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Foreign Safe Asset Demand and the Dollar Exchange Rate

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ABSTRACT

We develop a theory that links the U.S. dollar's valuation in FX markets to the convenience yield that foreign investors derive from holding U.S. safe assets. We show that this convenience yield can be inferred from the Treasury basis, the yield gap between U.S. government and currency-hedged foreign government bonds. Consistent with the theory, a widening of the basis coincides with an immediate appreciation and a subsequent depreciation of the dollar. Our results lend empirical support to models that impute a special role to the United States as the world's provider of safe assets and the dollar as the world's reserve currency.

IN THE POSTWAR ERA, THE United States has been the world's most favored supplier of safe assets. Investors forgo a sizeable return, the convenience yield, to own these assets (see Krishnamurthy and Vissing-Jorgensen (2012), for example). During episodes of global financial instability, there is a flight to the safety of U.S. Treasury bonds as the convenience yield on Treasurys rises. At the same time, the dollar appreciates in foreign currency markets. Our paper develops a theory that explains these stylized facts. In our new convenience yield theory of exchange rates, the dollar's valuation reflects the current and future convenience yields that foreign investors derive from the ownership of

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U.S. safe assets. We find that the convenience yields earned by foreign investors on U.S. Treasurys are large and account for a sizeable share of the variation in the dollar exchange rate. Specifically, on average, foreign investors earn an extra convenience yield of 2% on Treasury holdings, with 90% of this yield directly attributable to their dollar denomination. Our study therefore sheds light on how the role of the United States as the world's safe asset supplier, as analyzed by Gourinchas and Rey (2007b), Caballero, Farhi, and Gourinchas (2008), Caballero and Krishnamurthy (2009), Maggiori (2017), He, Krishnamurthy, and Milbradt (2019), and Gopinath and Stein (2018), has shaped the dynamics of the dollar exchange rate.

Our paper explores the response of the dollar exchange rate when foreign investors impute a higher convenience yield to U.S. safe assets, such as U.S. Treasurys, than U.S. investors. In equilibrium, foreign investors should receive a lower return in their own currencies on holding U.S. safe assets than U.S. investors. To produce lower expected returns on U.S. safe assets in foreign currency, the dollar has to appreciate today and, going forward, depreciate in expectation to deliver a lower expected return to foreign investors. We derive a novel expression for the dollar exchange rate as the expected value of all future interest rate differences and convenience yields less the value of all future currency risk premia, extending the work of Campbell and Clarida (1987), Clarida and Gali (1994), and Froot and Ramadorai (2005). Our theory predicts that a country's exchange rate will appreciate whenever foreign investors increase their valuation of the current and future convenience properties of that country's safe assets.

To develop a measure of the unobserved convenience yield on U.S. safe assets derived by foreign investors, we focus on U.S. Treasury bonds as the safest among the set of U.S. safe assets. U.S. Treasury bonds are known to offer liquidity and safety services to investors, which result in lower equilibrium returns to investors from holding such bonds (see Krishnamurthy and Vissing-Jorgensen (2012), Greenwood, Hanson, and Stein (2015)). In our model, the foreign convenience yield is proportional to the Treasury basis, the difference in yields between the dollar yield on short-term U.S. Treasury bonds and short-term foreign government bonds, currency-hedged, into U.S. dollars. Even in the absence of frictions, covered interest rate parity (CIP) cannot hold for Treasurys when investors derive convenience yields from cash positions in these securities.

We measure this wedge using data on spot exchange rates, forward exchange rates, and pairs of government bond yields for a panel of G10 countries that starts in 1988. We supplement our analysis with data for the U.S/U.K. pair that begins in 1970.[1] The U.S. Treasury basis is generally negative and widens during global financial crises. These negative bases are pervasive even before the 2007 to 2009 global financial crisis.

[1] Results for this data set are reported in Section VIII of the Internet Appendix and are broadly consistent with the results reported in the main text. The Internet Appendix is available in the online version of the article on *The Journal of Finance* website.

On average, foreigners earn at least an additional 2% convenience yield on U.S. Treasurys according to our estimates. Around 90% of the extra convenience yield is attributable to the dollar exposure rather than the safety/liquidity of Treasurys. If safe and liquid U.S Treasurys were not issued in dollars, they would carry a convenience yield of about 0.2% more than the average non-U.S. G10 government bond. Thus, investors particularly value safe and liquid payoffs that are denominated in dollars. Our findings imply that dollar-LIBOR deposits as well as other safe dollar-denominated assets are good substitutes for U.S. Treasurys and also carry a convenience yield.

Exchange rates seem only weakly correlated with the macroeconomic and financial variables that should drive exchange rate variation (see, for example, Froot and Rogoff (1995) and Frankel and Rose (1995) on the exchange rate disconnect puzzle). Our work helps resolve the exchange rate disconnect puzzle. Using simple univariate regressions, we show that innovations in the U.S. Treasury basis account for 17% of the variation in the spot dollar exchange rate, with the right sign: a decrease in the basis coincides with an appreciation of the dollar. Moreover, a decrease in the basis today predicts future depreciation of the dollar at longer horizons. We find a much weaker relation between foreign Treasury bases and the exchange rates of the corresponding currencies. For example, a widening of the U.K. Treasury basis does not lead to a significant appreciation of the pound against other currencies. Our results lend support to the view that the United States and the U.S. dollar occupy a unique position in the international monetary system.

Complete market models of exchange rates fall short when confronted with the data. Real exchange rates do not covary with macroeconomic quantities in the right way (see Backus and Smith (1993), Kollmann (1995)). Real exchange rates do not vary countercyclically, and real exchange rates are not sufficiently volatile when confronted with the evidence from asset prices (Brandt, Cochrane, and Santa-Clara (2006)). Convenience yields introduce a wedge into foreign investors' Euler equation. Adopting a preference-free approach, Lustig and Verdelhan (2019) demonstrate that incomplete market models without these wedges cannot simultaneously address the uncovered interest rate parity (UIP) violations, the exchange rate disconnect (i.e., the countercyclical variation), and the exchange rate volatility puzzle, while Itskhoki and Mukhin (2017) show that models with such a wedge can address the exchange rate disconnect puzzle. Our work identifies convenience yields as a key wedge between real exchange rates and the difference in the log pricing kernels that can quantitatively help resolve this disconnect.

In our VAR analysis, we find that a one-standard-deviation positive shock to the convenience yield widens the annualized Treasury basis by 20 bps and results in a 3% appreciation in the dollar over the next two quarters. Subsequently, there is a gradual reversal over the next two to three years as the high convenience yield leads to a negative excess return on owning the U.S. dollar. Using our new convenience yield valuation equation for the exchange rate, we implement a Campbell-Shiller-style decomposition of exchange rate innovations into a cash flow component that tracks interest rate differences, a discount rate component that tracks currency risk premia, and a convenience yield component. The convenience yield channel is quantitatively important: under our benchmark calibration in which around 90% of the Treasury's convenience yield is attributable to the dollar exposure, the convenience yield accounts for between 16% and 28% of the variation in the quarterly exchange rate. In Froot and Ramadorai's (2005) decomposition, the convenience yield component would have been absorbed by the discount rate component.

The paper proceeds as follows. Section I summarizes related literature. Section II sets out the stylized facts regarding the U.S. Treasury basis. Section III presents the convenience yield theory of exchange rates. Section IV takes the theory to data. Section V decomposes the dollar exchange rate variation into convenience yield, interest rate, and risk premium components. Section VI concludes. The Internet Appendix provides further derivations of the theory, additional empirical evidence, and details on our data sources.

I. Related Literature

Our results lend empirical support to theories of the United States as the provider of safe assets. Ample empirical evidence shows that non-U.S. borrowers tilt the denomination of their borrowings (loans, deposits, bonds) toward the U.S. dollar (see Shin (2012) and Bräuning and Ivashina (2020) on bank borrowing and Bruno and Shin (2017) on corporate bond borrowing). Moreover, foreign investors tilt their portfolio toward owning U.S. dollar-denominated corporate bonds when they invest in bonds denominated outside their home currencies (see Maggiori, Neiman, and Schreger (2020)). This quantity-based evidence does not identify whether demand or supply factors are the main drivers of the dollar bias in credit markets. Our asset price-based evidence from sovereign bond markets supports a demand-based explanation. The Treasury dollar basis is typically negative and reductions in the basis appreciate the dollar, suggesting that foreign investors' special demand for dollar-denominated assets lowers their expected returns.

A separate literature considers the special role of the U.S. dollar and U.S. asset markets in the world economy. Gourinchas and Rey (2007a), Gourinchas, Rey, and Govillot (2011), and Maggiori (2017) focus on the "exorbitant privilege" of the United States that drives low rates of return on U.S. dollar assets. In their analysis, the United States provides insurance to the rest of the world, while Gopinath (2015) highlights the dominant role of the dollar as an invoicing currency. Lustig, Roussanov, and Verdelhan (2014) present evidence that a global dollar factor drives currency returns around the world. Our results underscore that there is something special about the dollar but does not speak directly to the evidence of this literature.

Our empirical approach is directly related to four recent papers. First, Du, Im, and Schreger (2018a) also study the Treasury basis, but for a different purpose. They note that the U.S. Treasury basis is negative for short-maturity bonds, suggesting that short-maturity bonds carry a convenience yield. Delving into the term structure of the basis, they note that the basis for long-maturity bonds has been positive recently. We use the basis to infer a convenience yield, but our main interest is in showing that the basis has explanatory power for the dollar exchange rate.[2]

Second, Valchev (2020) shows that the quantity of outstanding U.S. Treasury bonds helps explain the return on the dollar. Valchev (2020) builds an open-economy model to relate the quantity of U.S. Treasury bonds to the convenience yield on Treasury bonds and the failure of the UIP. We show that the existence of a foreign convenience yield for U.S. Treasury bonds causes both the UIP and the CIP to fail. Moreover, we show that variation in the convenience yields as measured by the dollar basis explains a sizeable portion of the variation in the dollar exchange rate. In a closely related work, Koijen and Yogo (2020) estimate a global demand system for assets (short-term bonds, long-term bonds, and equities) in which exchange rates help to clear assets markets. Downward-sloping demand for sovereign bonds is consistent with convenience yields. They find that latent demand shocks play an important role in accounting for exchange rate variation.

Third, a recent literature explores the failure of LIBOR CIP (see Ivashina, Scharfstein, and Stein (2015), Du, Tepper, and Verdelhan (2018b)). A common conclusion from this literature is that the LIBOR-based CIP fails in part because of financial constraints faced by banks. Our results reinforce this conclusion, and indeed add to it by showing that LIBOR CIP fails when there are *both* foreign demand for dollar-LIBOR assets and financial constraints faced by banks in supplying dollar-denominated LIBOR deposits. When these constraints bind, the LIBOR basis reflects the foreign demand for dollar-denominated safe assets and helps explain movements in the dollar exchange rate. Our empirical evidence is consistent with this LIBOR mechanism.

Finally, in a work subsequent to ours, Engel and Wu (2018) analyze nondollar currency pairs, and report evidence that the CIP violations in sovereign bond markets for nondollar pairs have significant explanatory power for bilateral exchange rates. In our sample, we find this relation to be much weaker for other currencies when we exclude the dollar from all bilateral pairs.

II. The U.S. Treasury Basis: Stylized Facts

Our paper relates movements in the value of the dollar exchange rate to the demand for dollar safe assets. The key measure of this demand for dollar safe assets is the U.S. Treasury basis. In this section, we define the Treasury basis and present some stylized facts on the movement of the basis. In the next section, we present a theory to tie the basis to the demand for dollar safe assets.

We define the U.S. Treasury basis as the difference between the yield on a cash position in U.S. Treasurys $y_t^{\$}$ and the synthetic dollar yield constructed from a cash position in a foreign government bond, which earns a yield y_t^* in

[2] An abridged version of the theory in this paper as well as results similar to those presented in Table III are published in Jiang, Krishnamurthy, and Lustig (2018).

foreign currency, which is hedged back into dollars:

$$x_t^{Treas} \equiv y_t^{\$} + (f_t^1 - s_t) - y_t^*. \tag{1}$$

Here s_t denotes the log of the nominal exchange rate in units of foreign currency per dollar, f_t^1 denotes the log of the forward exchange rate, and x_t^{Treas} measures the violation of the CIP constructed from U.S. Treasury and foreign government bond yields. A negative U.S. Treasury basis means that U.S. Treasurys are expensive relative to their foreign counterparts. We also construct the LIBOR basis (x_t^{Libor}) using LIBOR rates. A recent literature examines the failure of the LIBOR CIP condition (see Ivashina, Scharfstein, and Stein (2015), Du, Tepper, and Verdelhan (2018b)). Our Treasury basis measure is closely related to the LIBOR CIP deviation. That deviation is constructed using LIBOR rates for home and foreign countries, while our basis measure is the same deviation but constructed using government bond yields for home and foreign countries. We discuss the relation between the Treasury basis and the LIBOR basis in more details in Section II of the Internet Appendix.

We develop and use two data sets, namely, a panel of countries that spans from 1988 to 2017 and a longer single time series from 1970 to 2016 for the U.S./U.K. pair. The shorter panel is based on quarterly data from 10 developed economies: Australia, Canada, Germany, Japan, New Zealand, Norway, Sweden, Switzerland, the United States, and the United Kingdom. The sample starts in 1988Q1 and ends in 2017Q2. However, the panel is unbalanced, with data for only a few countries at the start of the sample. To ensure that results from the Treasury basis and results from the LIBOR basis are comparable, we only include country-quarter observations if both bases are available. Because New Zealand's 12-month Treasury yield is available from 1987 whereas its 12-month LIBOR rate is available from 1996, and Sweden's 12-month Treasury yield is available from 1984 whereas its 12-month LIBOR rate is available from 1991, we omit the observations in which the Treasury basis is available but the LIBOR basis is not. We have confirmed that our main empirical results are robust in the sample that contains these additional observations of the Treasury basis. We also present results using the Treasury basis for bonds with maturities greater than one year from Du, Im, and Schreger (2018a). Their sample is shorter but includes longer maturity bonds.

