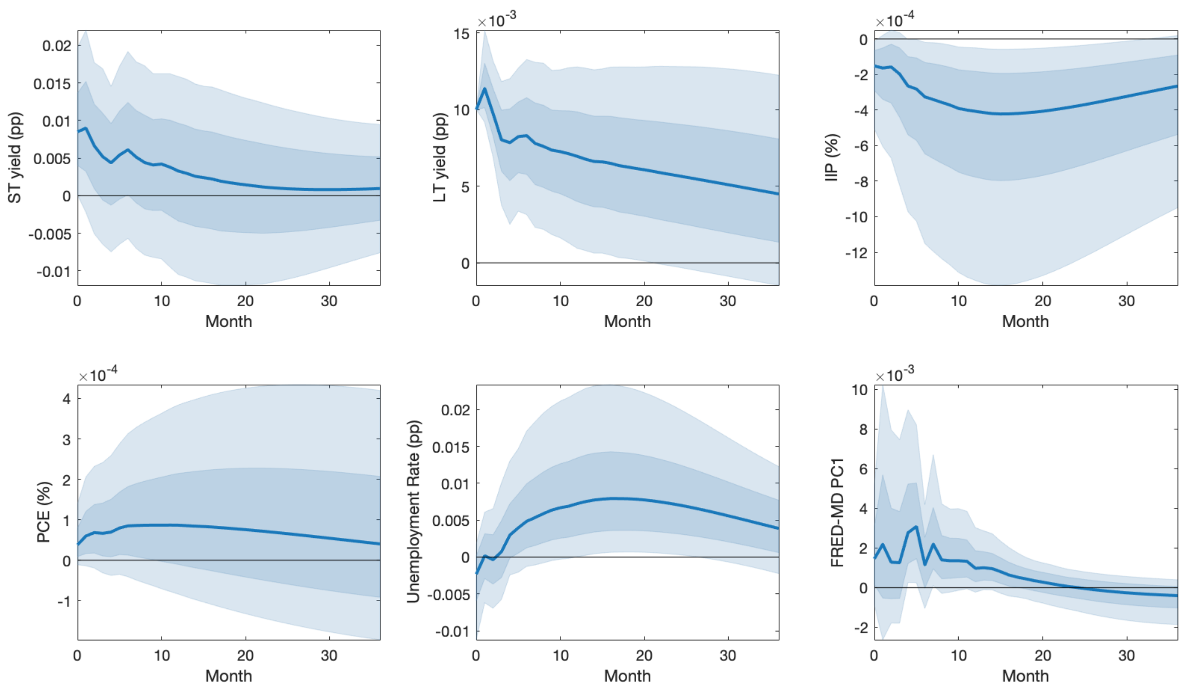


Figure (F.10) SVAR-IV impulse responses due to a surprise increase in the level of debt issuance, normalized to increase the long-term (15-year) yield by 1 basis point on impact. Solid line is the point estimate and the light and dark blue shaded regions are 68% and 90% confidence bands respectively.

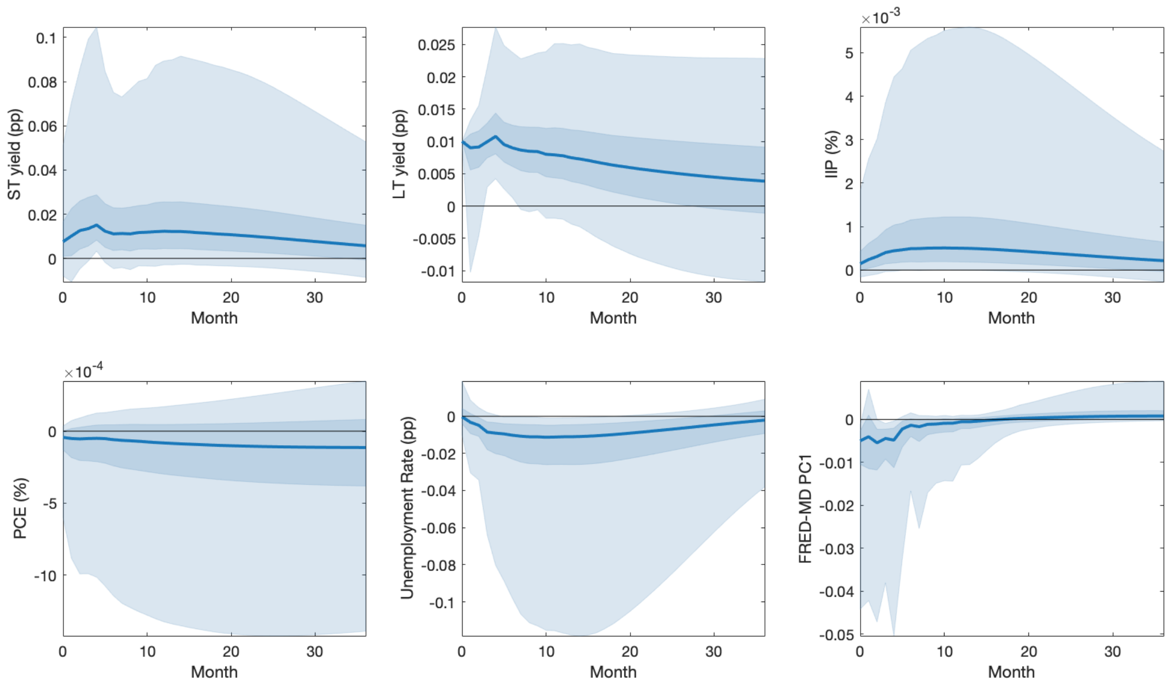


Figure (F.11) SVAR-IV impulse responses due to a surprise increase in maturity of debt issuance, normalized to increase the long-term (15-year) yield by 1 basis point on impact. Solid line is the point estimate and the light and dark blue shaded regions are 68% and 90% confidence bands respectively.

F.4 Stationary VAR

The variables in the baseline VAR are a mix of levels and rates with a maximum order of integration equal to 1. In this subsection, I convert all variables into their stationary counterparts and implement the SVAR-IV. I take the first difference of the short-term yield, the long-term yield, log IIP, and log PCE. The unemployment rate and the FRED-MD factor are already stationary and I do not transform them. Figures F.14 and F.15 report the results. The estimates are qualitatively similar to the baseline case.

