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Georgi Krustev

The natural rate of interest and the financial cycle

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Abstract

I extend the model of Laubach and Williams (2003) by introducing an explicit role for the financial cycle in the joint estimation of the natural rates of interest, unemployment and output, and the sustainable growth rate of the US economy. By incorporating the financial cycle – arguably an omitted variable from the system – the model is able to deliver more plausible estimates of business cycle dynamics. The sustained decline in the natural rate of interest in recent decades is confirmed, but I estimate that strong and persistent headwinds due to financial deleveraging have lowered temporarily the natural rate on average by around 1 p.p. below its long-run trend over 2008-14. This may have impaired the effectiveness of interest rate cuts to stimulate the economy and lift inflation back to target in the immediate aftermath of the GFC.

Keywords: natural rate of interest; output gap; financial cycle; Kalman filter; monetary policy.
JEL Classification: C32, E43, E44, E52

Non-technical summary

Prior to the Great Recession, financial imbalances and unsustainable growth trajectories co-existed with limited inflationary pressures in the United States and elsewhere (see Borio and Disyatat 2014). The implications of the financial cycle for the business cycle have since received increasing attention, but little is known as to how financial imbalances affect the natural rate of interest. In this paper, I extend the model of Laubach and Williams (2003) by introducing an explicit role for the financial cycle in the joint estimation of the natural rates of interest, unemployment and output, and the sustainable growth rate of the US economy over the 1961Q1-2016Q1 period.

In their seminal work, Laubach and Williams (2003) (henceforth: LW) estimated a time-varying natural rate of interest from a semi-structural model with the Kalman filter. Employing a framework inspired from the New Keynesian model, the LW statistical model and related empirical studies identify the unobservable natural rate of interest via the output gap in a dynamic IS equation, while the unobservable output gap estimate is informed by inflation dynamics via the Phillips curve. One limitation, however, is that financial imbalances are absent and do not play a role. Kiley (2015), Cukierman (2016) and Taylor and Wieland (2016) have argued that the omission of factors that are likely to influence output fluctuations – such as credit or more broadly, the financial cycle – may result in mis-specification and affect inference as regards the natural rate of interest. Another limitation is that updated estimates of output gaps from the LW model since the Global Financial Crisis (GFC) have shown substantial deviation from results derived on the basis of production-function approaches; consequently, their plausibility has been questioned (see Kiley 2015, Pescatori and Turunen 2016). Such doubts extend to the plausibility of the natural rate of interest estimates, which are closely tied to the position of the business cycle.

The main contribution of this paper is to assess the effect of financial imbalances on the natural rate of interest in the LW model and by doing so, address concerns about omitted variable bias and obtain more plausible estimates of business cycle dynamics. In extending their framework with the financial cycle, the natural rate is modelled as a function of sustainable ("finance-neutral") output growth, a concept advocated by Borio et al. (2017). This allows to distinguish low-frequency movements in the trend component of the natural rate from temporary but persistent deviations due to headwinds and tailwinds associated with the financial cycle.

The main findings can be summarised as follows. First, the natural rate of interest consistent with stable prices experienced a sustained decline over the sample period. Second, strong and persistent headwinds due to financial deleveraging have lowered the natural rate of interest on average by around 1 p.p. below its long-run trend over 2008-14. This might have impaired the effectiveness of interest rate cuts to stimulate the economy and lift inflation back to target immediately after the GFC. The dissipation of these headwinds implies that monetary policy should have regained traction since 2015 as the natural rate of interest rebounded, aligning itself to its long-run component. Finally, uncertainty around the estimates is large, a common feature found in related studies using similar methodologies.

1 Introduction

Prior to the "Great Recession", financial imbalances and unsustainable growth trajectories co-existed with limited inflationary pressures in the United States and elsewhere (see Borio and Disyatat 2014). The implications of the financial cycle for the business cycle have since received increasing attention, for example in Claessens et al. (2012) and Rünstler and Vlekke (2018) who examine the interactions between them. Yet little is known as to how financial imbalances affect the natural rate of interest. In this paper, I extend the model of Laubach and Williams (2003) by introducing an explicit role for the financial cycle in the joint estimation of the natural rates of interest, unemployment and output, and the sustainable growth rate of the US economy.

The natural rate of interest is typically defined as the real short-term rate consistent with output equalling (or converging to) its potential, which in turn is the level of output consistent with stable prices (see for example Holston et al. 2017). This definition is closely linked to the canonical New Keynesian model where the alignment of actual output with its natural counterpart ensures stable inflation via "divine coincidence".[1] However, this is not the only channel to connect the natural interest rate with price stabilisation. In his cumulative process of inflation, Wicksell (1898) proposed a theory of price determination triggered by disequilibria in the credit market, in turn associated with deviations of the market interest rate from the natural rate.[2] Consistent with such an interpretation of the natural rate as the one which ensures equilibrium in the credit market, Rungcharoenkitkul (2015) estimates a "finance-neutral" rate; he strips it out of the conventional price-stabilising property, however, in order to highlight the distinction between financial and macroeconomic stability. Recent studies have also argued that "non-inflationary" output may be an overly restrictive notion of potential output, advocating in favour of a broader concept of "sustainable" output, interpreted as trend output in the absence of financial imbalances (see Borio et al. 2017, Arseneau and Kiley 2014, Berger et al. 2015).[3]

In their seminal work, Laubach and Williams (2003) (henceforth: LW) estimated a time-varying natural rate of interest from a semi-structural model with the Kalman filter. Employing a framework inspired from the New Keynesian model, the LW statistical model and related empirical studies (see Manrique and Marqués 2004, Mésonnier and Renne 2007, Garnier and Wilhelmsen 2009) identify the unobservable natural rate of interest via the output gap in a dynamic IS equation, while the unobservable output gap estimate is informed by inflation dynamics via the Phillips curve.[4]

[1] Accordingly, in the New Keynesian model deviations of the actual interest rate from its natural counterpart (the interest rate gap) trigger deviation of actual output from its potential level (output gap), as captured by the IS equation. For instance, an actual real interest rate below the natural level implies a positive output gap, which in turn generates inflationary pressures through the Phillips curve. In the New Keynesian model, the alignment of actual output with its potential level achieves stable prices in an economy inhabited by only nominal rigidities, since the presence of other type of rigidities (e.g. real ones) no longer guarantees the divine coincidence of stabilising simultaneously output and inflation. See Woodford (2003) and Galí (2008).

[2] For a good discussion, see Amato (2005) and Weber et al. (2008).

[3] For an empirical application extending this approach to emerging market economies, see Grintzalis et al. (2017). These studies assign a key role to low-frequency fluctuations in the financial cycle in determining the sustainable level of economic activity. The authors argue that conventional approaches – such as those that rely on inflation as the main indicator informing the deviations of output from its potential – may be too restrictive and lead to overestimation of the underlying trend during credit and housing booms.

[4] One major difference between the natural interest rate concept in Laubach and Williams (2003) and the one employed in New Keynesian models is time horizon. Laubach and Williams (2003) focus on low-frequency movements in the natural rate and hence interpret it as the rate which maintains output at potential over time

One limitation, however, is that financial imbalances are absent and do not play a role. Kiley (2015), Cukierman (2016) and Taylor and Wieland (2016) have argued that the omission of factors that are likely to influence output fluctuations – such as credit or more broadly, the financial cycle – may result in mis-specification and affect inference as regards the natural rate of interest. Another limitation is that updated estimates of output gaps from the LW model since the Global Financial Crisis (GFC) have shown substantial deviation from results derived on the basis of production-function approaches; consequently, their plausibility has been questioned (see Kiley 2015, Pescatori and Turunen 2016). Such doubts extend to the plausibility of the natural rate of interest estimates, which are closely tied to the position of the business cycle.

The main contribution of this paper is to assess the effect of financial imbalances on the natural rate of interest in the LW model and by doing so, address concerns about omitted variable bias and obtain more plausible estimates of business cycle dynamics. In extending their framework with the financial cycle, the natural rate is modelled as a function of sustainable ("finance-neutral") output growth, a concept advocated by Borio et al. (2017). This allows to distinguish low-frequency movements in the trend component of the natural rate from temporary but persistent deviations due to headwinds and tailwinds associated with the financial cycle.