Our data comprise the bilateral exchange rates with respect to the U.S. dollar, 12-month bilateral forward foreign exchange contract prices, and 12-month government bond yields and LIBOR rates in all 10 countries. We use actual rather than fitted yields for government bonds whenever possible. The Bloomberg yield data used by Du, Im, and Schreger (2018a) are from a fitted yield curve, which can induce measurement errors. The main exception is the 2001:9 to 2008:5 period, in which the United States stopped issuing 12-month bills. We convert daily data to quarterly frequencies using end-of-quarter observations on the same day for bond yields, interest rates, forward rates, and exchange rates. There are some quarters for which all of the data are not available on the last day of the quarter. In this case, we find a date earlier but as

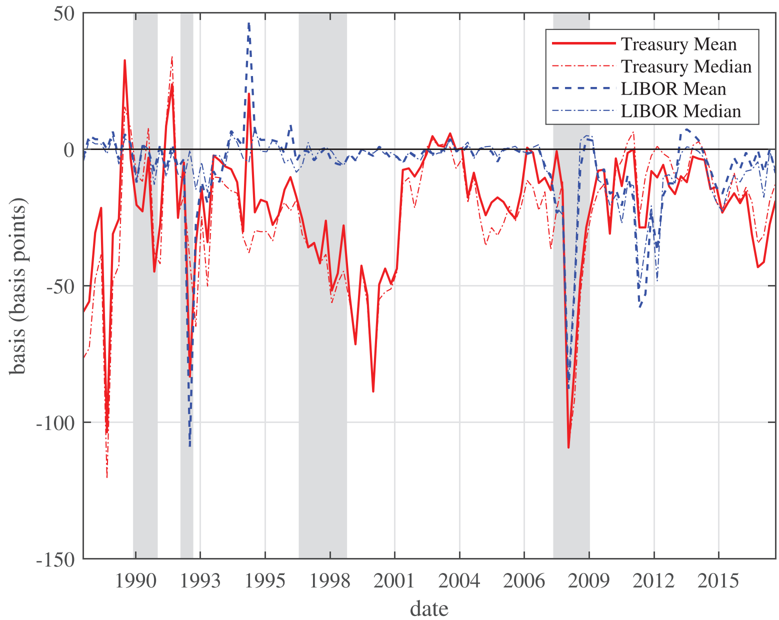

Figure 1. U.S. LIBOR and Treasury bases. The figure plots the U.S. LIBOR and Treasury basis in basis points from 1988Q1 to 2017Q2. The maturity is one year. We plot the cross-sectional mean and median for each of the bases. (Color figure can be viewed at wileyonlinelibrary.com)

close to the quarter end as possible, when all data are available. Section I of the Internet Appendix contains information about data sources.

We construct the Treasury and LIBOR basis using the 12-month yields and forwards for each currency following (1). In each quarter, we construct the mean basis across all of the countries in the panel for that quarter. Because the panel is unbalanced, we first construct country-level changes in the basis, and then take the cross-country average to arrive at the change in the basis. We denote the cross-sectional mean basis in the panel as $\overline{x}_t^{Treas}$. Similarly, we use $\overline{y}_t^* - y_t^{\$}$ to refer to the cross-sectional average of yield differences, and $\overline{s}_t$ to refer to the equally weighted cross-sectional average of the log bilateral exchange rates against the dollar. For each of these cross-sectional averages, we employ the same set of countries that are in the sample at time t.

Figure 1 plots these series. The dotted line is the mean LIBOR basis of the U.S. dollar against the basket of currencies. The precrisis spikes in the average LIBOR basis are driven by idiosyncrasies of LIBOR rates in Sweden (currency crisis) in 1992 and Japan in 1995 (note the difference between the mean and median LIBOR basis in 1992 and 1995). The LIBOR basis is close to zero for most of the sample and turns negative and volatile beginning in 2007. These stylized facts about the LIBOR basis are known from the work of Du, Tepper, and Verdelhan (2018b).

Table I

Summary Statistics for Cross-Sectional Mean Basis and Interest Rate Difference

This table reports summary statistics in percentage points for the 12M Treasury dollar basis $\overline{x}^{Treas}$, the LIBOR dollar basis $\overline{x}^{Libor}$, the 12M yield spread $y^{\$} - \overline{y}^{*}$, and the 12M forward discount $\overline{f - s}$ in logs. The reported numbers are time-series averages, time-series standard deviations, and correlations of the cross-sectional means of the unbalanced panel. The countries are Australia, Canada, Germany, Japan, New Zealand, Norway, Sweden, Switzerland, the United States, and the United Kingdom. The sample starts in 1988Q1 and ends in 2017Q2. For each of the cross-sectional averages, we employ the same set of countries that are in the sample at time t.

	$\overline{x}^{Treas}$	$\overline{x}^{Libor}$	$y^{\$} - \overline{y}^{*}$	$\overline{f - s}$
		Panel A: 1988Q1–2017Q2		
Mean	−0.22	−0.06	−0.74	−0.52
Stdev	0.23	0.17	1.68	1.75
Skew	−1.22	−3.04	−1.14	−0.89
$\overline{x}^{Treas}$	1.00	0.40	−0.24	−0.36
$\overline{x}^{Libor}$	0.40	1.00	0.37	0.30
$y^{U.S.} - \overline{y}^{*}$	−0.24	0.37	1.00	0.99
		Panel B: 1988Q1–2007Q4		
Mean	−0.22	−0.03	−0.76	−0.53
Stdev	0.24	0.14	1.98	2.06
Skew	−0.82	−4.51	−1.01	−0.79
$\overline{x}^{Treas}$	1.00	0.33	−0.29	−0.40
$\overline{x}^{Libor}$	0.33	1.00	0.46	0.40
$y^{U.S.} - \overline{y}^{*}$	−0.29	0.46	1.00	0.99
		Panel C: 2008Q1–2017Q2		
Mean	−0.21	−0.14	−0.70	−0.49
Stdev	0.22	0.20	0.69	0.72
Skew	−2.31	−1.84	0.54	0.59
$\overline{x}^{Treas}$	1.00	0.62	0.00	−0.30
$\overline{x}^{Libor}$	0.62	1.00	0.42	0.22
$y^{U.S.} - \overline{y}^{*}$	0.00	0.42	1.00	0.95

The solid line is the mean Treasury basis. Unlike the LIBOR basis, the Treasury basis has always been negative and volatile. Table I reports the time-series moments of the Treasury basis, the LIBOR basis, the 12-month (12M) Treasury yield difference, and the 12M forward discount. The average mean Treasury basis is −22 bps per annum, which means that foreign investors are willing to give up 22 bps per annum more for holding currency-hedged U.S. Treasurys than their own bonds. The standard deviation of the mean Treasury basis is 23 bps per quarter. In contrast, the average LIBOR basis is −6 bps. Section I of the Internet Appendix considers the U.S./U.K. Treasury basis over a longer sample and finds similar dynamics.

Table II

The Treasury Basis and Interest Rate Spreads

This table presents regression results of the quarterly average Treasury basis, $\bar{x}^{Treas}$, on a number of U.S. money market spreads and the United States to foreign government bond interest rate differential. The spreads and interest rate differential are constructed as the quarterly average of the indicated series. The data are from 1988Q1 to 2017Q2 for the regressions with 118 observations and 2001Q4 to 2017Q2 for the regressions with 63 observations. OLS standard errors are in parentheses. *, **, and *** indicate statistical significance at the 10%, 5%, and 1% level, respectively.

	(1)	(2)	(3)	(4)	(5)	(6)
U.S. 6-month OIS−T-bill	0.03					
	(0.17)					
U.S. 6-month LIBOR−OIS		−0.38***			−0.44***	
		(0.04)			(0.03)	
U.S. 6-month LIBOR−T-bill			−0.43***			−0.42***
			(0.05)			(0.05)
$y^{\$} - \bar{y}^{*}$				−0.03***	−0.08***	−0.02**
				(0.01)	(0.01)	(0.01)
Observations	63	63	118	118	63	118
R^2	0.0004	0.62	0.39	0.06	0.77	0.41

When LIBOR CIP holds, the Treasury basis is simply the difference between the U.S. Treasury-LIBOR spread and its foreign counterpart,

$$x_t^{Treas} = \left(y_t^{\$} - y_t^{\$,Libor}\right) - \left(y_t^{*} - y_t^{*,Libor}\right). \tag{2}$$

Before the financial crisis, when the LIBOR basis was close to zero (−3 bps), the Treasury basis (−22 bps) is due mostly to this differential in the Treasury-LIBOR spreads. The U.S. LIBOR-Treasury spread is 23 bps larger than its foreign counterpart. During and after the crisis, the U.S. LIBOR-Treasury spread is only 7 bps per annum higher than the foreign one, while the average LIBOR basis widens to −14 bps per annum. Over the entire sample, the Treasury and LIBOR basis have a correlation of 0.40. This correlation is driven largely by the postcrisis relation where the correlation 0.62. Finally, the Treasury basis is negatively correlated with the U.S.-foreign Treasury yield difference and the forward discount.

Table II provides statistics on the covariates of the Treasury basis. In the first column, we regress the basis on the overnight indexed swap (OIS)-Tbill spread, which is a measure of the liquidity premium on Treasury bonds. Note that the basis is negative on average (see Figure 1). There is little relation between the basis and the OIS-Tbill spread. The second column instead uses the spread between LIBOR and OIS. This spread is strongly negatively related to the basis and the R^2 of the regression is 62%. When the LIBOR-OIS spread rises, as in a flight-to-quality, the basis goes more negative. Note that OIS data are available only since 2001. Column (3) reports the correlation with the LIBOR-Tbill spread, which we can construct to the start of our sample in 1988.

There is a strong negative relation between the spread and the basis, and we learn from columns (1) and (2) that the relation is likely due to the LIBOR-OIS component of this spread (note also that the coefficient on LIBOR-OIS is quite similar to the coefficient on LIBOR-T-bill). Column (4) includes the spread between U.S. interest rates and the mean foreign interest rate. When U.S. rates are high relative to foreign rates, the basis is more negative. In specifications in which we include both U.S. and foreign interest rates, subject to the caveat that these rates do move together, the correlation seems to be driven by the U.S. interest rate and not the foreign rate. Columns (5) and (6) include both the LIBOR spread and the United States to world interest rate differential. The explanatory power for the basis is driven largely by the LIBOR spread. To see this, compare the R^2 in columns (5) and (6) to those in columns (3) and (4).

During episodes of global financial instability, a flight to the safety of U.S. Treasury bonds increases their convenience yield (see Krishnamurthy and Vissing-Jorgensen (2012), for example). During these episodes, the wedge between U.S. and foreign currency-hedged Treasury yields rises. Figure 1 illustrates this pattern for the 2008 financial crisis. The dollar appreciates by about 30% over this period. The hypothesis of this paper is that the increase in the convenience yield on U.S. Treasury bonds assigned by foreign investors will also be reflected in an appreciation of the U.S. dollar. The spot exchange rate of a safe asset currency will reflect the cumulative value of all future convenience yields.

III. A Theory of Spot Exchange Rates, Forward Exchange Rates, and Convenience Yields on Bonds

In this section, we develop a theory of spot and forward exchange rates and convenience yields. There are two countries, foreign ($*$), and the U.S. ($), each with its own currency. We use S_t to denote the nominal exchange rate in units of foreign currency per dollar, so that an increase in S_t corresponds to an appreciation of the U.S. dollar. There are domestic (foreign) nominal default-free government bonds denominated in dollars (in foreign currency). We derive bond and exchange rate pricing conditions that are implied by no-arbitrage.

We focus on the pricing of government bonds as the assets that produce convenience yields. As we make clear below, our theory applies to the pricing of all U.S. dollar-denominated safe assets, not just U.S. Treasury bonds, but our empirical work focuses largely on the measured convenience yields on U.S. Treasury bonds. As a result, the expressions we derive for U.S. Treasury bonds will guide our empirical work.

A. Convenience Yields and Exchange Rates

We use y_t^* to denote the nominal yield on a one-period risk-free zero-coupon bond in foreign currency. Likewise, $y_t^\$$ denotes the nominal yield on a one-period risk-free zero-coupon Treasury bond in dollars. The stochastic discount factor (SDF) of the foreign investor is denoted by M_t^*, while that of the U.S. investor is denoted by $M_t^\$$. We use $\lambda_t^{i,j}$ to denote the convenience yield of investors in country j for bonds issued by the government in country i. Foreign investors price foreign bonds denominated in foreign currency, and the foreign investor's Euler equation is given by

$$\mathbb{E}_t\left(M_{t+1}^* e^{y_t^*}\right) = e^{-\lambda_t^{*,*}}, \quad \lambda_t^{*,*} \geq 0. \tag{3}$$

The expression on the left side of the equation is standard. On the right side, we allow foreign investors to derive a convenience yield, $\lambda_t^{*,*}$, on their domestic bond holdings. This convenience yield is asset-specific and hence cannot be folded into the SDF. Our model abstracts from the fact that the value of Treasury bonds is ultimately derived from the government's budget constraint. Chernov, Schmid, and Schneider (2020), Jiang (2019a, 2019b), Jiang et al. (2019b), and Liu, Schmid, and Yaron (2019) study how the government budget affects currency returns and bond valuation.