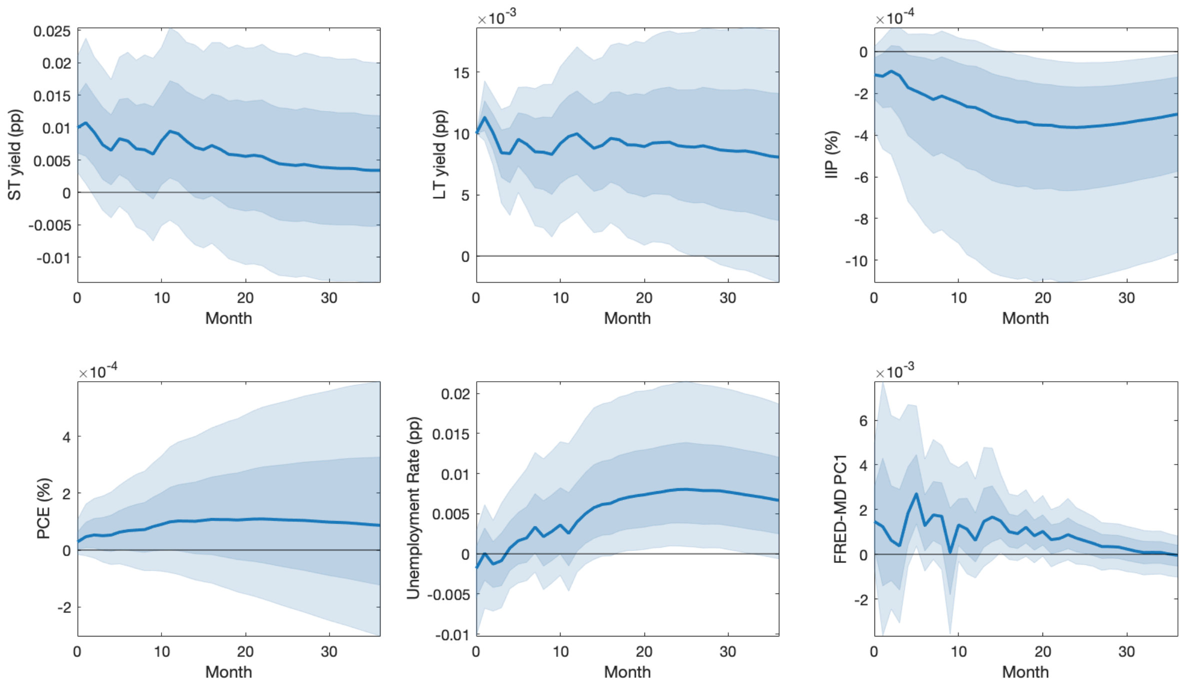


Figure (F.12) SVAR-IV impulse responses from a stationary VAR. Impulse responses are due to a surprise increase in the level of debt issuance, normalized to increase the long-term (15-year) yield by 1 basis point on impact. Solid line is the point estimate and the light and dark blue shaded regions are 68% and 90% confidence bands respectively. Cumulative responses for the LT yield, ST yield, IIP, PCE, and level responses for the unemployment rate and the FRED-MD factor.

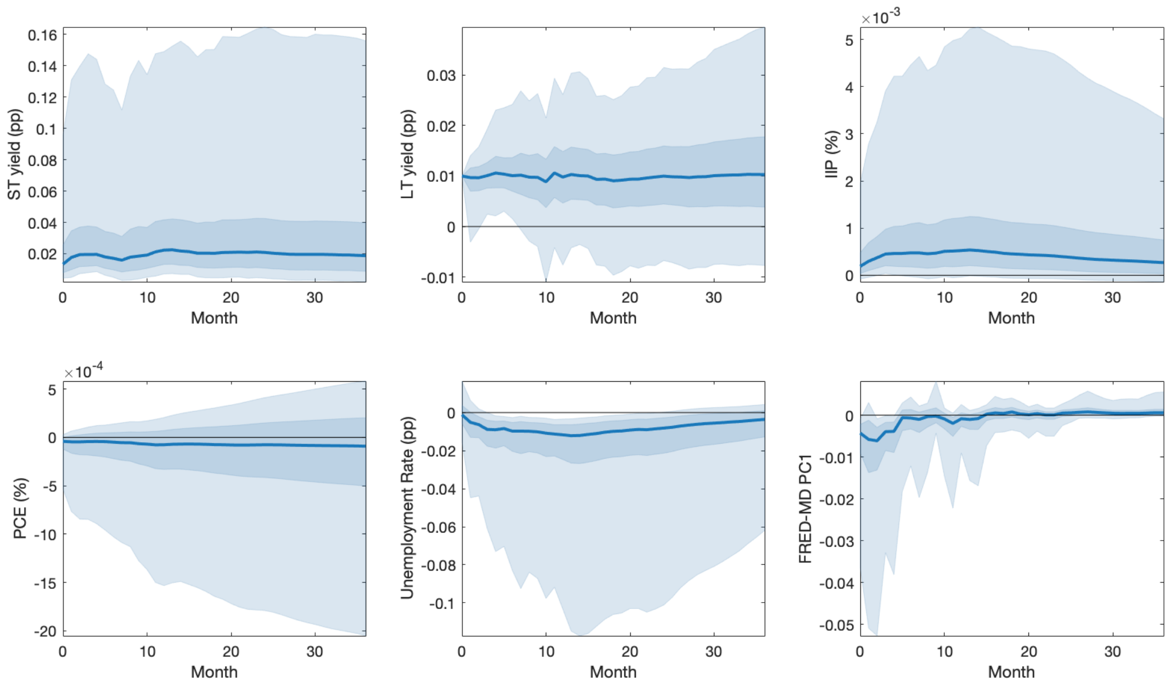


Figure (F.13) SVAR-IV impulse responses from a stationary VAR. Impulse responses are due to a surprise increase in maturity of debt issuance, normalized to increase the long-term (15-year) yield by 1 basis point on impact. Solid line is the point estimate and the light and dark blue shaded regions are 68% and 90% confidence bands respectively. Cumulative responses for the LT yield, ST yield, IIP, PCE, and level responses for the unemployment rate and the FRED-MD factor.