I make two key assumptions. The first is that a broader finance-neutral output gap can be decomposed in two components, an inflationary component and a non-inflationary one, the latter being identified through the financial cycle. The second assumption is that the natural rate of interest can deviate in the short run from its long-run trend component due to persistent financial headwinds and tailwinds to the growth rate of non-inflationary output.

These key simplifying assumptions are grounded in the idea that while the financial cycle may affect real activity, it does not generate inflationary pressures on consumer prices. This is akin to a conjecture of "disguised overheating" as in Borio and Lowe (2004), where the symptoms of an unsustainable expansion are more visible in excessive credit, asset price growth and over-stretched balance sheets rather than in price pressures. A constellation of this type could arise due to various factors, such as (1) the disconnect between asset prices and consumer prices; (2) the co-existence of positive supply-side shocks in boom phases of the credit cycle which generate downward pressures on prices while supporting asset price booms that ease financing constraints[5]; (3) expectations or judgemental errors by economic agents as regards the state of the economy or current and future productivity growth[6]; (4) finally, a monetary policy conduct that follows "blindly" an inflation targeting rule, as shown in the models of Christiano et al. (2008), Christiano et al. (2010) and De Fiore and Tristani (2013).

(i.e. after all transitory demand and supply shocks have abated). By contrast, the New Keynesian model and related DSGE model-based estimates envisage a natural rate which is driven primarily by transitory fluctuations around a constant steady state and is consistent with period by period price stability. Consequently, empirical DSGE-model based estimates of the natural rate exhibit substantial volatility, often exceeding the volatility of actual interest rates (see, for instance, Edge et al. 2008, Neiss and Nelson 2003, Smets and Wouters 2003, Barsky et al. 2014, Cúrdia et al. 2015).

[5]See Drehmann et al. (2012); Borio et al. (2017).

[6]A strong credit cycle supporting real activity may be misperceived for a sequence of positive productivity shocks which dampen inflation as they appear as negative cost-push factors in the Philips curve. For instance, the New Keynesian model with financial frictions in De Fiore and Tristani (2013) incorporates a credit spread which appears both in the IS equation and as a cost-push shock in the Phillips curve. A lower credit spread, as may be expected during a credit boom, exerts upward pressure on economic activity and at the same time dampens marginal costs and inflation.

The view that credit booms are linked with above-trend output growth and at the same time limited inflationary pressures is supported on both theoretical and empirical grounds. For instance, in the theoretical model with costly information about collateral quality by Ordoñez and Gorton (2015), endogenous credit booms are linked to the diffusion of technology in the first stage, followed in the second stage by decreasing marginal productivity and information acquisition which – by revealing the poor quality of the collateral – leads to a crisis with a crash in credit and output. Ordoñez and Gorton (2015) also document that credit booms have been associated with positive shocks to productivity based on empirical evidence from 34 countries over 50 years. In addition, Mendoza and Terrones (2008) point out that credit booms across emerging and industrial economies are associated with a well-defined pattern of economic expansion in the build-up phase of the booms, followed by contraction in the declining phase. All of this happens without major changes in inflation. Finally, Christiano et al. (2010) point out that U.S. stock market booms as well as the Japanese stock market boom of the 1980s were episodes coinciding with high credit growth and relatively low inflation.[7]

In extending the LW model, I incorporate information from the financial cycle in tracking the business cycle in the IS equation. Additionally, I augment the model with a labour market block which allows to estimate more precisely the cyclical position of the economy using labour market data. I also include inflation expectations into the Phillips curve. These modifications improve the plausibility of business cycle estimates and contribute to a more efficient identification of the relationship between resource utilisation gaps and price dynamics.

The main findings can be summarised as follows. First, the natural rate of interest consistent with stable prices experienced a sustained decline over the sample (1961Q1-2016Q1). The result is in line with other empirical studies, including updated estimates from the LW model.[8] My findings, however, do not provide support to the claims by Cukierman (2016) and Juselius et al. (2017) that the LW estimates of the natural rate are biased downwards due to the omission of financial factors. By incorporating such factors, my results suggest that – if anything – the LW estimates of the natural rate have a slight upward bias since the turn of the millennium. This is likely due to, on the one hand, overestimation of trend output growth since around 2000, where a marked slowdown was masked by a boom in the credit cycle; and on the other hand, not taking into account the effects of persistent "tailwinds" to the natural rate during 2001-07, a period marked by sustained build-up of financial leverage in the US economy.

Second, strong and persistent headwinds due to financial deleveraging have lowered the conventional natural rate of interest on average by around 1 p.p. below its long-run trend over 2008-14. This might have impaired the effectiveness of interest rate cuts to stimulate the economy and lift inflation back to target immediately after the GFC. The dissipation of these headwinds implies that monetary policy should have regained traction since 2015 as the natural rate of interest rebounded, aligning itself to its long-run component.

Finally, the unobservable variables are estimated imprecisely, a common feature found in related studies using similar methodologies. Uncertainty is particularly large around the estimates of

[7] Adalid and Detken (2007) provide additional evidence that inflation is on average weak during asset booms based on examination of boom/bust episodes in US and OECD data.

[8] See Holston et al. (2017), Johannsen and Mertens (2016), Kiley (2015), Laubach and Williams (2016), Lubik and Matthes (2015), Pescatori and Turunen (2016).

the finance cycle, but the results for the natural rate of interest are not overly sensitive to alternative financial cycle proxies.

The rest of the paper is organised as follows. Section 2 describes the empirical framework. Section 3 discusses estimation method and results, while Section 4 turns to the estimates for the unobservable variables. Section 5 examines sensitivity of the results. Section 6 concludes.

2 The model

The empirical framework extends the Laubach and Williams (2003) model in a way that allows financial imbalances to play a role.

2.1 Trend-cycle decomposition of output

I will start by assuming that output in every period can be decomposed into a trend and a cycle.

$$y_t = y_t^{*fn} + \underbrace{\tilde{y}_t + \gamma\tilde{c}_t}_{\tilde{y}_t^{fn}} \tag{1}$$

The cycle is defined in the broader sense of a "finance-neutral" output gap $\tilde{y}_t^{fn}$, in the spirit of Borio et al. (2017). It consists of two components, (1) a conventional output gap $\tilde{y}_t$ which enters into the Phillips curve and determines inflation dynamics, which I will call "inflationary" gap; and (2) a contribution from the financial cycle $\gamma\tilde{c}_t$, which is assumed to be neither inflationary nor deflationary. In line with empirical evidence of different periodicity between the two cycles, the inflationary output gap and the financial cycle are not synchronised. This means that there will be periods in which positive inflationary gaps could co-exist with lack of financial imbalances, and the other way around. For this reason, the broader measure of the "finance-neutral" output gap is modelled as the sum of two underlying cycles.

The "finance-neutral" trend output y_t^{*fn}, the counterpart to the broadly defined output gap $\tilde{y}_t^{fn}$, is interpreted as the level of sustainable economic activity that would prevail in the absence of price pressures (consistent with a closed inflationary gap) and absence of imbalances in the financial sector. In line with Laubach and Williams (2003), I assume that trend output follows an I(2) process, which allows for permanent shocks to affect both its level and its growth rate.

$$y_t^{*fn} = y_{t-1}^{*fn} + g_{t-1} + \varepsilon_{4t} \tag{2}$$

$$g_t = g_{t-1} + \varepsilon_{5t} \tag{3}$$

Following equation 1, the inflationary ("conventional") gap equals the broader output gap less the contribution from the financial cycle, $\tilde{y}_t = \tilde{y}_t^{fn} - \gamma\tilde{c}_t$. The level of inflation-neutral output corresponding to this gap is[9]