Foreign investors can also invest in U.S. Treasurys. To do so, they convert local currency to U.S. dollars to receive $\frac{1}{S_t}$ dollars, invest in U.S. Treasurys, and then convert the proceeds back to local currency at date $t+1$ at S_{t+1}. Foreign investors in U.S. Treasurys derive a convenience yield, $\lambda_t^{\$,*}$, on their Treasury bond holdings,

$$\mathbb{E}_t\left(M_{t+1}^* \frac{S_{t+1}}{S_t} e^{y_t^\$}\right) = e^{-\lambda_t^{\$,*}}, \quad \lambda_t^{\$,*} \geq 0. \tag{4}$$

Suppose the convenience yield $\lambda_t^{\$,*}$ rises, lowering the right side of equation (4). Then the required return on the investment in U.S. Treasury bonds (the left-hand side of the equation) falls—the expected rate of dollar appreciation declines, the yield $y_t^\$$ declines, or both.

Next, we use these pricing conditions to derive an expression linking the exchange rate and the convenience yield. We assume that $m_t^* = \log M_t^*$ and $\Delta s_{t+1} = \log \frac{S_{t+1}}{S_t}$ are conditionally normal. Then the Euler equation for the foreign bond in (3) can be rewritten as

$$\mathbb{E}_t\left[m_{t+1}^*\right] + \frac{1}{2}\mathrm{var}_t\left[m_{t+1}^*\right] + y_t^* + \lambda_t^{*,*} = 0, \tag{5}$$

and the Euler equation for the U.S. bond in (4) can be written as

$$\mathbb{E}_t\left[m_{t+1}^*\right] + \frac{1}{2}\mathrm{var}_t\left[m_{t+1}^*\right] + \mathbb{E}_t[\Delta s_{t+1}] + \frac{1}{2}\mathrm{var}_t[\Delta s_{t+1}] + y_t^\$ + \lambda_t^{\$,*} - RP_t^* = 0, \tag{6}$$

where $RP_t^* = -\mathrm{cov}_t(m_{t+1}^*, \Delta s_{t+1})$ is the risk premium the foreign investor requires for the exchange rate risk when investing in U.S. bonds. We combine these two expressions to find the following result.

LEMMA 1: *The expected return in levels on a long position in dollars earned by a foreign investor is decreasing in the convenience yield gap:*

$$\mathbb{E}_t[\Delta s_{t+1}] + \left(y_t^{\$} - y_t^*\right) + \frac{1}{2}var_t[\Delta s_{t+1}] = RP_t^* - (\lambda_t^{\$,*} - \lambda_t^{*,*}). \tag{7}$$

The left-hand side is the excess return earned by a foreign investor from investing in the U.S. bond relative to the foreign bond. This is the return on the reverse carry trade, given that U.S. yields are typically lower than foreign yields. On the right-hand side, the first term is the familiar currency risk premium demanded by a foreign investor going long U.S. Treasurys in dollars. The second term is the convenience yield attached by foreign investors to U.S. Treasurys minus the convenience yield foreign investors derive from their holdings of their own bonds ("convenience yield gap"). A positive convenience yield gap, $\lambda_t^{\$,*} - \lambda_t^{*,*} > 0$, lowers the required return on the reverse carry trade, that is, the return to investing in U.S. Treasury bonds. Even in the absence of priced currency risk, $RP_t^* = 0$, the UIP fails when the convenience yield gap is greater than zero.

B. U.S. Demand for Foreign Bonds

Since U.S. investors have access to foreign bond markets, there is another pair of Euler equations to consider. An increase in the foreign convenience yield imputed to U.S. Treasurys implies an expected deprecation of the dollar. For a U.S. investor, buying foreign bonds when the dollar is expected to depreciate produces a high carry return. The U.S. investor's Euler equation when investing in the foreign bond is

$$\mathbb{E}_t\left(M_{t+1}^{\$}\frac{S_t}{S_{t+1}}e^{y_t^*}\right) = e^{-\lambda_t^{*,\$}}, \quad \lambda_t^{*,\$} \geq 0. \tag{8}$$

We also assume that U.S. investors derive a convenience yield when investing in U.S. Treasurys:

$$\mathbb{E}_t\left(M_{t+1}^{\$}e^{y_t^{\$}}\right) = e^{-\lambda_t^{\$,\$}}, \quad \lambda_t^{\$,\$} \geq 0. \tag{9}$$

An increase in the U.S. investor's convenience yield lowers U.S. Treasury bond yields, holding the SDF fixed: $y_t^{\$} = \rho_t^{\$} - \lambda_t^{\$,\$}$, where $\rho_t^{\$} = -\log \mathbb{E}_t(M_{t+1}^{\$})$. We assume log-normality and rewrite these equations to derive an expression for the carry trade return,

$$\left(y_t^* - y_t^{\$}\right) - \mathbb{E}_t[\Delta s_{t+1}] + \frac{1}{2}\mathrm{var}_t[\Delta s_{t+1}] = RP_t^{\$} + (\lambda_t^{\$,\$} - \lambda_t^{*,\$}). \tag{10}$$

where $RP_t^{\$} = -\mathrm{cov}_t(m_{t+1}^{\$}, -\Delta s_{t+1})$ is the risk premium the U.S. investor requires for the exchange rate risk when investing in foreign bonds (i.e., the risk premium attached to the dollar appreciating).

Finally, we combine (7) and (10) to derive a cross-country restriction on the convenience yields imputed to Treasurys and the currency risk premia,

$$\left(\lambda_t^{\$,*} - \lambda_t^{*,*}\right) - \left(\lambda_t^{\$,\$} - \lambda_t^{*,\$}\right) = rp_t^{\$} + rp_t^{*}, \tag{11}$$

where we use $rp_t^{\$} = RP_t^{\$} - \frac{1}{2}\text{var}_t[\Delta s_{t+1}]$ and $rp_t^{*} = RP_t^{*} - \frac{1}{2}\text{var}_t[\Delta s_{t+1}]$ to denote the log currency risk premia.

LEMMA 2: *Under the assumption that the log currency risk premia are symmetric, $rp_t^{\$} = -rp_t^{*}$, foreign and domestic investors agree on the relative convenience of Treasurys versus foreign bonds, that is,*

$$\left(\lambda_t^{\$,*} - \lambda_t^{*,*}\right) = \left(\lambda_t^{\$,\$} - \lambda_t^{*,\$}\right). \tag{12}$$

We develop our model for this symmetric case because it is easiest to discuss. Under the symmetry assumption, the convenience yield gaps between foreign and domestic bonds are the same for foreign or U.S. investors, and it is this gap that enters exchange rate determination. We can deviate from symmetry in log currency risk premia and relax equation (12), but this comes at the cost of additional complexity that we do not think adds to the analysis. We pursue this approach more systematically in related work (see, for example, Jiang, Krishnamurthy, and Lustig (2019a, 2020)).

C. Exchange Rates, Interest Rates, and Convenience Yields

Next, we explore the implications of our theory for the level of the exchange rate. By forward iteration on (7), the level of exchange rates can be stated as a function of the interest rate differences, the currency risk premia, and the future convenience yields (see Froot and Ramadorai (2005) for a version without convenience yields). Campbell and Clarida (1987) and Clarida and Gali (1994) developed an early version of this decomposition that imposed the UIP.

LEMMA 3: *The level of the nominal exchange can be written as*

$$s_t = \mathbb{E}_t \sum_{\tau=0}^{\infty} \left(\lambda_{t+\tau}^{\$,*} - \lambda_{t+\tau}^{*,*}\right) + \mathbb{E}_t \sum_{\tau=0}^{\infty} \left(y_{t+\tau}^{\$} - y_{t+\tau}^{*}\right) - \mathbb{E}_t \sum_{\tau=0}^{\infty} rp_{t+\tau}^{*} + \mathbb{E}_t \left[\lim_{T\to\infty} s_{t+T}\right]. \tag{13}$$

The term $\mathbb{E}_t[\lim_{\tau\to\infty} s_{t+\tau}]$ is constant only if the nominal exchange rate is stationary.

The exchange rate level is determined by yield differences, the convenience yields, and the currency risk premia. This is an extension of Froot and Ramadorai's (2005) expression for the level of exchange rates. The first term involves the sum of expected convenience yields $\lambda_{t+\tau}^{\$,*}$ earned by *foreign investors* on their holdings of U.S. Treasurys in excess of the convenience yields $\lambda_{t+\tau}^{*,*}$ earned on their own bonds. The second term involves the sum of bond yield differences. Note that the convenience yield earned by *U.S. investors* on their holdings of U.S. Treasurys lowers the U.S. Treasury yield $y^{\$}_{t+\tau}$ and hence lowers the second term. This expression implies that an increase in the expected future convenience yields earned by foreigners relative to those earned by U.S. investors should lead the dollar to appreciate today.

To clarify this latter point regarding convenience yields of foreign investors relative to U.S. investors, we rewrite (13) as the sum of the convenience yield differentials, the fundamental yield differences, stripped of the convenience yields, and the risk premia,

$$s_t = \mathbb{E}_t \sum_{\tau=0}^{\infty} \left(\lambda^{\$,*}_{t+\tau} - \lambda^{\$,\$}_{t+\tau}\right) + \mathbb{E}_t \sum_{\tau=0}^{\infty} \left(\rho^{\$}_{t+\tau} - \rho^{*}_{t+\tau}\right) - \mathbb{E}_t \sum_{\tau=0}^{\infty} rp^{*}_{t+\tau} + \mathbb{E}_t \left[\lim_{\tau\to\infty} s_{t+\tau}\right]. \tag{14}$$

where $\rho^{\$}_t = -\log \mathbb{E}_t(M^{\$}_{t+1}) = y^{\$}_t + \lambda^{\$,\$}_t$ is the fundamental (no convenience effect) bond yield in dollars, and likewise for foreign. Expression (14) clarifies that the exchange rate responds only to the difference in convenience yields on U.S. Treasurys earned by foreigners and by domestic investors. When foreign investors' convenience yields on Treasurys increases relative to the U.S. convenience yields, the dollar appreciates.

Thus far we have not derived a process for the exchange rate. We begin by noting that when markets are complete, the unique exchange rate process that is consistent with an absence of arbitrage opportunities is

$$\Delta s_{t+1} = m^{\$}_{t+1} - m^{*}_{t+1}. \tag{15}$$

See, for example, Backus, Foresi, and Telmer (2001). When markets are incomplete, an exchange rate process that satisfies all four of the Euler equations (two investors in two bonds) is

$$\Delta s_{t+1} = m^{\$}_{t+1} - m^{*}_{t+1} + \eta_{t+1} + \lambda^{\$,\$}_t - \lambda^{\$,*}_t, \tag{16}$$

where η_{t+1} is an incomplete markets wedge that satisfies restrictions to enforce the Euler equations for bond investors (Lustig and Verdelhan (2019)). This expression also underscores that markets must be incomplete in our convenience yield theory. If markets were complete, η_{t+1} in all states of the world and the convenience yield gap, $\lambda^{\$,\$}_t - \lambda^{\$,*}_t$, must be zero. We can derive an expression for s_t by forward substitution (16), and after taking expectations, we recover the expression in (13). Section II of the Internet Appendix contains the detailed derivation behind these statements.

Next, we derive expressions for the real exchange rate, which is likely to be stationary regardless of the macroeconomic environment. We denote the log foreign and domestic price levels by p^*_t and $p^{\$}_t$, respectively. The real exchange rate is given by

$$q_t = s_t + p^{\$}_t - p^*_t. \tag{17}$$

We substitute the real exchange rate expression, (17), into the earlier expressions for nominal exchange rates and rewrite to find the following result.

LEMMA 4: *The level of the real exchange rate can be written as*

$$q_t = \mathbb{E}_t \sum_{\tau=0}^{\infty} \left(\lambda_{t+\tau}^{\$,*} - \lambda_{t+\tau}^{*,*}\right) + \mathbb{E}_t \sum_{\tau=0}^{\infty} \left(r_{t+\tau}^{\$} - r_{t+\tau}^{*}\right) - \mathbb{E}_t \sum_{\tau=0}^{\infty} rp_{t+\tau}^{*} + \mathbb{E}_t \left[\lim_{T\to\infty} q_{t+T}\right], \tag{18}$$

where $r_t^{\$}$ and r_t^* are the real interest rates, that is, $y_t^{\$} - \mathbb{E}_t[\Delta p_{t+1}^{\$}]$ is the real dollar interest rate.

The last term, $\bar{q} = \mathbb{E}_t[\lim_{\tau\to\infty} q_{t+\tau}]$, is constant if the real exchange rate is stationary.

The first component measures the impact of the variation in the convenience yield earned by foreign investors from holding U.S. Treasurys on the real exchange rate. The second component measures the impact of the real yield differences. The third component measures the impact of the risk premia. We estimate each of these components in Section V.