F.5 Event windows

The choice of the event window in high-frequency identification is crucial. A large event window would contaminate the observed shocks while a small window would be unable to pick up the entire reaction of market participants to the news. In the baseline case, I fix the event window based on the nature of the announcements. To check if the results are robust to the choice of the event window, I construct the factors using a wider 2-hour interval around all announcements. Except for the response of output to debt level shocks, the SVAR-IV estimates using the corresponding factors are qualitatively similar to the baseline case.

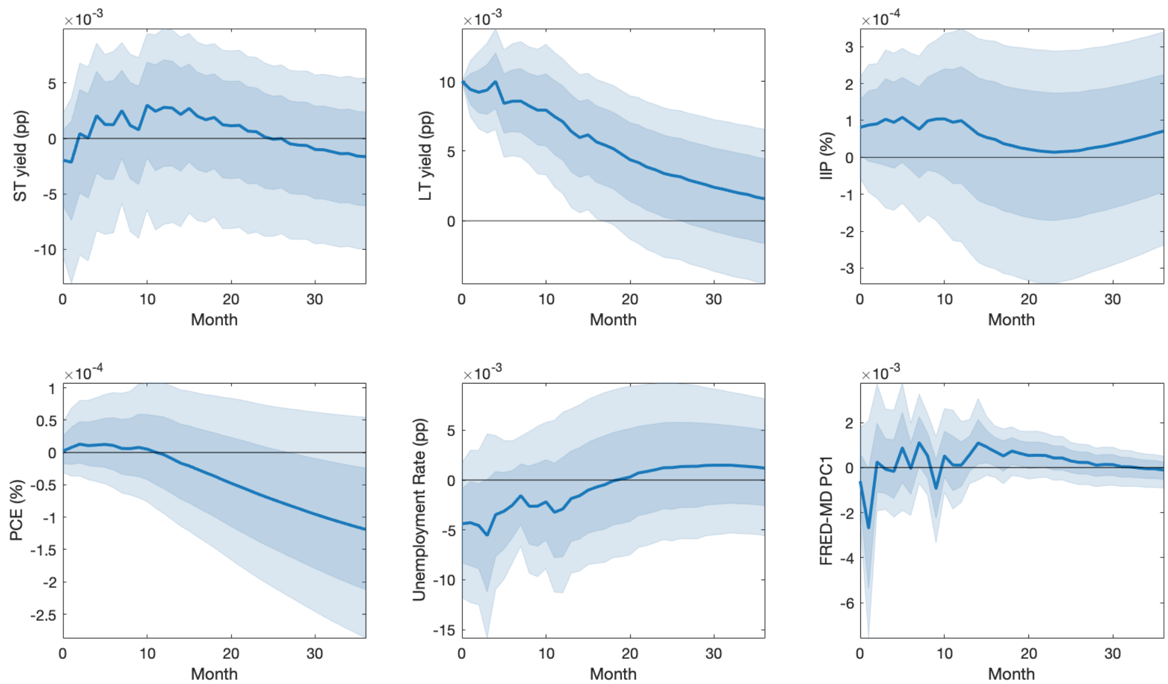


Figure (F.14) SVAR-IV impulse responses with instruments estimated using 2-hour windows. Impulse responses are due to a surprise increase in the level of debt issuance, normalized to increase the long-term (15-year) yield by 1 basis point on impact. Solid line is the point estimate and the light and dark blue shaded regions are 68% and 90% confidence bands respectively.

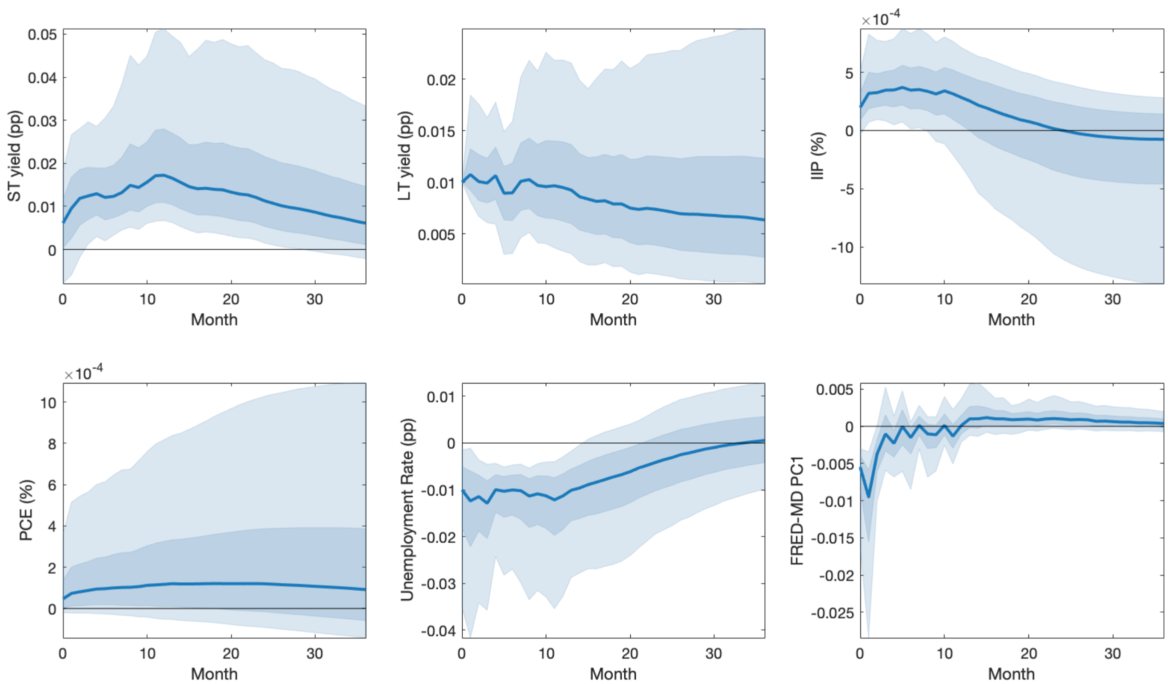
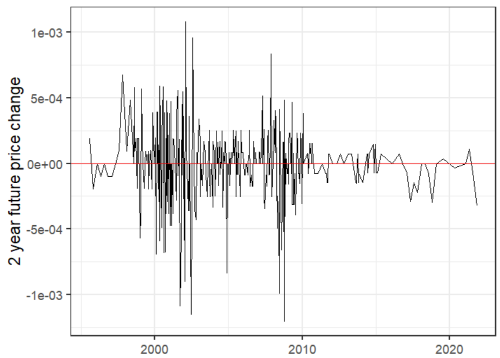
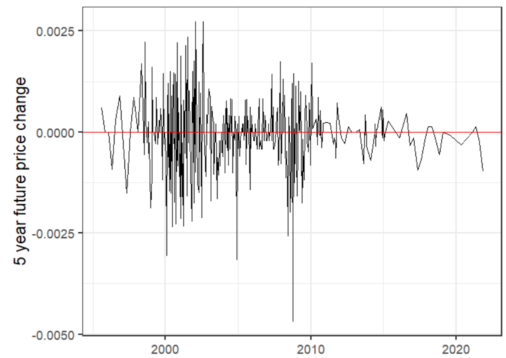