[9]Since price dynamics are determined by the narrow inflationary output gap, the contribution from the

$$y_t^* = y_t^{*fn} + \gamma \tilde{c}_t \quad (4)$$

Hence the contribution of the financial cycle drives a time-varying wedge between the two levels of trend output, the sustainable one y_t^{*fn} and the inflation-neutral one y_t^*. To gain some intuition, imagine a period of overheating in the financial cycle which has boosted economic activity above the sustainable level y_t^{*fn}. Consequently, the contribution of the financial cycle to the broader gap $\gamma \tilde{c}_t$ is positive. By assumption, this contribution is not inflationary, which means that the level of inflation-neutral output is exceeding the level of sustainable output by the same amount of $\gamma \tilde{c}_t$. The wedge between the two is mean-reverting and is proportional to the financial cycle. At this point it is useful to define the growth rate of the inflation-neutral output. By differencing equation 4, it follows that this growth rate is equal to the sum of g_t, the smoothed growth rate of finance-neutral trend output y_t^{*fn}, and changes in the contribution of the financial cycle to the broader gap:

$$g_t^{in} = g_t + \gamma \Delta \tilde{c}_t \quad (5)$$

Periods of leveraging (increases in the financial cycle gap) will imply faster growth in inflation neutral output relative to sustainable output ($g_t^{in} > g_t$). The opposite will be true for periods of deleveraging (declines in the financial cycle gap). The difference between the two growth rates will be mean-reverting but potentially persistent, given the length of the financial cycle or the alteration of leveraging and deleveraging cycles. We could think of this difference as financial headwinds/tailwinds, which temporarily boost or drag the growth of inflation-neutral output above or below sustainable growth.

The financial cycle $\tilde{c}_t$, defined as deviations of financial sector developments from a sustainable trend, is derived endogenously inside the model. Financial sector dynamics are proxied by real credit to the private non-financial sector. The trend in real credit is modelled as follows:

$$c_t^* = 2c_{t-1}^* - c_{t-2}^* + \varepsilon_{7t} \quad (6)$$

This is equivalent to an I(2) process where errors to the level of the trend in credit are set to zero, while the growth of the trend follows a random walk. The loading of the financial cycle into the broader output gap γ is also estimated freely inside the model.

2.2 Defining the natural rate of interest

The natural interest rate (r_t^*) is defined as the rate that closes, over time, the inflationary output gap $\tilde{y}_t$ and is consistent with price stability.

The natural rate of interest is modelled as a function of economic fundamentals, in line with theory. It is linked to the growth rate of the inflation-neutral potential output and an unobserved component z_t, which captures other determinants of the natural interest rate such as rate of

financial cycle $\gamma \tilde{c}_t = y_t^* - y_t^{*fn} = \tilde{y}_t^{fn} - \tilde{y}_t$ is equivalent to a cost-push shock in a Phillips curve when the broader "finance-neutral" output gap is used as an explanatory variable.

time preference.

$$r_t^* = cg_t^{in} + z_t = \underbrace{cg_t + z_t}_{long-run} + \underbrace{c\gamma\Delta\tilde{c}_t}_{headwinds} \tag{7}$$

One important question is whether to link the natural rate of interest to the growth rate of the broader "finance-neutral" output trend, or of the more narrowly defined "inflation-neutral" output. Since the natural rate here is the one that closes the inflationary gap in the IS equation, the theoretically consistent link is to the growth rate of the corresponding inflation-neutral output g_t^{in}.[10] From the definition of g_t^{in} it follows that the natural rate of interest could also be decomposed into a component linked with sustainable trend growth g_t and one linked with financial headwinds/tailwinds to growth, plus the z_t process. Assuming that z_t follows a random walk

$$z_t = z_{t-1} + \varepsilon_{3t} \tag{8}$$

one could define alternatively r_t^* as the sum of a permanent and a transitory, but persistent component. The permanent component can be interpreted as the "long-run" natural rate of interest r_t^{*lr}, being the sum of two I(1) processes $(cg_t + z_t)$; the r_t^* defined in equation 7 instead refers to a "short-run" concept as it includes financial headwinds/tailwinds, which lead to persistent but stationary deviations around the long-run natural rate.[11]

2.3 Measurement equations

The measurement block of the model consists of four equations. The first is a reduced-form IS equation which links the inflationary output gap ($\tilde{y}_t = \tilde{y}_t^{fn} - \gamma\tilde{c}_t$), to the interest rate gap, allowing for some persistence. While this specification is very similar to the LW model, my concept of the inflationary gap allows for the influence of the financial cycle on the "sustainable" output gap to be freely estimated. As such, this version of the IS equation captures the role of the financial cycle in output gap determination, as in Borio et al. (2017) and Kiley (2015).

$$\tilde{y}_t = a_1\tilde{y}_{t-1} + a_2\tilde{y}_{t-2} + \frac{a_3}{2}(r_{t-1} - r_{t-1}^*) + \frac{a_3}{2}(r_{t-2} - r_{t-2}^*) + \varepsilon_{1t} \tag{9}$$

The second equation is a Phillips curve which explains the dynamics of inflation by its own lags, long run expected inflation, a lagged measure of resource utilisation gap and cost-push factors (relative oil and import price inflation). The addition of inflation expectations improves

[10] See Galí (2008) for a distinction between the natural interest rate r_t^* consistent with natural output and price stability which is shown to be a function of expected growth in natural output (i.e. inflation-neutral), and the efficient interest rate r_t^{*e} which stabilises output at its efficient level y_t^{*e} and is a function of the corresponding expected growth of efficient output, which is not necessarily an inflation-neutral one.

[11] The distinction between short-run and long-run natural rate is conceptually appealing and has been emphasised in recent speeches by US Federal Reserve Chair Janet Yellen. An example can be found in her remarks on normalising monetary policy in March 2015, where Yellen (2015) argues that the equilibrium rate may have declined temporarily below its normal long-run level due to persistent headwinds to the recovery from factors such as household balance sheets adjustment, tighter underwriting standards and restricted access to credit.

the plausibility of gap estimates[12] and is supported by theory and empirical evidence.[13] The gap measure refers to unemployment gap $\tilde{u}_t = u_t - u_t^*$, defined in terms of deviation of the unemployment rate from the non-accelerating inflation rate of unemployment (NAIRU). Using the unemployment gap instead of the output gap resulted in a more efficient identification of the relationship between the business cycle and price dynamics in the US economy.

$$\pi_t = b_1\pi_{t-1} + \frac{b_2}{3}\sum_{j=2}^{4}\pi_{t-j} + (1-b_1-b_2)E_t\pi^{lr} + b_3\tilde{u}_{t-1} + b_4(\pi_{t-1}^o - \pi_{t-1}) + b_5(\pi_t^i - \pi_t) + \varepsilon_{2t} \quad (10)$$

The unemployment gap is linked to the inflationary output gap via a dynamic version of Okun's law. The specification assumes that there is a common cycle between the two, in line with Basistha and Startz (2008) which point to improved efficiency in gap estimates by combining information from output and labor-market indicators. Also, the specification excludes an error term since preliminary estimates found the variance of the error term to be zero and highly insignificant.[14]

$$\tilde{u}_t = f_0\tilde{y}_t + f_1\tilde{y}_{t-1} + d_1\tilde{u}_{t-1} + d_2\tilde{u}_{t-2} \quad (11)$$

At this stage I open a bracket to specify the last trend in the transition block. The natural rate of unemployment is assumed to follow a random walk without a drift.[15] Laubach (2001) argues that this specification captures well the dynamics of NAIRU in the United States.

$$u_t^* = u_{t-1}^* + \varepsilon_{8t} \quad (12)$$

The fourth measurement equation specifies the financial cycle gap as a function of its own lags and lags of the interest rate gap. In addition, I allow for corporate credit spreads to play a role. The equation follows Rungcharoenkitkul (2015), who provides a justification for this set-up via a theoretical model of credit booms with bank competition where the latter is proxied empirically with credit spreads.

[12] In the LW model, the output gap is extracted with the help of an "accelerationist" Phillips curve without expectations. Updated estimates of LW output gaps since the Global Financial Crisis have been criticised for showing an overly optimistic cyclical position of the US economy compared to production-function approaches, which might be due to this factor. This affects the plausibility of the estimates of the natural rate of interest, as they are closely tied to the estimated position of the business cycle. I will show later that the empirical framework in this paper results in output gaps which, relative to updated LW output gaps, are more strongly correlated with production-function based estimates from the Congressional Budget Office.