D. The Treasury Basis, Convenience Yields, and Dollarness

The key variable in our theory is $\lambda_t^{\$,*} - \lambda_t^{*,*}$, the extra convenience yield earned by foreign investors on their holdings of U.S. Treasurys in excess of the foreign government bond. This object can be inferred from the Treasury basis. To do so, we consider a foreign investor's Euler equation for an investment in a foreign government bond that is swapped into dollars via the forward market. The investor owns a bundle of a safe foreign government bond, providing a convenience yield $\lambda_t^{*,*}$ and a forward position. Together, these produce a synthetic "Treasury" that is not as safe and liquid as the cash position in U.S. Treasurys, because the synthetic position involves some bank counterparty risk and the foreign bond is not as liquid as the U.S. Treasury bonds. Accordingly, we posit that the synthetic position provides a convenience yield between that of the foreign government bond and U.S. Treasurys,

$$\mathbb{E}_t\left[M_{t+1}^* \frac{S_{t+1}}{S_t} \frac{S_t}{F_t^1} e^{y_t^*}\right] = e^{-\lambda_t^{*,*} - \beta^*(\lambda_t^{\$,*} - \lambda_t^{*,*})}. \tag{19}$$

Here, F_t^1 denotes the one-period forward exchange rate, in foreign currency per dollar, and β^*, $0 < \beta^* < 1$, denotes the fraction of the convenience yield on the cash position in the foreign bond hedged into dollars relative to the U.S. Treasury investment. We will estimate this fraction in our empirical work. If $\beta^* = 0$, then the "dollarness" created by adding the forward position to the foreign government bond provides no incremental convenience benefits to the foreign investor. In this case, both U.S. Treasury bonds and foreign government bonds are valued for their liquidity and safety properties in their respective currencies. If $\beta^* = 1$, then the "dollarness" provided by the hedge converts the foreign government bond to the equivalent of a U.S. Treasury. In this case, we learn that investors particularly value safe and liquid bonds whose payoffs are denominated in dollars.

We can use (19) together with the foreign investor's Euler equation for the U.S Treasury bond, (4), to find an expression for the unobserved U.S. Treasury convenience yield gap.

LEMMA 5: *The foreign convenience yield gap on U.S. Treasury bonds is proportional to the Treasury basis,*

$$x_t^{Treas} \equiv y_t^{\$} + \left(f_t^1 - s_t\right) - y_t^* = -(1-\beta^*)\left(\lambda_t^{\$,*} - \lambda_t^{*,*}\right). \tag{20}$$

This lemma is the key to our empirical work as it provides a measure of the convenience yields that drives our theory.

We can also consider the basis from the standpoint of the U.S. investor. Suppose the U.S. investor invests in the foreign bond swapped into dollars, and receives a convenience yield equal to $\lambda_t^{*,\$} + \beta^{\$}(\lambda_t^{\$,\$} - \lambda_t^{*,\$})$. Here again $\beta^{\$}$ measures the fraction of convenience gained, relative to the U.S. Treasury bond, by converting the foreign government bond into a dollar payoff. The basis can be shown to be equal to

$$x_t^{Treas} = -(1-\beta^{\$})\left(\lambda_t^{\$,\$} - \lambda_t^{*,\$}\right),$$

which is equal to (20) when $\beta^{\$} = \beta^*$, given the symmetry restriction in (12).[3]

E. Summary

We arrive at five key implications of our theory relating the Treasury basis to the dollar exchange rate. We test each of these implications in the data.

PROPOSITION 1: *(Treasury basis and the dollar)*

1. *The level of the nominal exchange can be written as*

$$s_t = -\mathbb{E}_t \sum_{\tau=0}^{\infty} \frac{x_{t+\tau}^{Treas}}{1-\beta^*} + \mathbb{E}_t \sum_{\tau=0}^{\infty} \left(y_{t+\tau}^{\$} - y_{t+\tau}^*\right) - \mathbb{E}_t \sum_{\tau=0}^{\infty} rp_{t+\tau}^* + \mathbb{E}_t \left[\lim_{T\to\infty} s_{t+T}\right]. \tag{21}$$

2. *The level of the real exchange can be written as*

$$q_t = -\mathbb{E}_t \sum_{\tau=0}^{\infty} \frac{x_{t+\tau}^{Treas}}{1-\beta^*} + \mathbb{E}_t \sum_{\tau=0}^{\infty} \left(r_{t+\tau}^{\$} - r_{t+\tau}^*\right) - \mathbb{E}_t \sum_{\tau=0}^{\infty} rp_{t+\tau}^* + \mathbb{E}_t \left[\lim_{T\to\infty} q_{t+T}\right], \tag{22}$$

[3] The observation that Treasury-based CIP violations may be driven by convenience yields was pointed out by Adrien Verdelhan in a discussion at the 2017 Macro Finance Society Workshop.

where $\mathbb{E}_t[\lim_{\tau\to\infty} q_{t+\tau}]$ *is constant under the assumption that the real exchange rate is stationary. The terms* $r_t^{\$}$ *and* r_t^* *are the real interest rates, that is,* $y_t^{\$} - \mathbb{E}_t[\Delta p_{t+1}^{\$}]$ *is the real dollar interest rate.*

3. *The expected log excess return to a foreign investor of a long position in Treasury bonds is increasing in the risk premium and the Treasury basis,*

$$\mathbb{E}_t[\Delta s_{t+1}] + \left(y_t^{\$} - y_t^*\right) = rp_t^* + \frac{1}{1-\beta^*} x_t^{Treas}. \tag{23}$$

4. *The expected log return to a foreign investor of going long the dollar via the forward contract is*

$$\mathbb{E}_t[\Delta s_{t+1}] - \left(f_t^1 - s_t\right) = rp_t^* + \frac{\beta^*}{1-\beta^*} x_t^{Treas}. \tag{24}$$

5. *The change in the nominal exchange rate can be decomposed as* $\Delta s_{t+1} = (\mathbb{E}_{t+1} - \mathbb{E}_t)s_{t+1} + \mathbb{E}_t[\Delta s_{t+1}]$*, where the innovation is given by*

$$\begin{aligned}(\mathbb{E}_{t+1} - \mathbb{E}_t)s_{t+1} = {}& -(\mathbb{E}_{t+1} - \mathbb{E}_t)\sum_{\tau=1}^{\infty} \frac{x_{t+\tau}^{Treas}}{1-\beta^*} + (\mathbb{E}_{t+1} - \mathbb{E}_t)\sum_{\tau=1}^{\infty}\left(y_{t+\tau}^{\$} - y_{t+\tau}^*\right) \\ & -(\mathbb{E}_{t+1} - \mathbb{E}_t)\sum_{\tau=1}^{\infty} rp_{t+\tau}^* + (\mathbb{E}_{t+1} - \mathbb{E}_t)\lim_{T\to\infty} s_{t+T}. \end{aligned} \tag{25}$$

IV. Joint Dynamics of the Dollar Exchange Rate, the Treasury Basis, and the Convenience Yield

Next, we explore the empirical implications of our theory. We begin by showing that innovations to the Treasury basis covary with innovations in the nominal dollar exchange rate, consistent with result 5 of Proposition 1. We also show that the basis predicts future returns to a foreign investor going long Treasury bonds relative to foreign bonds, consistent with result 3 of Proposition 1. We then show that our results correspond more broadly to dollar safe assets, relate our results to the violation of the LIBOR-based CIP, and show that our results are strongest for the dollar and do not extend to other currencies to the same extent.

A. Variation in the Treasury Basis and the Dollar

We start from the expression for exchange rate innovations (result 5) in Proposition 1. We run a regression of exchange rate innovations on innovations to the basis, controlling for news about future interest rate differences and currency risk premia, to estimate the effect of convenience yield news on the value of the dollar. Innovations to the basis capture shocks to the demand for safe dollars.[4] This regression does not require exchange rate stationarity. After controlling for discount rate and interest rate news, we get consistent estimates of the slope coefficient β^*, provided that the covariance between the news about convenience yields and the long-run exchange rate tends to zero: $\lim_{T\to\infty} \mathrm{Cov}((\mathbb{E}_t - \mathbb{E}_{t-1})\sum_{\tau=0}^{T} x_{t+\tau}^{Treas}, (\mathbb{E}_t - \mathbb{E}_{t-1})\, s_{t+T}) = 0$. If exchange rates are stationary, this condition is trivially satisfied.

We construct quarterly AR(1) innovations in the Treasury basis by regressing $\bar{x}_t^{Treas} - \bar{x}_{t-1}^{Treas}$ on $\bar{x}_{t-1}^{Treas}$ and $y_{t-1}^{\$} - \bar{y}_{t-1}^{*}$ and computing the residual, $\Delta\bar{x}_t^{Treas}$. We then regress the contemporaneous quarterly change in the spot exchange rate, $\Delta\bar{s}_t \equiv \bar{s}_t - \bar{s}_{t-1}$, on this innovation. Note that we have verified the robustness of the results reported here to the case in which the innovation $\Delta\bar{x}_t^{Treas}$ is the simple change in $\bar{x}_t^{Treas}$ rather than the AR(1) innovation. The results are reported in Section VII of the Internet Appendix. We simply use the change in the log exchange rate as the innovation.

Table III reports the results. From columns (1), (3), (5), (6), and (8) in Panel A, we see that the innovation in the Treasury basis strongly correlates with changes in the exchange rate. In the context of the well-known exchange rate disconnect puzzle (Froot and Rogoff (1995) and Frankel and Rose (1995)), the R^2s are quite high. Our regressors in Panel A account for 17% to 43% of the variation in the dollar's rate of appreciation. The sign is negative as predicted by Proposition 1. The point estimates increase in absolute value in the postcrisis, as does the explanatory power. From column (1), we see that a 10 bp decrease in the basis (or an increase in the foreign convenience yield) below its mean coincides with a 1.02% appreciation of the U.S. dollar.

The regression estimates provide a way to estimate β^*, which is the incremental convenience yield attached to safe and liquid dollar payoffs relative to foreign-currency safe and liquid payoffs. We assume that the annual basis follows an AR(1) with coefficient ϕ_a. From (5) in Proposition 1, it follows that the innovation to the log exchange rate reflects the revision in the forecast of the basis at t,

$$(\mathbb{E}_t - \mathbb{E}_{t-1})s_t = -\frac{(\mathbb{E}_t - \mathbb{E}_{t-1})x_t}{(1-\phi_a)(1-\beta^*)} + \mathbb{E}_t \sum_{\tau=0}^{\infty}\left(y_{t+\tau}^{\$} - y_{t+\tau}^{*}\right) - \mathbb{E}_t \sum_{\tau=0}^{\infty} rp_{t+\tau}^{*} + \bar{s}. \tag{26}$$

The basis is mean-reverting with a quarterly AR(1) coefficient of $\phi = 0.47$. Thus, from (26), the sum of expected future increases in the 12-month basis in response to a 10 bp rise in the 12-month basis today is $10 \times \frac{1}{1-0.47^4} = 10.5$. To rationalize the 1.02% appreciation in the exchange rate, we need a β^* of $1 - \frac{10.5}{102} = 0.90$, suggesting that much of the convenience yield attached to U.S. Treasury bonds derives from its attribute as a safe and liquid *dollar* payoff. Put differently, if U.S. Treasurys were issued in foreign currency, their convenience yields would be substantially lower.

[4] We cannot rule out the possibility that the innovations include shocks to the demand for dollars that are subsequently invested in safe assets.

Table III

Average Treasury Basis and the USD Spot Nominal Exchange Rate

This table presents the regression result in which the dependent variable is the quarterly change in the log of the spot USD exchange rate against a basket. In Panel A, the independent variables are the innovation in the average Treasury basis, $\Delta\bar{x}^{Treas}$, as a log yield (i.e., 50 bps is 0.005), the lagged value of the innovation, the innovation in the LIBOR basis, and the innovation in the U.S.-to-foreign Treasury yield differential. Panel B includes the quarterly change in the VIX (in percentage units). The data are quarterly. The constant term is omitted. OLS standard errors are in parentheses. *, **, and *** indicate statistical significance at the 10%, 5%, and 1% level, respectively.

Panel A: Benchmark Results

	1988Q1–2017Q2					1988Q1–2007Q4		2008Q1–2017Q2	
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
$\Delta\bar{x}^{Treas}$	−10.20***		−10.23***		−9.81***	−8.48***		−14.93***	
	(2.09)		(1.98)		(1.73)	(2.62)		(3.20)	
$\Delta\bar{x}^{Libor}$		−2.85					4.63		−13.51***
		(3.09)					(4.22)		(4.05)
Lag $\Delta\bar{x}^{Treas}$			−6.92***		−6.47***				
			(1.97)		(1.73)				
$\Delta(y^{\$} - \bar{y}^{*})$				3.76***	3.57***				
				(0.71)	(0.60)				
Observations	117	117	116	117	116	80	80	37	37
R^2	0.17	0.01	0.25	0.20	0.43	0.12	0.02	0.38	0.24

Panel B: Control for VIX

	1988Q1–2017Q2					1988Q1–2007Q4		2008Q1–2017Q2	
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
$\Delta\bar{x}^{Treas}$	−9.62***		−9.22***		−9.66***	−7.10**		−10.44***	
	(2.40)		(2.31)		(1.94)	(3.14)		(3.35)	
$\Delta\bar{x}^{Libor}$		−1.89					5.19		−8.07**
		(3.09)					(4.10)		(3.94)
Lag $\Delta\bar{x}^{Treas}$			−7.06***		−4.33**				
			(2.28)		(1.95)				
$\Delta(y^{\$} - \bar{y}^{*})$				4.71***	4.48***				
				(0.73)	(0.66)				
Δvix	0.05	0.09	0.06	0.12**	0.08	−0.12	−0.13	0.21***	0.26***
	(0.07)	(0.07)	(0.06)	(0.06)	(0.05)	(0.10)	(0.10)	(0.08)	(0.08)
Observations	109	109	109	109	109	72	72	37	37
R^2	0.15	0.02	0.22	0.29	0.46	0.09	0.05	0.50	0.42

Column (3) of Table III includes the contemporaneous and the lagged innovations to the basis. This specification increases the R^2 to 25%. The explanatory power of the lag is certainly not consistent with our rational expectations model, but it is the signature of delayed adjustment in the exchange rate to shocks to the basis. Time-series momentum has been shown to be a common phenomenon in many asset markets, including currency markets (see Moskowitz, Ooi, and Pedersen (2012)), although there is no commonly agreed upon explanation for such phenomena. The delayed adjustment lends support to the notion of expectational errors on the part of currency market investors. Section IV of the Internet Appendix develops a model of sticky expectations in currency markets that replicates the momentum evidence. Froot and Thaler (1990), Gourinchas and Tornell (2004), and Bacchetta and Van Wincoop (2005) argued that expectational errors are behind the failure of the UIP in currency markets.