Figure (F.15) SVAR-IV impulse responses with instruments estimated using 2-hour windows. Impulse responses are due to a surprise increase in maturity of debt issuance, normalized to increase the long-term (15-year) yield by 1 basis point on impact. Solid line is the point estimate and the light and dark blue shaded regions are 68% and 90% confidence bands respectively.

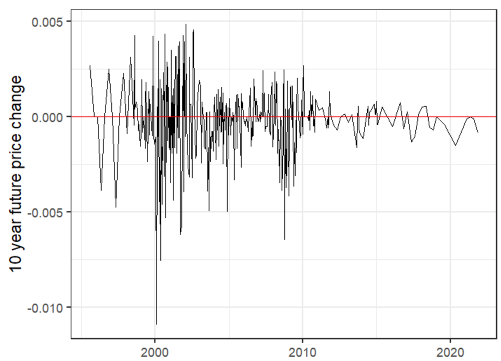
G Additional figures



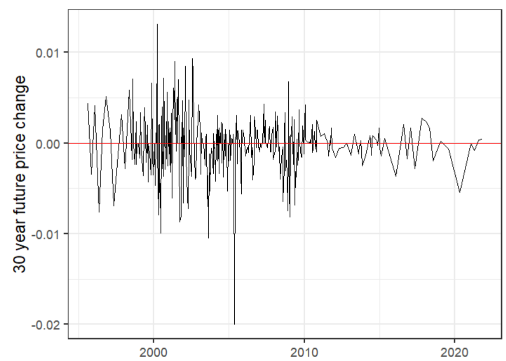
(a) 2 year futures



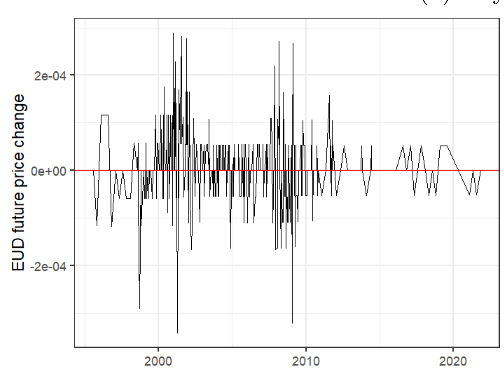
(b) 5 year futures



(c) 10 year futures

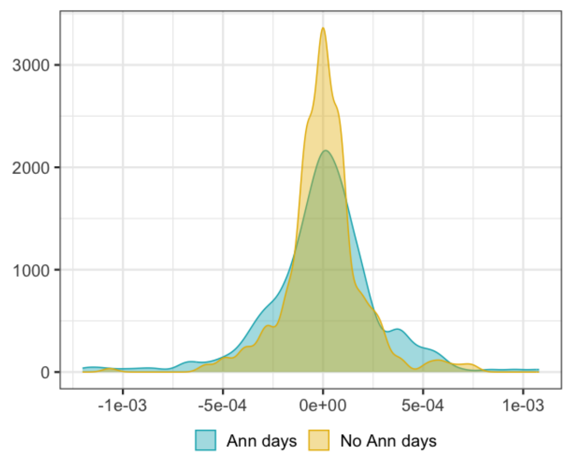


(d) 30 year futures

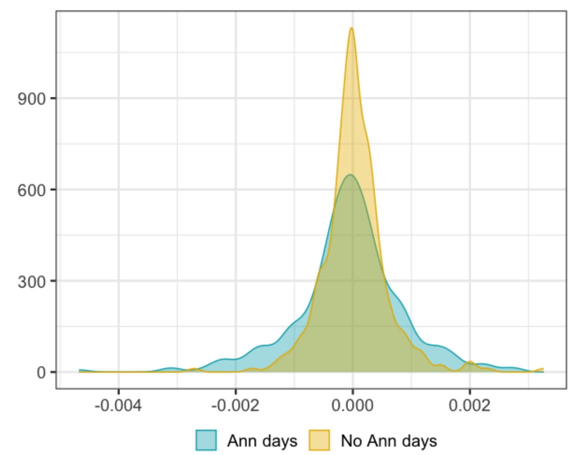


(e) 6 month Eurodollar futures

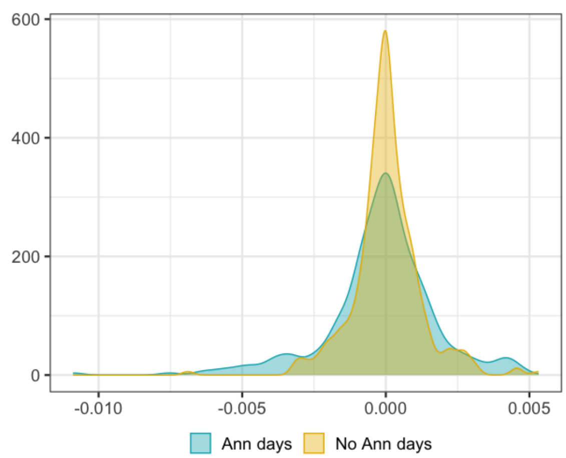
Figure (G.16) Futures price changes around Treasury primary market announcements which contain new information on debt supply at the maturity level. y-axis is in log prices.