[13] Blanchard et al. (2015) argue that long-run inflation expectations – a proxy for the central bank's target – matter for the Phillips curve and have grown more important since around 1995, leading to a shift from an "accelerationist Phillips curve", in which the unemployment gap or the output gap lead to a change in inflation, to something closer to a "level Phillips curve", in which the gap is associated with a level of inflation.

[14] The specification of a dynamic Okun's law without an error term effectively assumes that unemployment gap shocks are adequately described by contemporaneous and lagged shocks to the inflationary output gap $\tilde{y}_t$. The results from Basistha and Startz (2008) favour the use of such a "single gap" specification over "multiple gap" models which, in the present setup, would imply the use of separate error terms for the inflationary output gap $\tilde{y}_t$ and the unemployment gap $\tilde{u}_t$.

[15] This specification is supported by alternative versions of the model in which the random walk in equation 12 was allowed to include a deterministic or stochastic trend. In the first case, the constant capturing a deterministic trend was insignificant. In the second case, a median unbiased estimate for the variance of the error in the stochastic trend process was zero, rejecting a specification for the NAIRU as an I(2) process.

$$\tilde{c}_t = c_1\tilde{c}_{t-1} + \frac{c_2}{3}\sum_{j=2}^{4}\tilde{c}_{t-j} + \frac{c_3}{2}(r_{t-1} - r^{*lr}_{t-1} + s_{t-1}) + \frac{c_3}{2}(r_{t-2} - r^{*lr}_{t-2} + s_{t-2}) + \varepsilon_{6t} \quad (13)$$

The persistence in the gaps is modelled on the basis of the significance of the last lag and formal statistical tests (Box-Pierce) for autocorrelation in the errors.

2.4 Bridging the empirical framework to structural models

This section shows how key assumptions in my empirical framework, that depart from the standard LW set-up, can be justified by looking at qualitatively similar outcomes from micro-founded DSGE models. By expanding the framework with financial imbalances, I had made a key assumption of defining a broader concept of output gap that could be decomposed in two components, an inflationary component and a non-inflationary one, the latter being identified through the financial cycle.

To explain this reasoning, let us take for example the Christiano, Motto and Rostagno (2014) (henceforth: CMR) DSGE model with financial frictions. In this model, structural risk shocks are shown to produce procyclical movements in credit, output and inflation, and countercyclical movements in credit spreads. Such risk shocks are identifiable only through the inclusion of financial variables (such as credit), and are found to be the most important driver of business cycle fluctuations in the United States over the past several decades. This is coherent with my assumption that the credit cycle contains relevant information for informing the business cycle.

Next, to understand the decomposition of the broader output gap, it is useful to compare the impulse response functions to a risk shock in the CMR (2014) model under nominal rigidities and financial frictions with the same model, but under flexible prices (see Figures C.1 and C.2 in Appendix C).[16] Under nominal rigidities, higher risk leads to an increase in credit spreads and a decline in credit. This, in turn, lowers investment and output and leads to reduced inflation. Under flexible prices, output still declines below the steady-state but less so than in the previous scenario, while after an initial adjustment, inflation is zero (see panel G in Figure C.2). By analogy, we can interpret the dynamics in output under nominal rigidities as corresponding to my concept of broader finance-neutral output gap $\tilde{y}_t^{fn}$. The assumption that only a fraction of this decline is inflationary is inferred from output declining also under the flexible price setup, where by definition the inflationary output gap is closed. Hence the decline in output under the flexible prices tracks only the non-inflationary component of the output gap. My assumption that this component is adequately captured by a fraction of the credit gap ($\gamma\tilde{c}_t$) is supported by credit remaining procyclical under this scenario (panel B in Figure C.2). The inclusion of the credit gap in my model can be seen as a proxy for tracking time-varying risk in the CMR model or more broadly for tracking the non-inflationary component of the business cycle linked to financial imbalances. Obviously, the difference between the output gaps in Figure C.1 and in Figure C.2 would correspond to the "inflationary" component of output $\tilde{y}_t$.

[16] Figure C.1 in Appendix C shows the dynamic response of variables to an unanticipated shock in risk and to a two-year ahead anticipated shock in the CMR model. The figure reproduces Figure 2 from the CMR (2014) paper under the baseline model with nominal rigidities and financial frictions, with the exception that I have replaced the bottom left panel to show the dynamics of inflation. Figure C.2 in Appendix C reproduces the same simulation as in Figure C.1, but this time assuming flexible prices and wages in the CMR model.

Another useful example is given by Furlanetto et al. (2014), who derive the path of the historical output gap in the United States from a DSGE model with financial frictions. By acting as a new source of inefficiencies affecting the frontier of the economy, financial frictions enrich estimates of potential output and similarly to CMR (2014), are found to account for a large portion of output fluctuations. The authors construct a time varying measure of financial frictions as the difference between the output gap in a model with financial frictions and the output gap from the same model without financial frictions, and show that this measure is highly correlated with external indices of financial conditions based on credit or spreads. Thus their contribution is also supportive of my use of the financial cycle ($\gamma\tilde{c}_t$) to inform estimates of the broader output gap. In a nutshell, DSGE models with financial frictions are consistent with output gaps that could account for imbalances that are broader than inflationary ones.

As regards the natural interest rate, a second key assumption is the introduction of a short-term concept which allows for temporary but persistent deviations from the long-run rate due to financial headwinds and tailwinds to growth. Eggertsson and Krugman (2012) show, within a general equilibrium framework, how a tightening in the access to credit and private sector deleveraging may push down the natural rate of interest in the short-run. Similarly, Benigno et al. (2014) extend the standard New Keynesian model with dynamic deleveraging and derive an expression for an endogenous natural rate affected by private indebtedness. Modern DSGE models such as the FRBNY DSGE model featuring financial frictions as in Del Negro et al. (2015) find financial tailwinds to be the main driver of the natural rate in the short-term.[17]

3 Estimation method and results

By writing the model from the previous section in state-space form (see Appendix A), the parameters can be estimated by maximum likelihood using the Kalman filter. The procedure allows to jointly estimate the unobservable natural rates of output, interest and unemployment as well as the sustainable trend growth rate of the US economy. The data (described in Appendix B) is at quarterly frequency and spans the period 1961Q1-2016Q1. The estimation method follows Laubach and Williams (2003) in dealing with the pile-up problem, filter initialisation, and the computation of uncertainty around the unobservable states.

One common estimation issue is the so-called "pile-up problem", discussed in Stock (1994). This problem suggests that when the variation in the trend component is small compared to the overall variation in the series, maximum likelihood estimates of the signal-to-noise ratio are likely to be biased towards zero. In the present set-up, the pile-up problem is likely to affect the estimates of the standard deviations of the innovations to the output trend growth (ε_{5t}), to the credit trend growth (ε_{7t}), and to the z_t component of the natural rate of interest (ε_{3t}). To deal with this problem, I use the Stock and Watson (1998) median unbiased estimator to obtain estimates of the ratios $\lambda_g = \sigma_5/\sigma_4$, $\lambda_z = a_3\sigma_3/\sqrt{2}\sigma_1$ and $\lambda_k = \sigma_7\sqrt{1+c_1^2+c_2^2/3}/\sqrt{2}\sigma_6$. For this purpose, the model is estimated in three sequential steps as described in Laubach and Williams

[17] For a decomposition of the natural rate of interest from the FRBNY DSGE model showing that financial (and to a lesser extent) productivity shocks are the main drivers of r^*, see "Measures and Policy Applications of the Equilibrium Neutral Real Interest Rate", 2016 PBOC-FRBNY Joint Symposium, available at https://www.newyorkfed.org/medialibrary/media/research/economists/delnegro/delnegro_frbnydsge_pboc.pdf.

(2003), with the only difference being the addition of the ratio λ_k alongside λ_g after the first step.[18] The three ratios are then imposed in the final step when the remaining parameters of the model are estimated by maximum likelihood.