Column (4) of the table includes the innovation in the interest rate differential, $y^{\$} - \overline{y}^{*}$, constructed by taking an equal-weighted average of the one-year Treasury yields. We see that an increase in this interest rate spread has significant explanatory power in our sample. A rise in the U.S. rate relative to the foreign rate appreciates the dollar, which is what textbook models of exchange rate determination predict (and is what (13) predicts). Note that a decrease in the convenience yields earned by U.S. investors will increase the U.S. Treasury yield $y^{\$}$ and lead the dollar to appreciate. We include this covariate in column (5) along with the basis innovation. The R^2 rises to 43% and the coefficient estimates and standard errors are nearly unchanged. This is because the basis innovation and interest rate innovation are nearly uncorrelated in this sample (note that the levels are negatively correlated).

These results are largely robust to controlling for changes in the VIX, a commonly used measure of the quantity of risk in global equity markets. The results are reported in Panel B. The baseline coefficient estimate decreases slightly to −9.62. Following the same logic, we need a β^* of $1 - \frac{10.5}{96.2} = 0.89$. In the postcrisis sample, controlling for VIX brings the coefficient estimates back in line with the precrisis estimates. The point estimate decreases from −14.93 to −10.44.

Krishnamurthy and Vissing-Jorgensen (2012) estimate that the convenience yield on U.S. Treasury bonds relative to AAA-rated corporate bonds averages 0.75%. They interpret the 0.75% in terms of the liquidity services and extra safety of Treasury bonds relative to corporate bonds. We estimate that foreigners earn an extra convenience yield between 1.96% ($\frac{1}{0.112} \times 0.22$) and 2.09% ($\frac{1}{0.105} \times 0.22$) per annum on dollar Treasury bonds relative to foreign-currency government bonds. Since β^* is around 0.9, we additionally learn that much of this convenience benefit derives from the fact that the U.S. Treasury bond is a liquid and safe dollar payoff.

Another approach to estimating the average convenience yield is to evaluate the spread between the real long-run returns earned by foreign investors on U.S. Treasurys and domestic bonds,

$$\lambda^{\$,*} - \lambda^{*,*} = -(R^{\$,*} - R^{*,*}).$$

In the short run, the dollar exchange rate adjusts in response to changes in the convenience yields. If real exchange rates are stationary, then there is no long-run currency adjustment and the long-horizon currency risk premium disappears from (13) (see Backus, Boyarchenko, and Chernov (2018) and Lustig, Stathopoulos, and Verdelhan (2019)). Hence, this spread reveals the (average) extra convenience yields earned by foreign investors when buying Treasurys.

Our convenience yield estimate implies that real returns earned by foreign investors on Treasurys need to be about 2% lower than the returns earned on foreign bonds to maintain a stationary exchange rate.[5] The Treasury International Capital (TIC) system records the purchases of Treasurys by foreign investors. We use TIC system data to compute the dollar-weighted returns realized by foreign investors as the internal rate of return realized on the cash flows invested by foreign investors. We assume that investors are fully invested in the Bloomberg Barclays Treasury Index. Between 1980 and 2019, private foreign investors earned a dollar-weighted real return on their Treasury purchases of 2.77%, expressed in real dollars. In comparison, foreign investors earned a dollar-weighted real return of 4.66% on their holdings of foreign bonds. The return gap,

$$R^{*,*} - R^{\$,*} = 4.66\% - 2.77\% = 1.89\% = \lambda^{\$,*} - \lambda^{*,*},$$

is a direct estimate of the long-run difference in convenience yields ($\lambda^{\$,*} - \lambda^{\$,\$}$). Foreign investors buy U.S. Treasurys when Treasurys are expensive, consistent with our hypothesis that foreigners have a special demand for U.S. dollar safe assets. This estimate is quantitatively in line with the estimates we backed out of the Treasury basis and FX markets.

B. LIBOR and Treasury Bases

Columns (2), (7), and (9) of Table III show that the LIBOR basis has explanatory power in the postcrisis sample. This result has been documented in prior work by Avdjiev et al. (2019). We note that the LIBOR basis has no explanatory power in the precrisis sample, and moreover has less explanatory power for the dollar than the Treasury basis. Furthermore, Du, Tepper, and Verdelhan (2018b) document that the LIBOR basis was near zero precrisis and has often been significantly different from zero postcrisis. They show that the movements in the LIBOR basis are closely connected to frictions in financial intermediation that hamper arbitrage activities. We discuss these results and connect them to our safe asset theory below. Section II of the Internet Appendix develops a model of the supply of dollar-denominated LIBOR deposits. Suppose that foreign investors derive a convenience yield on both dollar Treasury bonds and other dollar safe assets, including bank deposits paying LIBOR, consistent with our estimate of β^* near 0.9. Krishnamurthy and Vissing-Jorgensen (2012) present evidence that there is a convenience yield on both U.S. Treasury bonds and other near-riskless private bonds such as U.S.

[5] Our result is qualitatively in line with the savings glut hypothesis (see, for example, Caballero, Farhi, and Gourinchas (2008) and Caballero and Krishnamurthy (2008)) and the low r-star discussion (see Laubach and Williams (2003, 2016), and Holston, Laubach, and Williams (2017)).

bank deposits. Some investors view near-riskless private bonds as partial substitutes for Treasury bonds.

This being the case, we expect an increase in foreign demand for Treasurys to drive down the foreign return to holding Treasurys, that is, to induce a widening of the Treasury basis, and to drive down the foreign return to holding dollar LIBOR bank deposits. In particular, consider the LIBOR basis, which is the spread between dollar LIBOR deposits and a foreign LIBOR deposit swapped into dollars,

$$x_t^{Libor} \equiv y_t^{\$,Libor} + \left(f_t^1 - s_t - y_t^{*,Libor}\right). \tag{27}$$

All else equal, an increase in foreign demand for dollar safe assets will drive down $y_t^{\$,Libor}$ and widen the LIBOR basis. However, this widening of the LIBOR basis presents a riskless profit opportunity for a bank that funds itself in both dollars and foreign currency. In particular, faced with a widening LIBOR basis, a bank can increase its supply of dollar deposits by one dollar, swap the one dollar into foreign currency so that its currency risk remains unchanged, and strictly increase its profits by x_t^{Libor}.

In the precrisis period, banks were active on this margin and hence the LIBOR basis is zero, consistent with the analysis of Du, Tepper, and Verdelhan (2018b). The LIBOR basis did not reflect foreign safe asset demand. In effect, quantities rather than prices adjusted to accommodate shifts in safe asset demand. In the postcrisis period, regulatory constraints on banks limit the capacity of banks to conduct this arbitrage, as Du, Tepper, and Verdelhan (2018b) emphasize. In this case, the LIBOR basis opens up. Prices adjust because quantities cannot. The LIBOR basis now reflects both safe asset demand and banks' regulatory constraints. Under our explanation, the LIBOR basis widens because of both "demand"—a willingness on the part of one set of agents to overpay for dollar deposits—and "supply"—a limited capacity of other agents to supply these dollar deposits. Other recent papers similarly cite both a demand factor and a limited supply factor as driving the LIBOR basis (see Ivashina, Scharfstein, and Stein (2015)).

Our analysis explains why the LIBOR basis comoves with the Treasury basis in the postcrisis period, as is evident from Figure 1, and why the LIBOR basis also comoves with the dollar exchange rate postcrisis. In short, when bank regulatory constraints restrict their arbitrage activities, the LIBOR basis reflects movements in $\lambda_t^{\$,*}$. This raises the question of why the Treasury basis persists, given that the Treasury is unconstrained and could issue more Treasurys, similar to what banks do in LIBOR markets prior to the crisis. The answer must be that the Treasury, unlike unconstrained banks, chooses not to exploit this basis because it has other objectives in managing the government debt portfolio. For example, as in the analysis of Farhi and Maggiori (2018), the U.S. Treasury may seek to earn monopoly rents on in its provision of convenience-yielding Treasury bonds.

Table IV

PCA of Treasury Bases

Panel A reports the standard deviation and the variance of the first three principal components. Panel B reports the loadings of each principal component on the Treasury bases with tenors of 1Y, 2Y, 3Y, 5Y, 7Y, and 10Y. The data are quarterly from 1991Q2 to 2017Q2.

Panel A: Summary Statistics			
	PC_1	PC_2	PC_3
Std Dev	0.41	0.19	0.17
% of Variance	69.50	15.14	11.44
Cumulative %	69.50	84.64	96.08
First-order autocorrelation	0.86	0.48	0.79
Panel B: Loadings			
1Y Basis	0.30	−0.93	−0.15
2Y Basis	0.43	−0.05	0.41
3Y Basis	0.46	0.09	0.33
5Y Basis	0.51	0.24	0.13
7Y Basis	0.36	0.20	−0.21
10Y Basis	0.35	0.17	−0.80

C. Term Structure of Treasury Bases

Thus far we have focused exclusively on the one-year (1Y) Treasury basis, but there is additional information contained in the term structure of Treasury bases about convenience yields. We compute the average G10 Treasury basis for each tenor (1Y, 2Y, 3Y, 5Y, 7Y, and 10Y), by averaging across countries in a similar manner as we have described. The 1Y basis comes from our data, and the other bases are from Du, Im, and Schreger (2018a). To reduce the dimension of the Treasury bases constructed by Du, Im, and Schreger (2018a), we conduct principal component analysis (PCA) on these Treasury bases. Their data cover a shorter sample than we do and hence here we limit the analysis to the period ranging from 1991Q2 to 2017Q2.

The results of the PCA are reported in Table IV. Similar to the term structure of bond yields, the first three principal components of the Treasury bases correspond to a level, a slope, and a curvature basis factor. We can see this from the loadings on the principal components. These three factors explain 96% of the variation in the Treasury bases.

Table V reports the results of a regression of the quarterly rate of appreciation of the dollar on the innovations in the level factor and the slope factor, controlling for changes in the interest rate differences. The quarterly innovations are obtained from an AR(1) model with lagged PC1, lagged PC2, and lagged Treasury yield differential. A one-standard-deviation decline in the level of the bases by 0.41% induces an appreciation of the dollar by 3.78% (9.29×0.41). There is also information in the innovations in the slope factor. If the slope rises, that is, the short-term bases fall relative to the long-term bases, the dollar appreciates. A rise in the slope may be coincident with a flight to quality

Table V
Principal Components in Treasury Basis and the USD Spot Nominal Exchange Rate

This table presents the regression results in which the dependent variable is the quarterly change in the log of the spot USD exchange rate against a basket. The data are quarterly. OLS standard errors are in parentheses. *, **, and *** indicate statistical significance at the 10%, 5%, and 1% level, respectively

	1991Q2–2017Q2					1991Q2–2007Q4		2008Q1–2017Q2	
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
$\Delta PC1$	−9.29***		−8.19***		−5.13***	−7.92**	−4.39*	−7.18**	−3.47
	(2.06)		(2.13)		(1.75)	(3.10)	(2.44)	(3.51)	(3.19)
$\Delta PC2$		7.69***	4.76*		7.09***	3.27	5.91**	8.61	9.09*
		(2.70)	(2.65)		(2.14)	(3.25)	(2.52)	(5.82)	(5.01)
$\Delta(y^{\$} - \bar{y}^{*})$				4.86***	4.60***		4.34***		10.57***
				(0.66)	(0.60)		(0.64)		(2.94)
Observations	104	104	104	105	104	67	67	37	37
R^2	0.17	0.07	0.19	0.35	0.49	0.11	0.48	0.38	0.56

that affects short-term bonds more than long-term bonds. That is, the basis on the one-year bond may be a better measure of foreign investors' convenience valuations than the basis on long-term bonds.

D. Monetary Policy Shocks and the Basis

To help us identify the causal effect of shocks to the basis on the dollar exchange rate, we rely on Federal Funds Rate (FFR) surprises. There is a growing literature on high-frequency identification, going back to Rudebusch (1998), Kuttner (2001), Cochrane and Piazzesi (2002), and Faust, Swanson, and Wright (2004). FOMC announcements are a useful source of variation because the news in these announcements corresponds primarily to short rates. We use Kuttner's (2001) FFR surprises as our measure of monetary shocks. There are 96 observations in our sample. We end the sample when the FFR hits the zero lower bound.[6]

How does a monetary policy surprise cause a change in the convenience yield? In Jiang, Krishnamurthy, and Lustig (2019a), we develop a theory that creates a role for monetary policy in the determination of convenience yields. In that model, tighter monetary policy induces banks to scale down their balance sheets. Since banks are important providers of dollar safe assets, the contraction reduces the supply of dollar safe assets. Given a downward-sloping demand for safe assets, the contraction in supply drives up the price of these assets, leading to an increased convenience yield.

In the first stage, we regress the change in the first principal component of the basis on the monetary policy shock. We argue that a contractionary

[6] These results are also discussed and reported in Krishnamurthy and Lustig (2019).