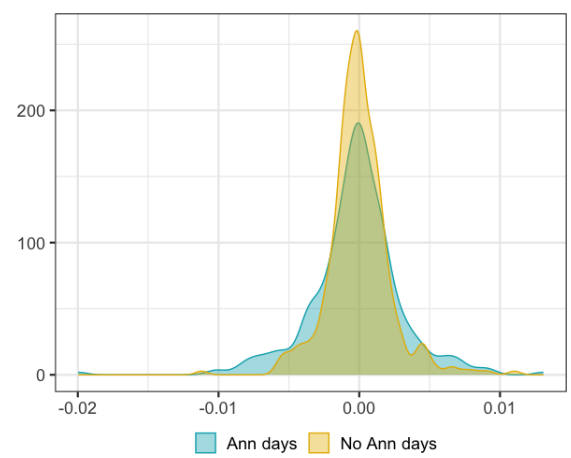
(a) 2 year futures



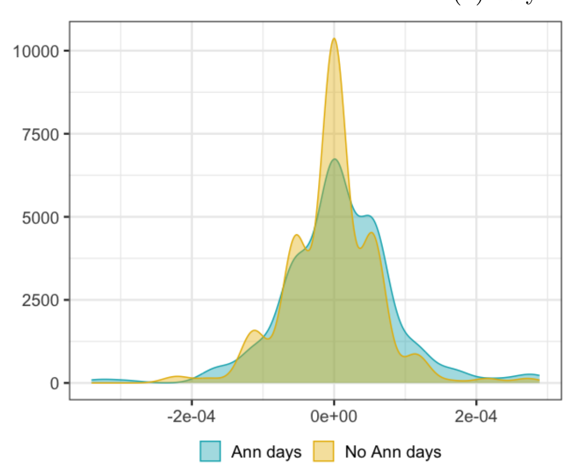
(b) 5 year futures



(c) 10 year futures

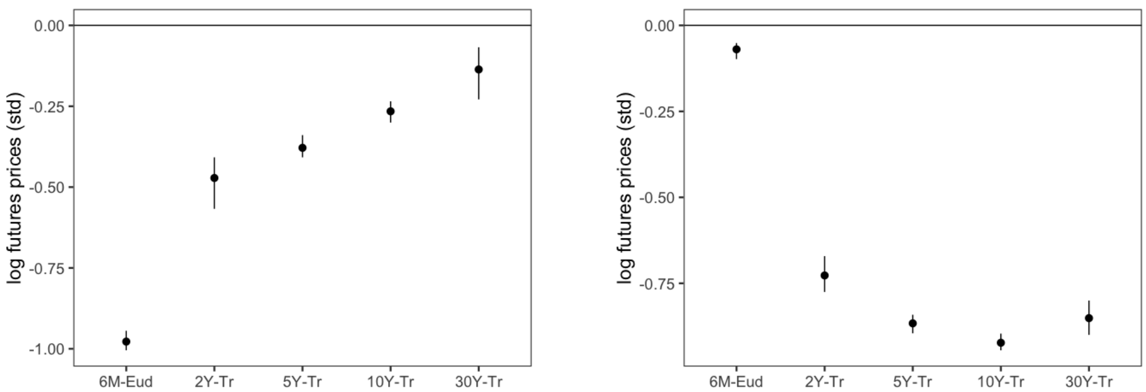


(d) 30 year futures



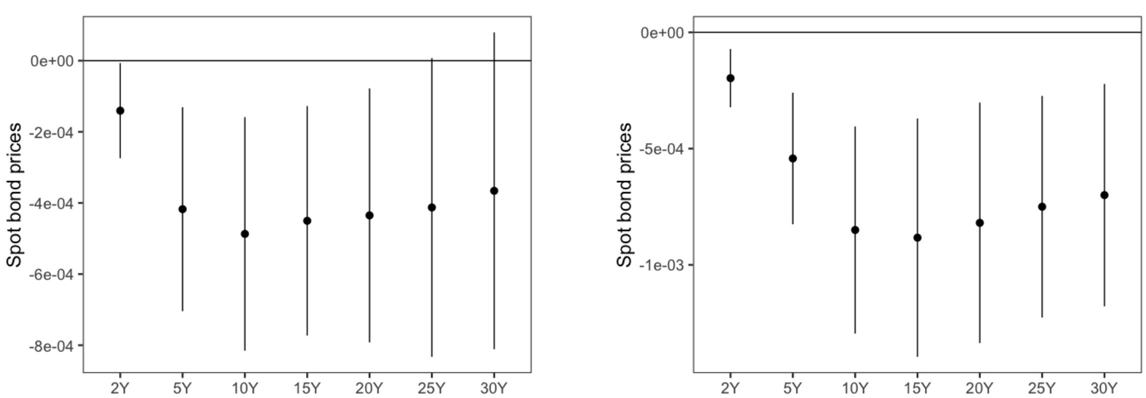
(e) 6 month Eurodollar futures

Figure (G.17) Kernel density of futures price changes. Ann days correspond to price changes around Treasury primary market announcements which contain new information on debt supply at the maturity level. No Ann days correspond to price changes between 12:20am-12:50am (EST) for a set of randomly chosen dates in the sample period. x-axis is in log prices