In initialising the parameters to be estimated, I use preliminary estimates of the output and unemployment gaps by assuming a segmented trend for the corresponding levels of sustainable output and the NAIRU, plus an auxiliary regression of the output gap on the financial gap to gain an initial estimate of the inflationary gap. The nonstationary processes in the state vector for the first period in the Kalman filter are initialised with the GLS method proposed by Harvey (1989).[19]

Confidence intervals and corresponding standard errors around the estimates of the states take into account both filter and parameter uncertainty. The computation is based on Hamilton's (1986) Monte Carlo procedure and is the same as the one used in Laubach and Williams (2003) and more recently in Holston et al. (2017). The simulations draw parameters from a normal distribution with the covariance matrix of the parameter vector computed by the outer product of the gradients, and initialise the state vector each time drawing from a normal distribution with a mean and covariance given by the smoothed estimate of the initial state and its covariance matrix. Similar to Holston et al. (2017), during the simulation draws I impose a mild constraint that $c_3 < 0$ in equation 13.

Table 1 shows the estimated parameters of the system. Starting with the IS curve, the coefficient γ which determines the contribution of the financial cycle to the broader "finance-neutral" output gap is positive and statistically significant. Its estimate implies that a 10 percentage point positive financial cycle gap is associated with output being 1.9 percentage points above its sustainable trend. The result nods in support of the conclusions of Borio et al. (2017), Arseneau and Kiley (2014) and Berger et al. (2015) that proxies for financial imbalances contain useful information for estimating the business cycle. The coefficient a_3 which measures the interest rate gap sensitivity of output, is highly significant and negative. Its estimated value (-0.086) falls within the ranges reported in earlier studies.[20]

In the Phillips curve equation, a major point of interest is the parameter that links resource utilisation to inflation dynamics. While in Laubach and Williams (2003) this parameter is weakly

[18] In analogy to λ_g which refers to the IS equation 9, the λ_k ratio is based on a test statistic for an intercept shift at unknown date in the financial gap equation 13. Under the constraints I impose on the estimated coefficients, λ_k is the ratio of $\sigma_7\sqrt{1 + c_1^2 + c_2^2/3}$ to $\sqrt{2}\sigma_6$.

[19] The GLS method proposed by Harvey (1989) consists of using the first n observations, where n is the number of variables in the state vector, in order to form an estimate of the initial values of the nonstationary processes in the Kalman filter and the corresponding covariance matrix. Since initial conditions are a function of the parameter values, certain parameter draws render an ill-conditioned covariance matrix which makes the GLS method fail. As in Laubach and Williams (2003), the GLS method fails invariably in the third estimation step. In this case, I follow their approach of initialising y_t^{*fn}, g_t and u_t^* on the basis of the estimated segmented trends, while z_t is initialised at 0 and c_t^* from an HP filter with a smoothing parameter λ of 400,000. The covariance matrix of the initial state vector in these cases is computed as discussed in Laubach and Williams (2003).

[20] In the original Laubach and Williams (2003) study, the corresponding a_3 parameter is estimated to be -0.098 in their baseline and to fall in the range [-0.063 to -0.122] under several alternative specifications. The baseline LW estimate declined to -0.058 for the updated dataset until 2015Q4, as reported in Holston et al. (2017) that, in turn, report an estimate of -0.071 under a slightly modified LW model specification for the United States. Alternative empirical estimates fall in the range of [-0.076 to -0.126] in Kiley (2015), [-0.05 to -0.06] in Pescatori and Turunen (2016), -0.18 in Garnier and Wilhelmsen (2009), [-0.058 to -0.100] in Clark and Kozicki (2005), -0.059 in Juselius et al. (2017). The vast majority of these estimates are highly statistically significant.

Table 1: Parameter estimates

Parameter	Loading on	Estimated value	T-statistic
IS curve ($\tilde{y}_t$)			
$a_1 + a_2$	$\sum_{j=1}^{2} \tilde{y}_{t-j}$	0.938	[13.66 3.41][a]
a_3	$\sum_{j=1}^{2}(r_{t-j} - r^*_{t-j})/2$	-0.086	5.09
γ	$\tilde{c}_t$	0.185	3.72
c	g_t^{in}	1.357	
Phillips curve (π_t)			
$b_1 + b_2$	$\sum_{j=1}^{4} \pi_{t-j}$	0.812	[10.02 5.42][a]
$1 - (b_1 + b_2)$	$E_t \pi^{lr}$	0.188[b]	
b_3	$\tilde{u}_{t-1}$	-0.134	3.27
b_4	$(\pi^o_{t-1} - \pi_{t-1})$	0.003	3.09
b_5	$(\pi^i_t - \pi_t)$	0.031	3.83
Okun's law ($\tilde{u}_t$)			
f_0	$\tilde{y}_t$ (short-run effect)	-0.279	8.77
$(f_0 + f_1)/(1 - d_1 - d_2)$	$\tilde{y}_t$ (long-run effect)	-0.341	
Financial gap equation ($\tilde{c}_t$)			
$c_1 + c_2$	$\sum_{j=1}^{4} \tilde{c}_{t-j}$	0.983	[55.14 17.69][a]
c_3	$\sum_{j=1}^{2}(r_{t-j} - r^{*lr}_{t-j} + s_{t-j})/2$	-0.026	2.00

S.D.		**Ratios**		**S.E. (sample mean)**	
σ_1	0.507	λ_g	0.050	y^{*fn}	1.94
σ_2	0.743	λ_z	0.020	r^* (long-run)	1.32
σ_4	0.422	λ_k	0.001	g	0.30
σ_6	0.499			u^*	0.69
σ_8	0.159			c^*	3.96

[a] T-statistics reported separately for the two parameters.
[b] Constrained parameter.

identified,[21] in the present framework the corresponding parameter (b_3) turns out to be highly significant. This outcome is due to the extension of the LW framework with a labour market block which identifies an unobserved unemployment gap from the Phillips curve, and then links it to the inflationary output gap via the Okun's law.[22] A better identification of the link between resource utilisation and inflation in turn helps reduce uncertainty around the estimates of the unobservable trend output and the natural rate of interest. It should also be noted that the hybrid specification of the Phillips curve assigns a weight of 0.81 to inflation persistence ($b_1 + b_2$) and 0.19 to expected inflation, under the constraint that the sum of the coefficients on lagged and expected inflation is one. As shown in Appendix D, there is no empirical evidence that the

[21] In Laubach and Williams (2003), the corresponding parameter is insignificant at the 5% level for all but one of the seven specifications reported by the authors, including their baseline. The one exception is the LW model augmented with a labour market variable to better identify the output gap. In this case, the authors use detrended private nonfarm employee hours, and report a "dramatic" improvement in the precision of the estimates of the output gap.

[22] It is interesting to note that the estimate of b_3 consistently turned out to be insignificant also in the case of my model estimated without labour market variables, but instead using the inflationary output gap directly in the Phillips curve as a measure of resource utilisation.

credit cycle helps explaining inflation in a statistically significant way.

The results from the Okun's law equation suggest that a change in the inflationary output gap $\tilde{y}_t$ is associated with a change in the opposite direction in the unemployment gap $\tilde{u}_t$, as predicted by theory. The estimated short-run and long-run impact of such a change is close to the one found in Moazzami and Dadgostar (2009) for the United States. As regards the dynamics of the credit cycle, its estimated elasticity (c_3) to the interest rate gap (including spreads) is negative and smaller than the elasticity of the output gap to the "conventional" interest rate gap in the IS curve (a_3). However, accounting for the larger persistence of the financial cycle ($c_1 + c_2$) relative to the output gap ($a_1 + a_2$), the implied long-run effect is about the same.