Table VI

Average Treasury Basis and the USD Spot Nominal Exchange Rate Around FOMC Announcements

Panel A presents the results of the first-stage regression of the change in Treasury basis on the monetary policy shock. Panel B presents the results of the second-stage regression of change in dollar exchange rate on the change in basis induced by an FOMC shock, controlling for the change in interest rate differences (column (1)) and the change in the VIX (column (2)). The change in the basis is the change in the first principal component (ΔPC_1) of the average Treasury bases across maturities. The interest rate difference is the first principal component of the average yield differences across maturities. The sample covers 96 FOMC announcements (excluding unscheduled FOMC meetings) between January 22, 1997 and December 30, 2008. We use a one-day window around FOMC announcements. OLS standard errors are in parentheses. *, **, and *** indicate statistical significance at the 10%, 5%, and 1% level, respectively.

Panel A: First Stage		
	(1)	(2)
Monetary Policy Shock	-0.58^{**}	-0.58^{**}
	(0.25)	(0.25)
Observations	96	96
R^2	0.05	0.05
Panel A: Second Stage		
	(1)	(2)
$\Delta\bar{x}^{Treas}$	-13.93^{***}	-11.98^{***}
	(2.71)	(2.89)
$\Delta(y^{\$} - \bar{y}^{*})$	0.71	1.00^{*}
	(0.55)	(0.57)
ΔVIX		0.08^{*}
		(0.05)
Observations	96	96
R^2	0.25	0.27

monetary policy shrinks the supply of liquid and safe assets and widens the basis. The first-stage regressions confirm this effect. These results are reported in the upper panel in Table VI. We use PC_1 as the average basis measure. A 10 bp surprise rate increase widens the average Treasury basis by more than 5.8 bps. In the second stage, we regress the dollar appreciation on the exogenous variation in the basis induced by the FFR surprise. These results are reported in the lower panel in Table VI. The exclusion restriction is that shocks to monetary policy do not covary with the exchange rates once we control for changes in interest rates. In terms of the exchange rate decomposition in (21), we assume that only the future convenience yields and future interest rates respond to FFR surprises, but not the future currency risk premia. Given that most of the news on these days corresponds to short rates, this seems like a plausible restriction. There is one caveat: we include unscheduled announcements, which are more likely to include the release of news about fundamentals.

The second-stage slope coefficients are comparable in magnitude to the OLS estimates in Table III: the slope coefficients vary between -11.98 and -13.93. A 10 bps widening of the Treasury basis induces an appreciation of the dollar between 1.20% and 1.39%. Controlling for changes in the VIX decreases the size of these coefficients in absolute value, but only moderately so.

Based on these results, a more precisely identified estimate of the fraction β^* is given by $1 - \frac{10.5}{119.8} = 0.91$. Hence, a better estimate of the average convenience yield earned by foreign investors is 2.51% per annum ($\frac{1}{1-0.91} \times 0.22$).

E. The Treasury Basis and Dollar Safe Asset Demand

Our theory posits that a specific form of capital flows consisting of flows into safe dollar assets drives the value of the U.S. dollar. In this section, we discuss how our evidence supports this interpretation.

First, note that we construct the basis from the safest asset, the U.S. Treasury bond, and document a relation between this basis and the dollar. Second, we show that the LIBOR basis also helps explain movements in the dollar postcrisis, consistent with the broad dollar safe asset demand theory. Third, we show that β^* is around 0.90, indicating that safe foreign government bonds when swapped into dollars carry a convenience yield. Fourth, in Section V of the Internet Appendix, we compute a KfW bond basis. KfW is a German issuer whose bonds are backed by the German government, so they are near default-free. KfW issues bonds in different currencies, which allows us to compute the basis for the bonds of the same issuer, that is, holding safety fixed, in different currencies. We compute the basis for KfW bonds using one-year yields on these bonds for Australia, the Euro, the United Kingdom, and Switzerland against the United States. The KfW and the Treasury bases have roughly the same magnitude and track each other closely. This evidence indicates that foreign investors demand a broad set of safe assets denominated in U.S. dollars.

Lastly, we perform a placebo test of dollar safe asset demand. We repeat the univariate regression of Table III, column (1), but use other non-U.S. countries as the base country. In Table VII, we use a different base country, and we calculate the equally weighted cross-sectional average exchange rate and Treasury basis of other non-U.S. countries against this base country's currency. In the top panel, we report the coefficient of the regression of nominal exchange rate movements on Treasury basis innovations. For other countries, the regression coefficients are largely statistically insignificant and/or the R^2s are considerably lower than that for the U.S. regressions. That is, the negative association between exchange rate movements and the Treasury basis is particularly strong for the United States where we posit that the safe asset demand effects should be most pronounced. In Panel B of the table, we include both innovations in the basis and the change in interest rate differences. Now the regression R^2 rises uniformly. Additionally, more of the currencies exhibit a negative relation between bases and exchange rates. In the last panel, we report the results of a univariate regression with only changes in interest rate differences. In comparing the regression R^2s in Panels B and C, we can see that only in the

Table VII

Explain Exchange Rate Movement Using Treasury Basis Innovation in Different Countries

This table presents the results of regressions of exchange rate movements on concurrent Treasury basis innovations and changes in the Treasury yield. A higher exchange rate means a stronger base currency. For each non-U.S. country, we exclude the United States when we calculate its average Treasury basis and average exchange rate movement against other non-U.S. countries. *, **, and *** indicate statistical significance at the 10%, 5%, and 1% level, respectively. We use DEM as a stand-in for EUR prior to the creation of the Euro.

Panel A: Univariate Regressions

	(1) USD	(2) AUD	(3) CAD	(4) EUR	(5) JPY	(6) NZD	(7) NOK	(8) SEK	(9) CHF	(10) GBP
Innov $\bar{x}^{Treas}$	−10.20***	0.19	2.06	−6.21	4.31	−3.97**	0.24	−0.80	1.94	2.45
	(2.09)	(3.48)	(1.67)	(3.81)	(4.86)	(1.90)	(0.96)	(0.85)	(1.50)	(2.38)
Observations	117	70	94	79	88	52	109	105	109	79
R^2	0.17	0.000	0.02	0.03	0.01	0.08	0.001	0.01	0.02	0.01

Panel B: Bivariate Regressions

	(1) USD	(2) AUD	(3) CAD	(4) EUR	(5) JPY	(6) NZD	(7) NOK	(8) SEK	(9) CHF	(10) GBP
Innov $\bar{x}^{Treas}$	−9.79***	−2.76	2.13	−8.71**	3.70	−4.75**	0.38	−1.85*	3.21**	−0.61
	(1.81)	(3.22)	(1.70)	(3.68)	(4.49)	(1.97)	(0.95)	(1.09)	(1.55)	(2.32)
Change in IR Diff	3.80***	6.23***	0.26	4.41***	6.87***	1.62	1.11*	0.88	−1.65**	4.62***
	(0.61)	(1.51)	(0.82)	(1.38)	(1.72)	(1.16)	(0.62)	(0.58)	(0.66)	(1.19)
Observations	117	70	94	79	88	52	109	105	109	79
R^2	0.38	0.20	0.02	0.15	0.17	0.12	0.03	0.03	0.07	0.18

Panel C: IR Differential Only

	(1) USD	(2) AUD	(3) CAD	(4) EUR	(5) JPY	(6) NZD	(7) NOK	(8) SEK	(9) CHF	(10) GBP
Change in IR Diff	3.92***	5.94***	0.12	3.72***	6.92***	1.17	1.09*	0.25	−1.21*	4.51***
	(0.68)	(1.47)	(0.81)	(1.39)	(1.71)	(1.04)	(0.62)	(0.46)	(0.63)	(1.11)
Observations	117	70	94	79	88	70	109	105	109	79
R^2	0.22	0.19	0.000	0.09	0.16	0.02	0.03	0.003	0.03	0.18

case of the dollar does the basis add substantial explanatory power. The Euro shares some of the U.S. dollar patterns, but to a much lesser extent.

F. Predictability of Exchange Rates and Excess Returns

We next turn to result 3 of Proposition 1, which can be read as a forecasting regression. A more negative x_t (i.e., a higher convenience yield) today is associated with a higher dollar exchange rate today, which induces expected depreciation in the future. For the forecast horizon k, we define the annualized log excess return as $rx_{t\to t+k} = \frac{4}{k}(\Delta s_{t\to t+k} + y^{\$}_{t\to t+k} - \bar{y}^{*}_{t\to t+k})$. Note that the left-hand side of equation (23), reproduced below,

$$\mathbb{E}_t[\Delta s_{t+1}] + \left(y_t^{\$} - y_t^*\right) = \frac{1}{1-\beta^*} x_t^{Treas} + rp_t^*,$$

is akin to the return on the reverse currency carry trade. It involves going long the U.S. Treasury bond, funded by borrowing at the rate of the foreign government bond. The carry trade return has a risk premium term (RP). Following the literature, a proxy for this risk premium is the interest rate differential across the countries. Accordingly, we include the mean Treasury yield differential ($y^{\$}_{t\to t+k} - \overline{y}^*_{t\to t+k}$) as a control in our regression. As we show in Table III, there is slow adjustment to basis shocks. We therefore use the average Treasury basis $\overline{x}_{t-1}^{Treas}$ lagged by one quarter as the main explanatory variable. The regression equation is

$$rx_{t\to t+k} = \alpha^k + \beta_x^k \overline{x}_{t-1}^{Treas} + \beta_y^k \left(y^{\$}_{t\to t+k} - \overline{y}^*_{t\to t+k}\right) + \epsilon^k_{t+k}.$$

Our theory suggests that the coefficient β_x should be positive. We run this regression using quarterly data, but compute the returns on the left-hand side as three-months, one-year, two-year, and three-year returns. Because there is overlap in the observations, we compute heteroskedasticity- and autocorrelation-adjusted standard errors.

Table VIII reports the results obtained when forecasting the annualized excess returns on a long position in the dollar. Overall, the results are in line with our theory: a more negative basis (i.e., higher convenience yields) predicts lower returns on the carry trade. However, we should note that the statistical significance of the results is weak, and the results of this section should be seen as a consistency check of our theory. The sample for a forecasting regression is relatively short, and even the known forecaster of currency returns, the interest rate differential, has limited power in this sample.

Panel A reports the regression results for the full sample. The slope coefficient on the average basis β_x^k varies from -1.46 at the three-month horizon to 4.44 at the three-year horizon. The long-horizon estimates are an accurate reflection of the basis effect after stripping away the short-run momentum effect that we have documented whereby the exchange rate adjusts slowly to changes in the basis. The effects are economically significant: a one-standard-deviation basis shock of 23 bps raises the expected excess return by 1.02% per annum over the next three years. These regressors jointly explain about 14% of the variation in excess returns at the three-year horizon. The basis is not a persistent predictor, and the Stambaugh (1999) bias is likely small. Further, there is no strong mechanical relation between the forecasting horizon and the R^2.

Panels B and C of Table VIII report the regression results for the pre- and postcrisis sample. The momentum effect is present only prior to the crisis. In the postcrisis sample, the slope coefficients on the basis are all positive. At the three-year horizon, the coefficient is 10.04: a one-standard-deviation basis shock increases the expected excess return by 2.31% per annum over the next three years. Consistent with the findings of Lilley et al. (2019), we note

Table VIII

Forecasting Currency Excess Returns in Panel Data

This table presents the results of regressions whose dependent variable is the annualized nominal excess return (in logs) $rx^{fx}_{t\to t+k}$ on a long position in U.S. Treasuries and a short position (equal-weighted) in all foreign bonds with maturities of k quarters. The independent variables are the average Treasury basis $\bar{x}^{Treas}$ lagged by one quarter, and the nominal Treasury yield difference $(y^{\$}_{t\to t+k} - \bar{y}^{*}_{t\to t+k})$ with maturities of k quarters. The data are quarterly from 1988Q1 to 2017Q2. We omit the constant, and report Newey-West standard errors with lags equal to the length of the forecast horizon k. *, **, and *** indicate statistical significance at the 10%, 5%, and 1% level, respectively.

	(1) Three Months	(2) One Year	(3) Two Years	(4) Three Years
Panel A: 1988Q1–2017Q2				
Lag $\bar{x}^{Treas}$	−1.46	4.15	4.41	4.44*
	(5.89)	(6.42)	(3.19)	(2.30)
$y^{\$}_{t\to t+k} - \bar{y}^{*}_{t\to t+k}$	0.47	0.83	1.72	1.59
	(0.92)	(1.04)	(1.13)	(1.02)
Observations	117	117	117	115
R^2	0.004	0.03	0.13	0.14
Panel B: 1988Q1–2007Q4				
	(1) Three Months	(2) One Year	(3) Two Years	(4) Three Years
Lag $\bar{x}^{Treas}$	−10.00	−2.38	−0.42	3.59
	(6.25)	(7.64)	(2.96)	(2.58)
$y^{\$}_{t\to t+k} - \bar{y}^{*}_{t\to t+k}$	0.64	0.69	1.64	2.42**
	(0.91)	(1.06)	(1.24)	(0.96)
Observations	80	80	80	80
R^2	0.04	0.03	0.15	0.30
Panel C: 2008Q1–2017Q2				
	(1) Three Months	(2) One Year	(3) Two Years	(4) Three Years
Lag $\bar{x}^{Treas}$	16.47	19.81***	16.00***	10.04***
	(10.27)	(6.32)	(3.33)	(1.83)
$y^{\$}_{t\to t+k} - \bar{y}^{*}_{t\to t+k}$	−5.52*	0.52	1.41	1.28
	(3.10)	(0.91)	(0.96)	(1.01)
Observations	37	37	37	35
R^2	0.13	0.29	0.40	0.34

that there is much more predictability after the crisis. In the postcrisis sample, these regressors jointly explain about 34% of the joint variation in excess returns at the three-year horizon.