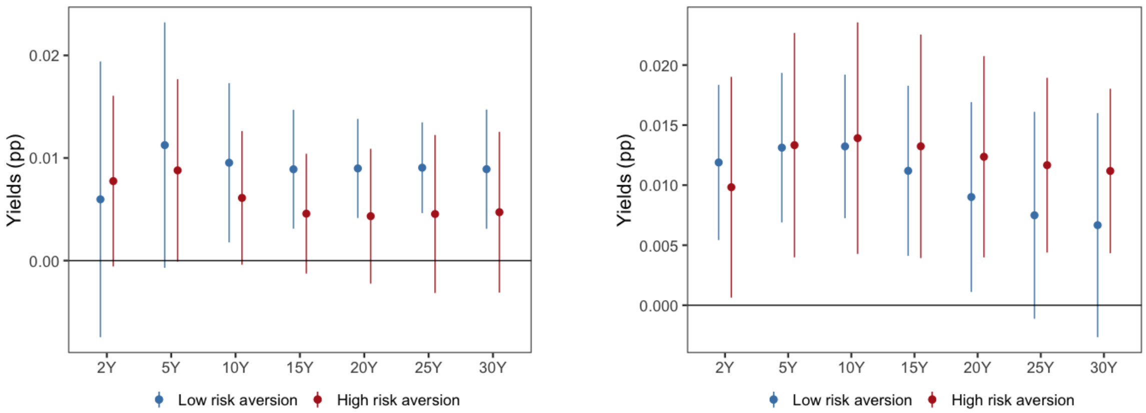
(a) Level factor (b) Maturity factor

Figure (G.18) Effect of an increase in level and maturity factors on log futures price changes f_t^τ , where τ goes from 6 months to 30 years. x-axis corresponds to the 6-month Eurodollar and the 2 to 30 year Treasury futures prices. y-axis is in log prices. 90% confidence intervals are based on 0.1 and 0.9 percentiles of the empirical distribution of OLS estimates from bootstrap samples following Swanson (2021)



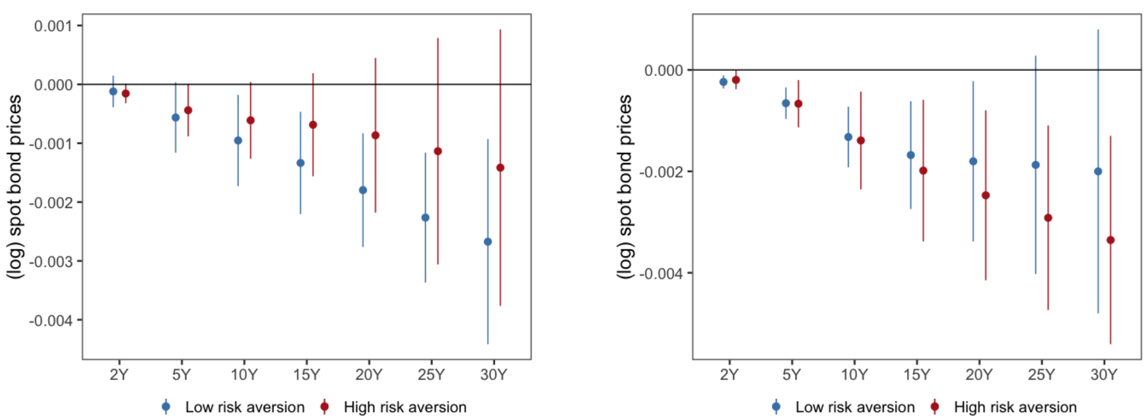
(a) Level factor (b) Maturity factor

Figure (G.19) Effect of an increase in level and maturity factors on spot price changes P_t^τ , where τ goes from 2 years to 30 years. x-axis is the maturity of the bonds. y-axis is in prices. Confidence intervals are based on Newey-West standard errors at 90% confidence level



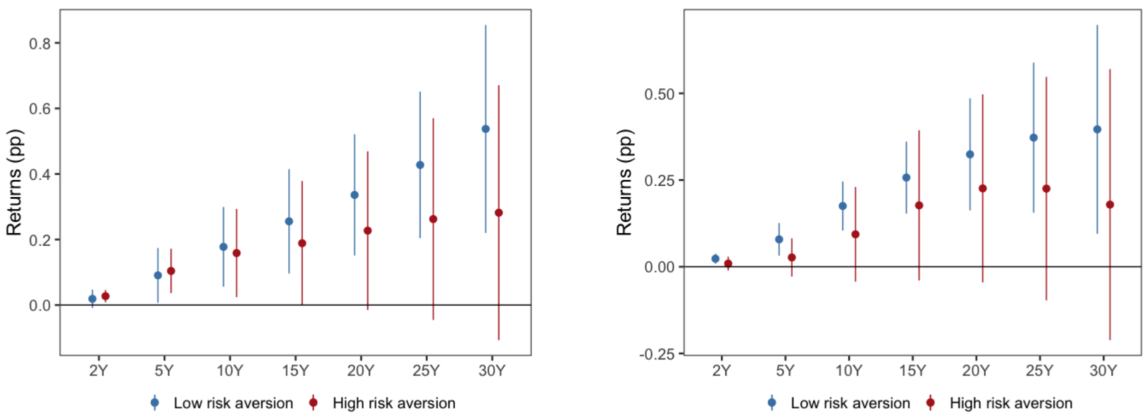
(a) Level factor (b) Maturity factor

Figure (G.20) Effect of an increase in level and maturity factors on the zero coupon nominal yield y_t^τ, where τ goes from 2 years to 15 years. x-axis is the maturity of the bonds. y-axis is in percentage. Red lines indicate estimates from periods of high risk aversion (RA). Blue dashed lines indicate estimates from periods of low risk aversion. Low and high risk aversion periods are decided based on the measure of time-varying relative risk aversion computed in Bekaert, Engstrom and Xu (2022). If the measure for the day is above the median value over the entire sample, it is a period of high risk aversion, else it is a period of low risk aversion. The specification is estimated separately for the two subsamples. Confidence intervals are based on Newey-West standard errors at 90% confidence level



(a) Level factor (b) Maturity factor

Figure (G.21) Effect of level and maturity factor on log spot price changes p_t^τ, where τ goes from 2 years to 15 years. x-axis is the maturity of the bonds. y-axis is in percentage. Red lines indicate estimates from periods of high risk aversion (RA). Blue dashed lines indicate estimates from periods of low risk aversion. Low and high risk aversion periods are decided based on the measure of time-varying relative risk aversion computed in Bekaert, Engstrom and Xu (2022). If the measure for the day is above the median value over the entire sample, it is a period of high risk aversion, else it is a period of low risk aversion. The specification is estimated separately for the two subsamples. Confidence intervals are based on Newey-West standard errors at 90% confidence level