The lower panel in Table 1 reports the estimated variances in the system. The median unbiased estimate of the ratios λ_g and λ_z imply a fair degree of time variation in sustainable trend output growth g_t and in the long-run component of the natural rate of interest r^*_t. The degree of time variability is broadly similar to the one found for the corresponding processes in the LW model.[23]

The right-hand side of the lower panel in Table 1 reports the sample average of standard errors for the key unobserved variables, based on the two-sided (smoothed) estimates. At first sight, the average error bands around the estimates of trend output, its growth rate and the long-run component of the natural interest rate are tighter than the corresponding values in the original Laubach and Williams (2003) paper. However, the precision of the estimates is comparable to the LW model based on a similar updated sample for the United States. Hence the improvement in uncertainty appears to stem from increased data availability relative to the original LW data vintage, rather than from differences in model specification. The precision of the estimates for the NAIRU is comparable to those reported in Laubach (2001). It should also be noted that the uncertainty around the trend component of credit (and correspondingly, the credit gap) is very large. In a nutshell, even though the unobserved variables are estimated imprecisely, the degree of uncertainty is comparable to the one found in related studies using similar methodologies.[24] These considerations throw a shadow of doubt as regards the reliable use of statistical estimates of the natural rate in practical policy applications – a point emphasised in previous contributions.[25] With these caveats in mind, the next section turns to discuss the estimated historical path for the unobservable variables.

[23]The standard deviation σ_5 of the error term in the process governing sustainable output growth g_t (expressed in annualised terms) equals 0.08 and corresponds to $4\lambda_g\sigma_4$. A comparable value for potential output growth as defined in the LW model falls in the range [0.04 to 0.12]. The standard deviation of the first difference in the long-run component of r^*_t in my model equals 0.20 and corresponds to $\sqrt{c^2\sigma_5^2 + \sigma_3^2}$ where $\sigma_3^2 = 2(\lambda_z \frac{\sigma_1}{a_3})^2$. This corresponds to LW estimates in the range [0.19 to 0.34] for their definition of r^*_t, which is comparable to my long-run concept of r^*_t excluding financial headwinds. The reported ranges of estimates for the original LW model (sample: 1961Q1-2002Q2) and their updated model (sample: 1961Q1-2015Q4) can all be found in a slightly modified version of the LW model in Holston, Laubach and Williams (2017).

[24]It should be emphasised that the standard errors do not account for model uncertainty and uncertainty regarding the ratios λ_g, λ_z, and λ_k. In addition, one-sided estimates which rely only on past data (and thus more similar to the information set available to policy makers), are even more imprecise. Therefore the scale of imprecision around the estimates as reported here should be seen as the lower bound for true uncertainty.

[25]On this point see, among others, Clark and Kozicki (2005) and Beyer and Wieland (2017).

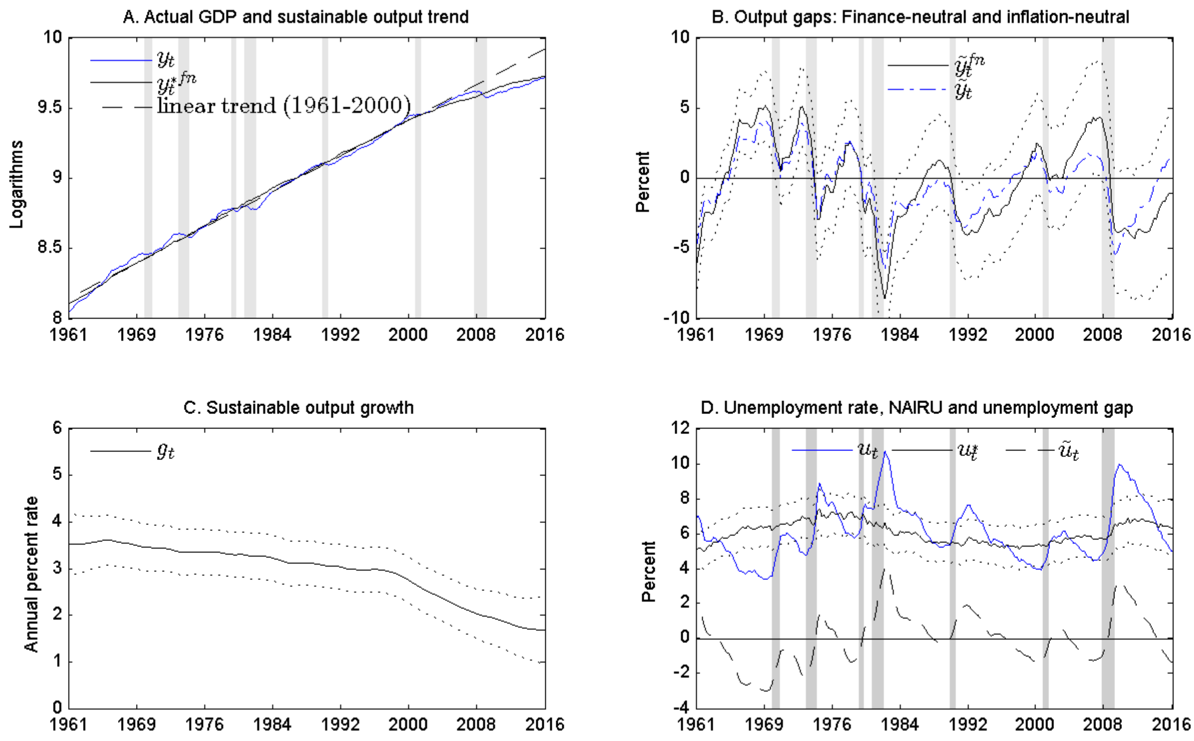
4 Estimates of unobservable variables

Since the natural rate of interest is derived as part of a system, one cannot assess the plausibility of its estimates in isolation. In other words, it is necessary to examine the path of other key unobservable variables that are jointly determined, such as output gaps, trend output growth, etc. For this reason, I will first focus on the estimates of the indicators describing the business cycle, before turning to the natural rate of interest in the second part of this section.

4.1 Business cycle dynamics

The trend-cycle decomposition of output and unemployment derived from the model provides a plausible picture of the business cycle in the United States over the past 55 years (Figure 1). The estimated output and unemployment gaps track well the official expansion and contraction phases of the economy as dated by the NBER (see Panels B and D). In addition, the gradual slowdown in trend output growth in Panel C is consistent with alternative estimates from production function approaches. The trend component of the unemployment rate also appears reasonable and exhibits common characteristic features documented in the literature. These features include a gradual increase up to the late 1970s, followed by a reversal in the next couple of decades and, finally, a modest upturn around the Great Recession (Panel D).

Figure 1: Estimates of cyclical indicators



Note: The dotted black lines show 90% confidence intervals around the estimates represented by solid black lines.

Panel A shows the logarithms of real GDP and the estimated level of sustainable output. The slope of these indicators is hardly distinguishable from a linear trend fitted to actual output over the first four decades of the sample (1961-2000). In other words, one can hardly notice a decline in trend output growth over that period. A slowdown relative to the pre-2000 linear trend, however, is clearly apparent in the latter part of the sample. The model assigns a significant portion of this slowdown to the trend component, which can also be seen in the downward shift in its growth rate around the start of the new millennium (see Panel C). From a more general perspective, this narrative is consistent with the evidence of slowing productivity and population growth in the United States in later years. But there is another factor at play here. The emphasis on a concept of sustainable output penalises the estimates of the trend during periods of unsustainable booms in the financial cycle. From this perspective, it is not surprising that the model associates the build-up of significant financial leverage in the economy after the year 2000 with a lower estimate of sustainable output. As a consequence, a slowdown in the trend component occurs somewhat earlier and is more pronounced in the years leading up to the Global Financial Crisis (GFC), compared to estimates where the trend-cycle decomposition of output focuses more narrowly on price dynamics. The latter type of estimates might have missed the slowdown due to the tame developments in inflation over the pre-crisis period.