The return predictability is driven mostly by the exchange rate component of returns. Section VII of the Internet Appendix reports predictability results for exchange rate changes rather than excess returns. We find solid statistical evidence that the average Treasury basis forecasts changes in exchange rates: the slope coefficient estimate is 5.17, implying that the dollar appreciates by 1.19% per annum over the next three years following one-standard-deviation widening of average Treasury basis.

In Section VIII of the Internet Appendix, we construct a longer sample for the U.S./U.K. Treasury basis (the sample starts 1970Q1 and ends in 2016Q2), and we run the same battery of statistical tests. The results are broadly in line with the results obtained on the shorter sample for the G-10 currencies.

G. Term Structure and Excess Returns

We next investigate whether other maturities of the basis have forecasting power for excess returns on the reverse carry trade. We summarize the other maturities using the principal component of the term structure and use these to forecast excess returns. As before, we lag these principal components by one period.

Panel A of Table IX reports the predictability results for the entire sample. When the bases widen across all tenors, this leads to lower excess returns at all horizons, with results that are statistically stronger at longer horizons. A one-standard-deviation widening of PC_1 by 41 bps leads to a 2.92% (2.01%) per annum reduction in the excess return at the two-year (three-year) horizon. The second principal component, the slope factor PC_2, has much less information for returns than the level factor. The coefficient on PC_2 is positive but only statistically different from zero at the three-month horizon. According to our theory, the coefficient on the slope should be negative, that is, we find in Table V that an increase in the slope leads to a contemporaneous appreciation of the dollar. We should therefore expect that an increase in the slope predicts future depreciation of the dollar. The results do not support this prediction. The positive coefficient at the three-month horizon may be another manifestation of the momentum phenomenon. Panels B and C of Table IX report the results for the pre- and postcrisis subsamples. The results are stronger in the postcrisis sample, consistent with earlier results.

A significant finding from this analysis is that there is considerable information in the term structure of the bases. We note the high R^2 in Table IX compared to that of Table VIII. The principal components explain significant variation in excess returns, rising to 30% at the three-year horizon, compared to 14% at the three-year horizon in Table VIII.

V. Reduced-Form VAR and Impulse Response Functions

We run a VAR with three variables: the basis, the real interest rate difference $i_{t-1} = d_{t-1} - \pi_t^{US} + \pi_t^*$, and the log of the real exchange rate q_t,

$$\boldsymbol{z}_t' = \left[x_t \ i_t \ q_t \right].$$

Table IX

Forecasting Currency Excess Returns using Principal Components

This table reports the results of regressions whose dependent variable is the annualized nominal excess return (in logs) $rx^{fx}_{t\to t+k}$ on a long position in U.S. Treasuries and a short position (equal-weighted) in all foreign bonds with maturities of k quarters. The nominal Treasury yield difference $(y^{\$}_{t\to t+k} - \overline{y}^{*}_{t\to t+k})$ also has a maturity of k quarters, averaged across the same set of foreign countries. The data are quarterly from 1991Q2 to 2017Q2. We omit the constant. Heteroskedasticity- and autocorrelation-adjusted standard errors are in parentheses; we use the Newey-West estimator with the number of lags equal to the overlap in returns. *, **, and *** indicate statistical significance at the 10%, 5%, and 1% level, respectively.

	(1) Three Months	(2) One Year	(3) Two Years	(4) Three Years
Panel A: 1988Q1–2017Q2				
Lag $PC1$	3.41	5.41	7.11**	4.90*
	(5.08)	(4.79)	(3.21)	(2.67)
Lag $PC2$	10.91*	4.18	1.67	0.34
	(6.50)	(7.82)	(5.36)	(3.82)
$y^{\$}_{t\to t+k} - \overline{y}^{*}_{t\to t+k}$	0.38	0.83	2.57**	2.48***
	(1.43)	(1.46)	(1.15)	(0.94)
Observations	104	104	104	102
R^2	0.02	0.05	0.29	0.30
Panel B: 1988Q1–2007Q4				
Lag $PC1$	−2.38	−0.13	5.40	4.78
	(4.35)	(6.81)	(4.50)	(3.90)
Lag $PC2$	20.80***	11.91	4.18	−2.69
	(6.73)	(8.90)	(5.28)	(2.14)
$y^{\$}_{t\to t+k} - \overline{y}^{*}_{t\to t+k}$	0.44	0.32	2.81**	4.04***
	(1.53)	(1.74)	(1.35)	(1.55)
Observations	67	67	67	67
R^2	0.09	0.06	0.29	0.50
Panel C: 2008Q1–2017Q2				
Lag $PC1$	16.16**	11.28**	11.60***	9.90***
	(7.87)	(4.81)	(1.75)	(1.94)
Lag $PC2$	17.56	−2.48	4.42**	7.86*
	(15.03)	(8.19)	(2.15)	(4.02)
$y^{\$}_{t\to t+k} - \overline{y}^{*}_{t\to t+k}$	−8.34***	−1.23	−0.68	−1.29
	(3.07)	(1.44)	(1.16)	(1.15)
Observations	37	37	37	35
R^2	0.17	0.34	0.57	0.63

We estimate following the first-order VAR for $\boldsymbol{z}_t$,

$$\boldsymbol{z}_t = \boldsymbol{\Gamma}_0 + \boldsymbol{\Gamma}_1 \boldsymbol{z}_{t-1} + \boldsymbol{a}_t,$$

where $\boldsymbol{\Gamma}_0$ is a three-dimensional vector, $\boldsymbol{\Gamma}_1$ is a 3×3 matrix, and $\boldsymbol{a}_t$ is white noise random vector with mean zero and variance-covariance matrix Σ.

A. Estimation

We estimate the VAR system using quarterly data. To convert the one-year Treasury basis to an equivalent three-month Treasury basis, we scale the one-year Treasury basis and interest rate differentials. Section VI of the Internet Appendix provides the details.

We identify the VAR(1) as the optimal specification using the Bayesian information criterion (BIC). This specification assumes that the log of the real U.S. dollar index is stationary, which seems to be case in this sample period. We order the VAR so that shocks to the basis affect all variables contemporaneously, shocks to the interest rate affect the exchange rate and the interest rate differential but not the basis, and shocks to the exchange rate only affect itself. This ordering implies that nominal and real exchange rates can respond instantaneously to all of the structural shocks. As we discuss below, the evidence from the VAR supports a causal interpretation of our regression evidence: shocks to convenience yields drive movements in the exchange rate.

Figure 2 plots the impulse response from orthogonalized shocks to the basis. The top left panel plots the dynamic behavior of the basis (in percentage points), the top right panel plots the dynamic behavior of the interest rate difference (in percentage points), and the bottom left panel plots the behavior of the exchange rate (in percentage points). The dynamics in the figure are consistent with the regression evidence from the tables. An increase in the annualized Treasury basis of 0.2% (quarterly basis of 0.1% in the figure) depreciates the real exchange rate contemporaneously by about 3% over two quarters. The finding that the depreciation persists over two quarters is consistent with the time-series momentum effect discussed earlier. Thus, the exchange rate exhibits classic Dornbusch (1976) overshooting behavior. A gradual reversal then occurs over the next five years—the effect on the level of the dollar gradually dissipates. There is no statistically discernible effect of the basis on the interest rate differential. Finally, the bottom right panel plots the quarterly log excess return on a long position in dollars, $rx_t = q_t - q_{t-1} + i_{t-1}$. The quarterly excess return drops over the first two quarters. It is then higher than average over the next 15 to 18 quarters, consistent with higher expected returns on long positions in Treasurys.

Once we add the basis shock, the UIP roughly holds for the dollar against this panel of currencies. Figure 3 plots the response to interest rate shocks. The dollar appreciates in real terms in the same quarter by more than 100 bps in response to a 100 bp increase in the U.S. yields above the foreign yields. The bottom right panel of the figure plots the excess return on the currency. We see

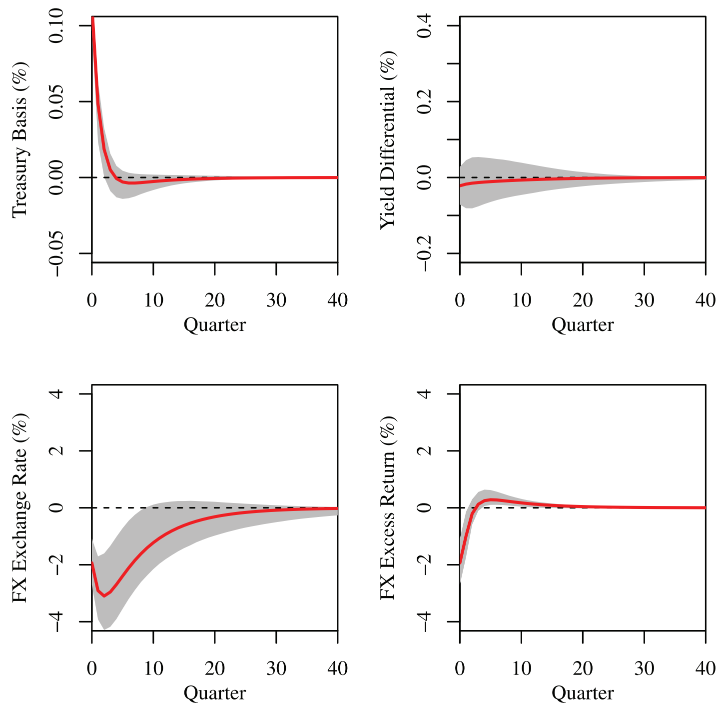

Figure 2. Dynamic response to Treasury basis shocks: Panel. The red line plots the impulse response of a one-standard-deviation orthogonalized shock to the average Treasury basis on the basis (top left panel), the real interest rate differential (top right panel), the log real spot exchange rate (bottom left panel), and the quarterly log excess return on a long position in dollars (bottom right panel). The y-axis is in percentage points. The gray areas indicate 95% confidence intervals. Standard errors are generated using 10,000 Monte Carlo simulations. The VAR is estimated over the period from 1988Q1 to 2017Q2. The ordering is $[\bar{x}_t, r_t^{\$} - \bar{r}_t^{*}, q_t]$. (Color figure can be viewed at wileyonlinelibrary.com)

that this return is zero after the first quarter, indicating that the UIP holds after we account for shocks to the basis. As Lustig, Roussanov, and Verdelhan (2014) point out, the deviations from the UIP in univariate time-series regressions are larger for the dollar. Our results indicate that these deviations may be due to variation in the convenience yield on dollar safe assets.

Figure 4 reports all of the impulse responses. The lower right panel plots the variance decomposition of the exchange rate against the horizon. Basis shocks account for a large fraction of the exchange rate forecast error variance, especially at longer horizons. At the one-quarter horizon, basis shocks account for around 20% of the forecast error variance; this fraction increases to 35% at longer horizons. In contrast, the interest rate shocks account for less than 25% of the forecast error variance at all horizons. Thus, while the initial impact of a one-standard-deviation interest rate shock on the dollar is similar to that of a one-standard-deviation basis shock (roughly 2%), its effect builds up more gradually.

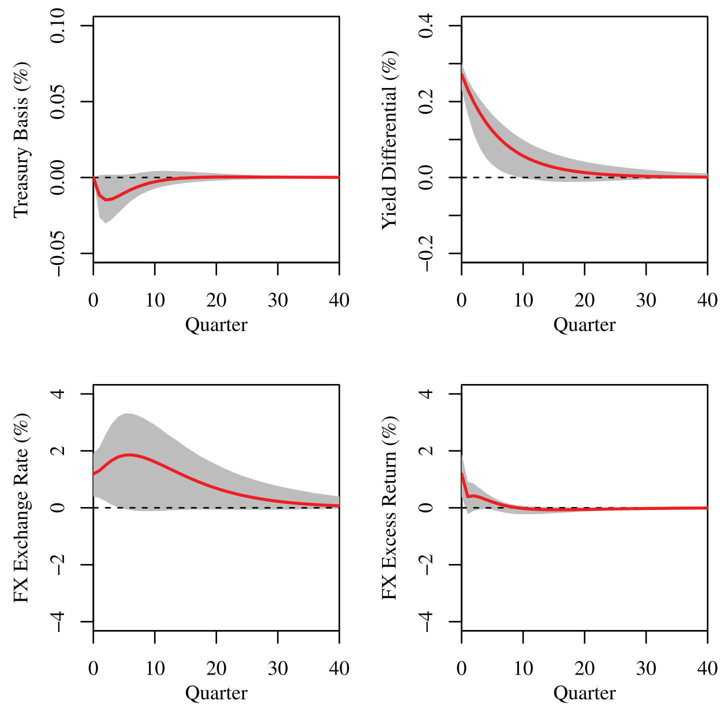

Figure 3. Dynamic response to interest rate shocks: Panel. The red line plots the impulse response of a one-standard-deviation orthogonalized shock to the yield difference on the basis (top left panel), the real interest rate differential (top right panel), the log real spot exchange rate (bottom left panel), and the quarterly log excess return on a long position in dollars (bottom right panel). The y-axis is in percentage points. The gray areas indicate 95% confidence intervals. Standard errors are generated using 10,000 Monte Carlo simulations. The VAR is estimated over the period from 1988Q1 to 2017Q2. The ordering is $[\bar{x}_t, r_t^{\$} - \bar{r}_t^*, q_t]$. (Color figure can be viewed at wileyonlinelibrary.com)

Importantly, the results are not sensitive to switching the order of the basis and interest rate differentials, indicating that we can plausibly interpret the relation between the basis and exchange rate causally: a shock to convenience yields moves both the Treasury basis and the exchange rate. We draw this conclusion because we have allowed for other known determinants of the exchange rate—relative interest rates—and yet recover the same relation between the basis and the exchange rate. These results are reported in Section VI of the Internet Appendix.