(a) Level factor

(b) Maturity factor

Figure (G.22) Effect of level and maturity factor on the 1-year holding period return $r^{\tau}_{t,t+1}$, where τ goes from 2 years to 15 years.x-axis is the maturity of the bonds. y-axis is in percentage. Red lines indicate estimates from periods of high risk aversion (RA). Blue dashed lines indicate estimates from periods of low risk aversion. Low and high risk aversion periods are decided based on the measure of time-varying relative risk aversion computed in Bekaert, Engstrom and Xu (2022). If the measure for the day is above the median value over the entire sample, it is a period of high risk aversion, else it is a period of low risk aversion. The specification is estimated separately for the two subsamples. Confidence intervals are based on Newey-West standard errors at 90% confidence level

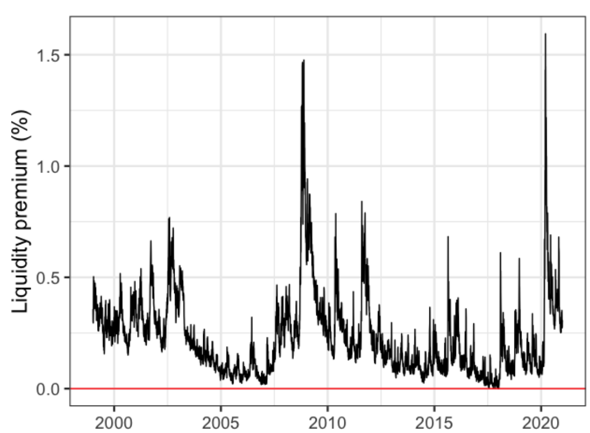
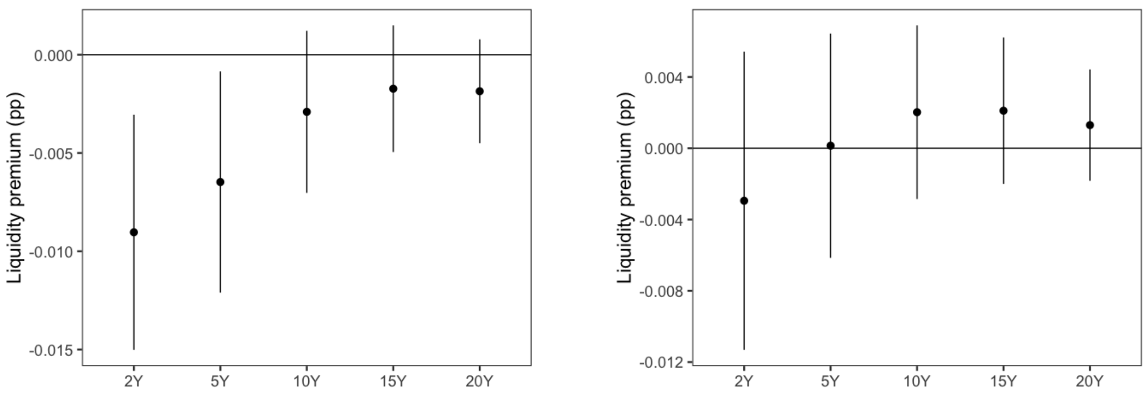
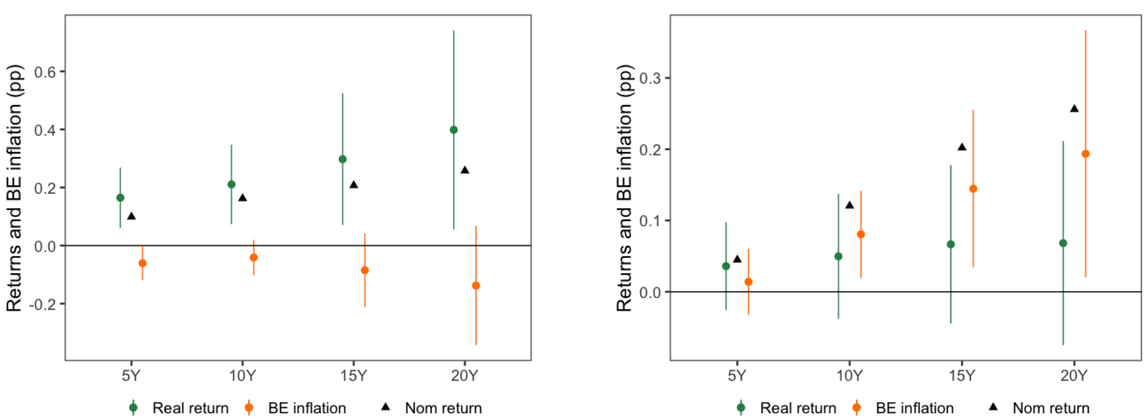


Figure (G.23) Liquidity premium at the 10 year maturity. y axis is in percent



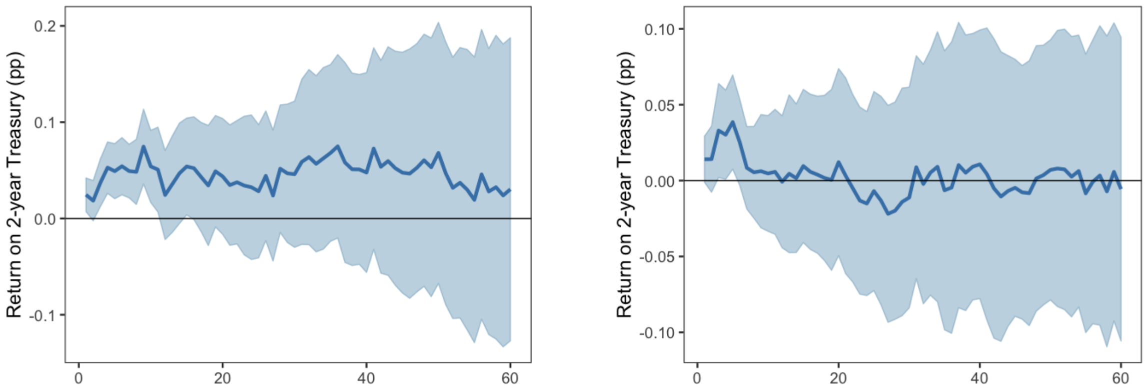
(a) Level factor (b) Maturity factor

Figure (G.24) Effect of an increase in level and maturity factors on the liquidity premium LP_t^τ, where τ goes from 2 years to 20 years. x-axis is the maturity of the bonds. y-axis is in percentage. Confidence intervals are based on Newey-West standard errors at 90% confidence level