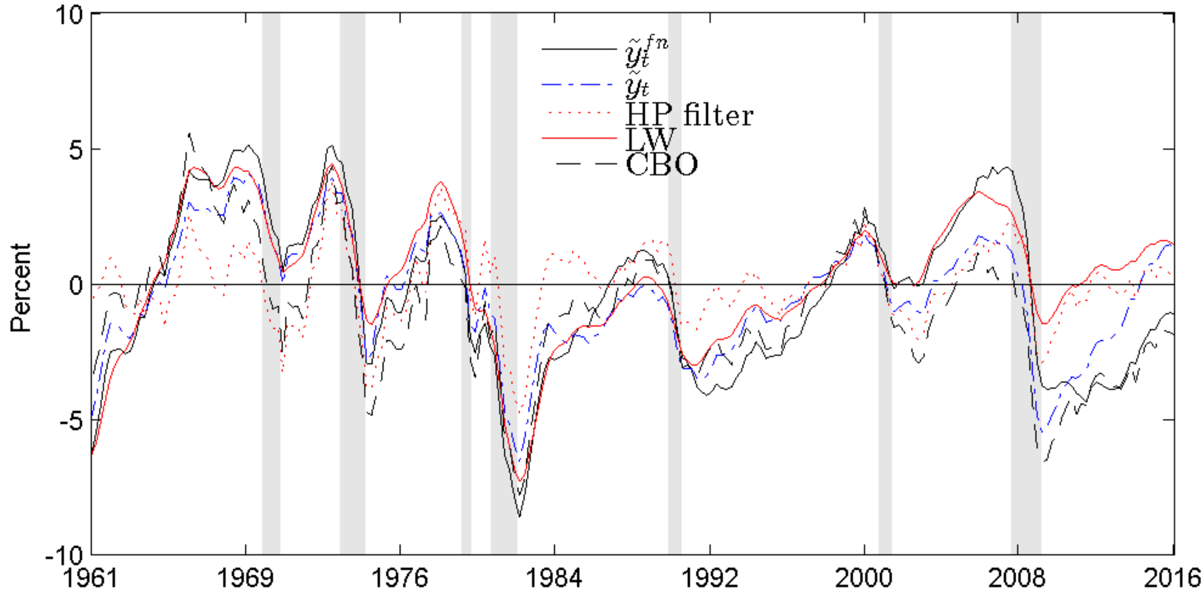
The point is even more apparent when one compares the inflation-neutral with the finance-neutral output gaps in Panel B. The latter concept displays a larger degree of overheating in the economy immediately before the Great Recession. While the finance-neutral output gap peaks at around +4% in 2006-07, the inflation-neutral gap barely exceeds +1.5% around the same period. Following the recession, the finance-neutral gap hovers around -4% from late-2009 to late-2011, before moving back closer to a balanced position by early 2016 (estimated gap: -1.1% in 2016Q1). The path of the inflationary gap in the aftermath of the GFC is somewhat similar, but its trough in the recession is deeper (-5.5% in mid-2009), and followed by a somewhat sharper recovery by the end of the sample.

The difference between the two output gaps over the full historical sample is nuanced. But it becomes more pronounced since the financial liberalisation of the 1980s, which was followed by ever larger swings in the credit cycle. This "gap between the gaps" invites us to reflect in particular on the narrative of the Great Recession in 2007-09. On the one hand, the inflationary output gap provides a more conventional interpretation – starting from an almost balanced position, the economy experienced a deep slump in output, leading to a large negative output gap. The finance-neutral output gap, on the other hand, points to a somewhat different story. It assigns only about half of the actual decline in output to an opening of a negative output gap. Yet another half of the decline is to be seen as a (welcome) correction of an overheated economy with excessive financial leverage, back to its lower sustainable trend. Certainly, this interpretation is not new: recent estimates of a "finance-neutral" notion of the cycle by means of credit-augmented models as in Borio et al. (2017) and Arseneau and Kiley (2014) point to a qualitatively similar picture – namely, they reveal a much larger overheating in the US economy over the 2000-07 period relative to estimates of the cycle coming from traditional approaches.

The finding that high financial leverage is associated with lower trend output is also consistent with studies that estimate supply-side effects from credit booms and busts stemming from resource misallocations in the economy. For instance, the results from Borio et al. (2016) suggest that credit booms tend to undermine productivity growth, as they induce labour reallocations towards lower productivity growth sectors of the economy. To some extent, this reconciles the use of financial cycle proxies in empirical estimates of the business cycle, with production function approaches that emphasise the supply side.

A comparison with external, production-function-based estimates of the US output gap provides further support for the plausibility of the estimated cycle (see Figure 2).

Figure 2: Output gaps: comparison with external estimates



Source: Author's calculations from model's two-sided estimates and from a Hodrick-Prescott (HP) filter with a smoothing parameter $\lambda = 1,600$. Laubach and Williams (LW) model estimates from the Federal Reserve Bank of San Francisco's web site available as of 30 June 2016 (`https://www.frbsf.org/economic-research/files/Laubach_Williams_updated_estimates.xlsx`). Congressional Budget Office (CBO) estimates from "An Update to the Budget and Economic Outlook: 2016 to 2026", August 2016.

For instance, the model-based sustainable output gap tracks rather closely the output gap estimates from the Congressional Budget Office (CBO). Both measures point to the presence of a sizeable and persistent slack in resource utilisation in the aftermath of the Great Recession. By contrast, updated estimates from the LW model show a small and short-lived negative output gap around the same period, with a trough at -1.5% in mid-2009 and a fast reversal to positive territory as early as the second quarter of 2011. The degree of co-movement between different measures of the business cycle is illustrated further in Table 2, which shows a correlation matrix of the various estimates of the US output gap as shown in Figure 2.

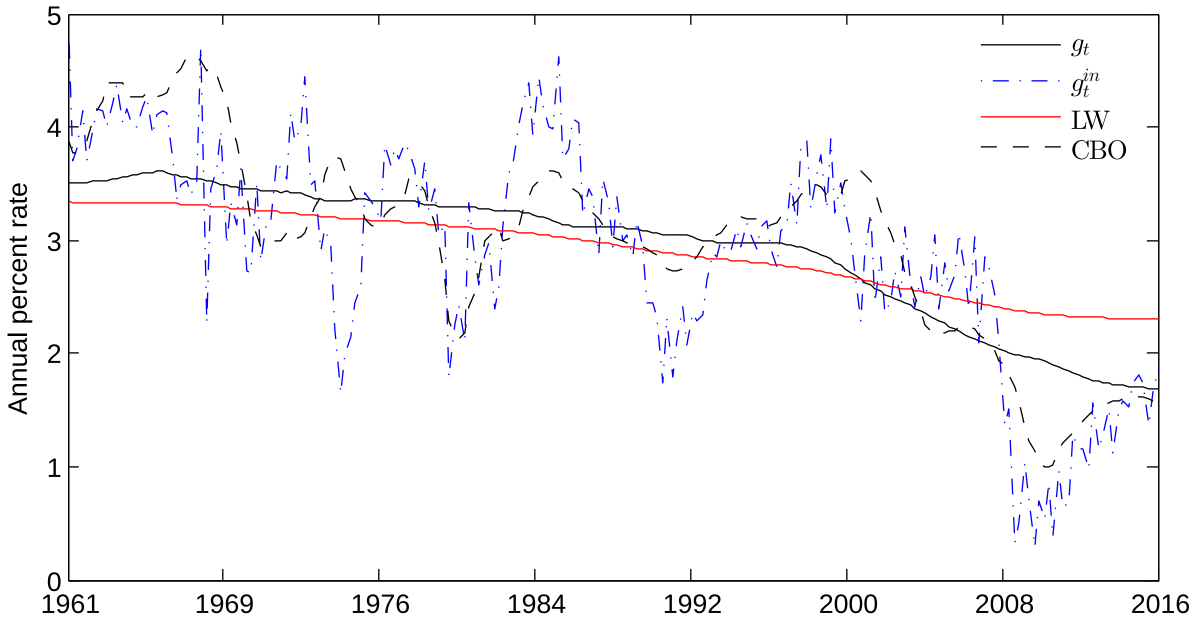
Table 2: Correlations between output gaps

	$\tilde{y}^{fn}$	$\tilde{y}$	HP	LW	CBO
$\tilde{y}^{fn}$	1.00				
$\tilde{y}$	0.92	1.00			
HP	0.61	0.65	1.00		
LW	0.88	0.89	0.59	1.00	
CBO	0.86	0.87	0.75	0.72	1.00

The finance-neutral and inflationary output gaps defined and estimated in this paper exhibit a high co-movement with the production-function-based estimate of the CBO, with correlation coefficients in the order of 0.86-0.87 (see last row of Table 2). With the output gap from the LW model, the correlation drops to 0.72. Generally speaking, the differences could be ascribed to the extensions of the LW model in this paper which affect the estimates of the output gap, namely: (1) incorporating information from the financial cycle in tracking the business cycle; (2) the extension of the LW model with a labour market block which allows to estimate more precisely the cyclical position of the economy using both output and labour market data; and (3) the inclusion of inflation expectations into the Phillips curve equation. All of these elements appear to contribute in the direction of improving the plausibility of business cycle estimates.