B. Campbell-Shiller Decomposition

The log currency excess return is given by $rx_t = q_t - q_{t-1} + i_{t-1}$. By result 3 of Proposition 1, the realized risk premium component of the log currency excess return is the realized log excess return minus the convenience yield: $rp_t = rx_t - \frac{1}{1-\beta^*} \times x_{t-1}$. As a result, we can add an equation for the risk premium

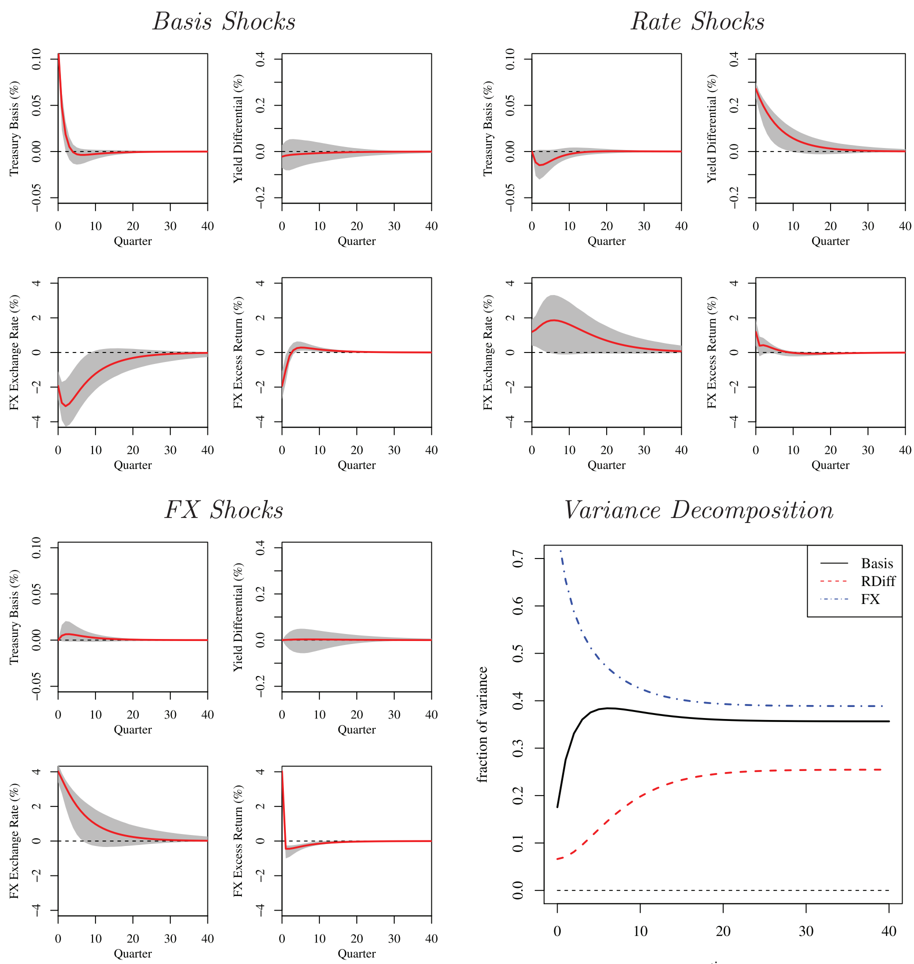

Figure 4. Panel impulse responses. The red line plots the impulse response of an orthogonalized one-standard-deviation shock on the basis (top left panel), the real interest rate differential (top right panel), the log real spot exchange rate (bottom left panel), and the quarterly log excess return on a long position in dollars (bottom right panel). The y-axis is in percentage points. The gray areas indicate 95% confidence intervals. Standard errors are generated using 10,000 Monte Carlo simulations. The VAR is estimated over the period from 1988Q1 to 2017Q2. The ordering is $[\bar{x}_t, r_t^{\$} - \bar{r}_t^*, q_t]$. (Color figure can be viewed at wileyonlinelibrary.com)

component of the log excess return to the VAR. We end up with the following first-order VAR:

$$\begin{bmatrix} rp_t \\ x_t \\ i_t \\ q_t \end{bmatrix} = \begin{bmatrix} \gamma_0 \\ \Gamma_{0,1} \\ \Gamma_{0,2} \\ \Gamma_{0,3} \end{bmatrix} + \begin{bmatrix} 0 & \Gamma_{3,1} - \frac{1}{1-\beta^*} & \Gamma_{3,2}+1 & \Gamma_{3,3}-1 \\ 0 & \Gamma_{1,1} & \Gamma_{1,2} & \Gamma_{1,3} \\ 0 & \Gamma_{2,1} & \Gamma_{2,2} & \Gamma_{2,3} \\ 0 & \Gamma_{3,1} & \Gamma_{3,2} & \Gamma_{3,3} \end{bmatrix} \begin{bmatrix} rp_{t-1} \\ x_{t-1} \\ i_{t-1} \\ q_{t-1} \end{bmatrix} + \begin{bmatrix} a_{3,t} \\ a_{1,t} \\ a_{2,t} \\ a_{3,t} \end{bmatrix}. \quad (28)$$

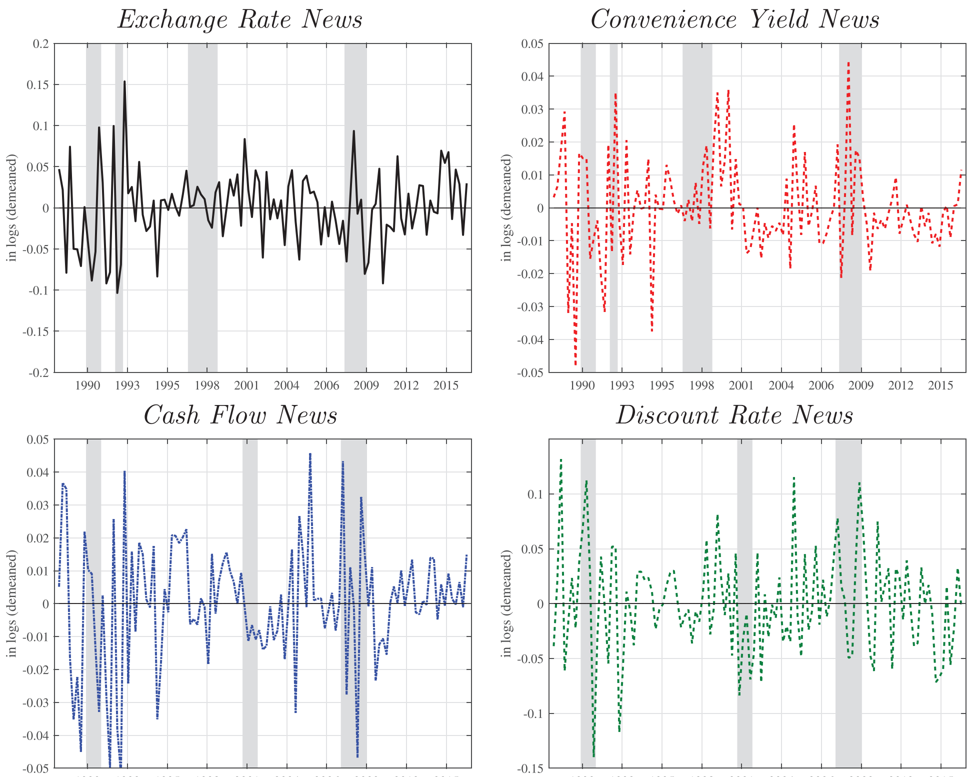

Figure 5. News about dollar real exchange rate and its components. This figure plots the quarterly news about exchange rates $\boldsymbol{e}_1'\boldsymbol{u}_t$ as well as its convenience yield $N_{CY,t}$, cash flow $N_{CF,t}$, and discount rate $N_{DR,t}$ components. The VAR is estimated over the period 1988Q1 to 2017Q2. The VAR(1) includes $[\overline{x}_t, r_t^{\$} - \overline{r}_t^*, q_t]$. β^* is 0.9. In the first row, the shaded areas correspond to the European Exchange Rate Mechanism (ERM) crisis, the Gulf War, the Russian default and LTCM crisis, and the recent global financial crisis. In the second row, the shaded areas correspond to NBER recessions. (Color figure can be viewed at wileyonlinelibrary.com)

Accordingly, we can define the state as the vector of demeaned variables, $\boldsymbol{y}_t' = [\tilde{rp}_t \quad \tilde{x}_t \quad \tilde{i}_t \quad \tilde{q}_t]$, where $\boldsymbol{y}_t$ is a VAR process of order one,

$$\boldsymbol{y}_t = \boldsymbol{\Psi}_1 \boldsymbol{y}_{t-1} + \boldsymbol{u}_t,$$

$\boldsymbol{\Psi}_1$ is the 4×4 matrix defined in (28), and $\boldsymbol{u}_t$ is the 4×1 vector of residuals defined above. Following Campbell and Shiller (1988), we can define the news about discount rates, news about cash flows, and news about convenience yields:

$$N_{DR,t} = (\mathbb{E}_t - \mathbb{E}_{t-1}) \left[\sum_{j=1}^{\infty} rp_{t+j} \right] = \boldsymbol{e}_1' \boldsymbol{\Psi}_1 (I - \boldsymbol{\Psi}_1)^{-1} \boldsymbol{u}_t,$$

Table X

News Decomposition of Real Exchange Rates Innovations

This table reports the decomposition of quarterly innovations in log of the average dollar real exchange rate in the panel for different values of β^*. The VAR is estimated over the period 1988Q1 to 2017Q2. The VAR(1) includes $[\bar{x}_t, r_t^{\$} - \bar{r}_t^*, q_t]$.

β^*	var(CY)	var(CF)	var(DR)	2cov(CY, CF)	−2cov(CY, DR)	−2cov(CF, DR)
0.95	0.63	0.17	1.62	0.36	−1.35	−0.43
0.925	0.28	0.17	1.24	0.24	−0.62	−0.31
0.9	0.16	0.17	1.10	0.18	−0.36	−0.25
0.875	0.10	0.17	1.04	0.14	−0.24	−0.22

$$N_{CF,t} = (\mathbb{E}_t - \mathbb{E}_{t-1})\left[\sum_{j=0}^{\infty} i_{t+j}\right] = \boldsymbol{e}_3'(I - \boldsymbol{\Psi}_1)^{-1}\boldsymbol{u}_t,$$

$$N_{CY,t} = -(\mathbb{E}_t - \mathbb{E}_{t-1})\left[\sum_{j=0}^{\infty} \frac{1}{1-\beta^*} x_{t+j}\right] = -\frac{1}{1-\beta^*}\boldsymbol{e}_2'(I - \boldsymbol{\Psi}_1)^{-1}\boldsymbol{u}_t.$$

These components satisfy the identity,

$$N_{CY,t} = -N_{CF,t} + N_{DR,t} + \boldsymbol{e}_1'\boldsymbol{u}_t.$$

We need an estimate of β^* to decompose the FX news. We use the estimate of $\beta^* = 0.90$ from the monetary policy shock analysis of Section IV.D. We also estimate β^* under the VAR system following the procedure described in Section VI of the Internet Appendix, and obtain a similar estimate of $\beta^* = 0.91$.

Figure 5 plots the news about the dollar exchange rate and its three components about convenience yields, cash flows, and discount rates, respectively. For the first two panels, the shaded areas correspond to the European Exchange Rate Mechanism (ERM) crisis, the Gulf War, the Russian default and LTCM crisis, and the recent global financial crisis. The dollar's exchange rate and the convenience yield component tend to rise during these periods of increased global uncertainty, as global investors seek the safety of dollar safe assets. During the recent crisis, for example, convenience yield news led the dollar to appreciate by 5%. These effects are largely transitory, however, given that the basis quickly reverts back to its mean.

While the convenience yield component is tied to global crises, the cash flow component appears to be more related to the U.S. business cycle. The third panel plots the cash flow news and the shaded areas correspond to NBER recessions. The cash flow news appears to be procyclical. At the start of NBER recessions, U.S. yields decline relative to foreign yields, contributing to a weakening of the dollar. Lastly, the discount rate component, as shown in the last panel, appears to be not strongly correlated with these recessions.

Table X presents the variance decomposition of quarterly dollar exchange rate innovations for the panel of countries. When $\beta^* = 0.90$, convenience yield news (CY) accounts for 16% of the variance in quarterly exchange rates. Interest rate news (CF) accounts for a similar share of the variance, while discount rate news (DR) accounts for a sizable share of 110%. These results are sensitive to the exact value of β^*. When $\beta^* = 0.875$, the convenience yield news accounts for only 10% of exchange rate innovations, while if $\beta^* = 0.95$, it accounts for 63% of the innovations. The ratio of the convenience yield to the observed basis, $\frac{1}{1-\beta^*}$, is highly sensitive to β^*.

VI. Conclusion

We present a theory of exchange rates that departs from existing theories by imputing a central role to international flows in Treasury debt and related dollar safe asset markets in exchange rate determination. According to our theory, the spot exchange rate of a safe asset currency will reflect the cumulative value of all future convenience yields that are earned by foreign investors on safe assets denominated in that currency. The empirical evidence strongly supports the theory. Our results shed light on two important issues in international finance. First, we help resolve the exchange rate disconnect puzzle by demonstrating that shocks to the demand for dollar-denominated safe assets drive a sizeable portion of the variation in the dollar exchange rate. Second, we provide strong empirical support for recent theories regarding safe assets and the central role of the United States in the international monetary system.

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Supporting Information

Additional Supporting Information may be found in the online version of this article at the publisher's website:

Appendix S1: Internet Appendix.
Replication Code.