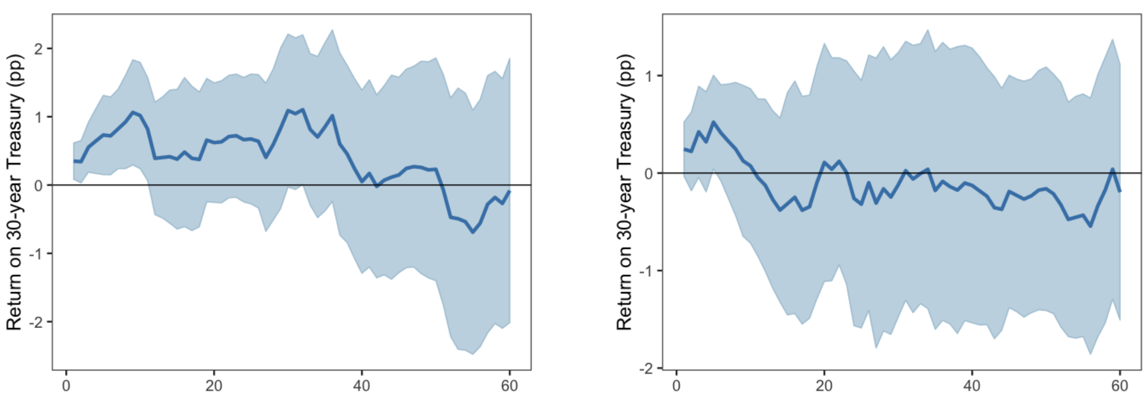
(a) Level factor (b) Maturity factor

Figure (G.25) Effect of an increase in level and maturity factors on the real 1-year return $\tilde{r}_{t,t+1}^\tau$ and breakeven inflation $\pi_{t,t+1}^{BE,\tau}$, where τ goes from 5 years to 20 years. x-axis is the maturity of the bonds. y-axis is in percentage. Green lines indicate real returns, Orange lines indicate breakeven inflation, and triangles denote nominal returns. Confidence intervals are based on Newey-West standard errors at 90% confidence level



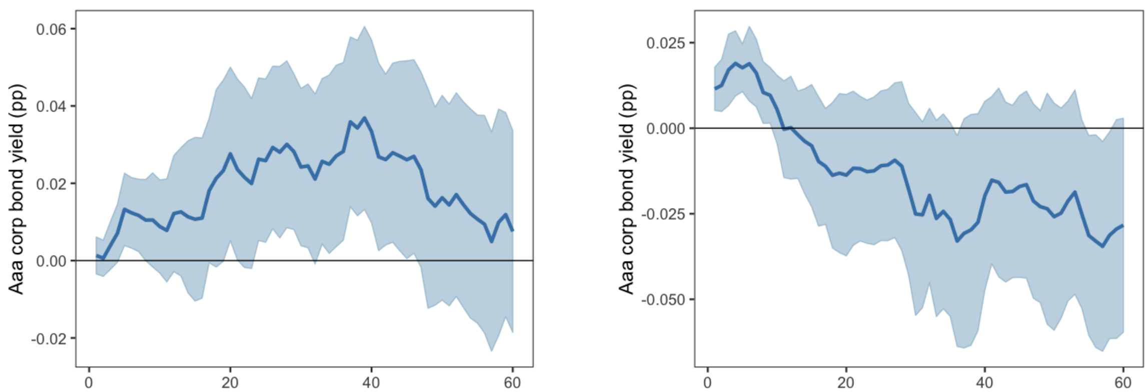
(a) Level factor (b) Maturity factor

Figure (G.26) Estimated $\beta_{1,h}$ and $\beta_{2,h}$ from the regression $y_{t+h} - y_{t-1} = \alpha_h + \beta_{1,h} s_{L,t} + \beta_{2,h} s_{M,t} + \epsilon_{t,h}$ where h is the x-axis, $s_{L,t}$ is the level factor and $s_{M,t}$ is the maturity factor. The dependent variable is the change in return on Treasury bonds at maturity $\tau = 2$ over h business days. y-axis is in percentage points. Blue shaded regions are confidence intervals based on Newey-West standard errors and a 90% level of confidence



(a) Level factor (b) Maturity factor

Figure (G.27) Estimated $\beta_{1,h}$ and $\beta_{2,h}$ from the regression $y_{t+h} - y_{t-1} = \alpha_h + \beta_{1,h} s_{L,t} + \beta_{2,h} s_{M,t} + \epsilon_{t,h}$ where h is the x-axis, $s_{L,t}$ is the level factor and $s_{M,t}$ is the maturity factor. The dependent variable is the change in return on Treasury bonds at maturity $\tau = 30$ over h business days. y-axis is in percentage points. Blue shaded regions are confidence intervals based on Newey-West standard errors and a 90% level of confidence



(a) Level factor

(b) Maturity factor

Figure (G.28) Estimated $\beta_{1,h}$ and $\beta_{2,h}$ from the regression $y_{t+h} - y_{t-1} = \alpha_h + \beta_{1,h} s_{L,t} + \beta_{2,h} s_{M,t} + \epsilon_{t,h}$ where h is the x-axis, $s_{L,t}$ is the level factor and $s_{M,t}$ is the maturity factor. The dependent variable is the change in Aaa-rated corporate bond yields over h business days. y-axis is in percentage points. Blue shaded regions are confidence intervals based on Newey-West standard errors and a 90% level of confidence