Finally, we consider in some more detail the estimates of trend output growth, not least due to its importance for the path of the natural rate of interest. Figure 3 shows the estimates for the annualised growth rates of sustainable output g_t and of inflation-neutral output g_t^{in}, where the latter includes also the effect of financial headwinds and tailwinds to growth. These estimates are compared with potential output growth from the LW model and from the CBO.

Figure 3: Trend output growth: comparison with external estimates



Source: Two-sided estimates from the model. Laubach and Williams (LW) and Congressional Budget Office (CBO) estimates from sources as explained under Figure 2.

As already shown in Figure 1, the growth rate of sustainable output g_t slows from the early 1960s up to present. The decline accelerates in the last 15 years and brings sustainable output growth to 1.7% at the end of the sample – a point estimate which is very close to the CBO's assessment as of 2016Q1.[26] At the same time, the updated estimates from the LW model place US potential growth at almost 2.5% in 2016Q1, an overly optimistic view from the perspective of alternative estimates available today.

[26] Other recent estimates also point to trend output growth of the US economy of slightly below 2% at present. For instance, in September 2016, members of the Federal Open Market Committee saw real GDP growth in the longer-run in the range of 1.7-2.0%, based on the central tendency of participants' views. The OECD estimates that US potential output growth in 2016 stands at 1.6% in their 2016 Economic Survey of United States (`http://www.oecd.org/eco/surveys/economic-survey-united-states.htm`).

Figure 3 also shows that my estimate of sustainable output growth g_t and in particular the LW model estimate display a lower degree of time variation compared to the CBO. This comes from the fact that the Kalman filter and the median unbiased estimate of the ratio λ_g (which governs the variability of trend output growth) tend to "over-smooth" some of the fluctuations visible from a production function perspective. However, my measure of inflation-neutral output growth g_t^{in}, which is conceptually closer to the CBO's traditional perspective of potential output, does appear to pick up some of that additional time variation.[27] My model's interpretation is that sustained periods of leveraging (deleveraging) in the financial cycle provide persistent support (drag) to non-inflationary output growth via the estimated contribution $\gamma\Delta\tilde{c}_t$.

The excessive smoothness of the LW measure, which shares the same inflation-neutral perspective as the CBO and g_t^{in} estimates, poses an important question. Does this measure neglect a "hidden cycle" of persistent headwinds and tailwinds to growth apparent in the other estimates? Looking at the difference between the LW smoothed estimate (shown in Figure 3) and their unsmoothed estimate of trend output growth (which includes on top also innovations to the level of potential output), might provide the answer. In fact, there appears to be a pattern in the LW innovations to the level of potential output associated with the dynamics of the financial cycle (see Figure E.1 and Table E.1 in Appendix E). A clustering of positive innovations occurs during periods of financial leveraging ($\Delta\tilde{c}_t > 0$), and of negative innovations during periods of financial deleveraging ($\Delta\tilde{c}_t < 0$). This pattern is filtered out in the smoothed estimate of trend output growth and not passed on to the LW estimate of the natural rate of interest. By contrast, the innovations to the level of sustainable output (ε_{4t}) estimated here do not exhibit clear patterns of clustering over the various phases of the financial cycle, once its effects are modelled explicitly. More generally, incorporating the financial cycle in the model allows to account for persistent tailwinds and headwinds around sustainable growth, and to estimate their effect on the natural rate of interest in the short term over and beyond its long-run path determined by permanent components.

4.2 Estimates of the natural rate of interest

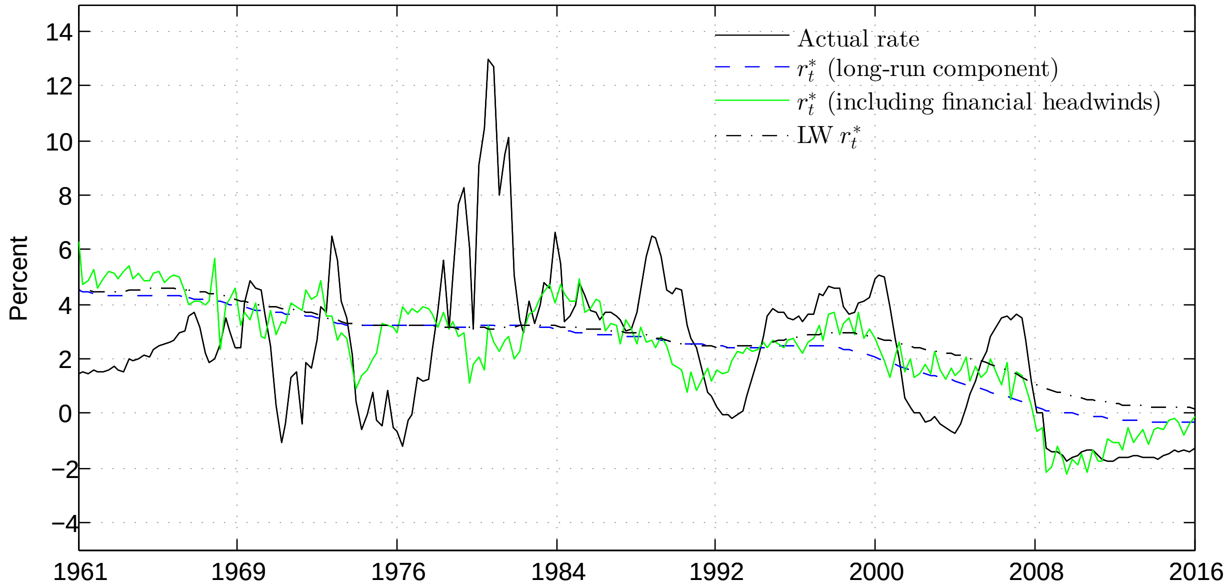
This section discusses the results for the natural rate of interest, as defined in this paper, and compares them with the updated estimates from the Laubach and Williams (2003) model.

The estimated long-run component of the natural rate consistent with price stability (r_t^*) exhibits a sustained decline over time which brings it to -0.35% at the end of the sample (see Figure 4). The decline can be ascribed to both the slowdown in sustainable output growth and to the downward shift in the unobserved component z_t, which captures other determinants of r_t^* such as the rate of time preference. Up to the late 1990s, my long-run r_t^* follows closely the LW estimate which, similarly, targets the slow-moving trend component of the natural rate consistent with

[27] The CBO defines potential output as the level of real GDP in a given year that is consistent with a stable rate of inflation. This resembles the notion of inflation-neutral output in this paper. The CBO uses a production function that explains output in terms of labour, capital, and total factor productivity (TFP). Labour input and TFP are cyclically adjusted in the production function to yield values of potential output. To clean the input factors from the business cycle, the CBO uses an unemployment gap (the difference between the unemployment rate and the NAIRU) estimated from a Phillips curve using the historical relationship between the unemployment rate and changes in the rate of inflation. This assigns an interpretation of the CBO's NAIRU and potential output as, correspondingly, the natural rates of unemployment and output consistent with a stable rate of inflation.

price stability. Thereafter, my estimate shows a more sustained decline, departing from the LW measure, before the two estimates reconcile somewhat towards the end of the sample. This pattern is consistent with my model's estimate of a more pronounced decline in sustainable output growth taking place already some years before the GFC, as described earlier.

Figure 4: Estimates of the natural rate of interest



Source: Two-sided estimates from the model. Laubach and Williams (LW) estimates from sources as explained under Figure 2.

My short-run estimate of r_t^*, shown with the solid green line in Figure 4, incorporates the effects of persistent (but ultimately, cyclical) financial headwinds and tailwinds on top of the long-run component. For instance, over the period of sustained build-up of financial leverage from the mid-1990s up to 2008, seen in almost uninterrupted increases in the credit gap, the short-term natural rate is on average about 1/2 p.p. above its underlying trend component. Such financial "tailwinds" imply that the stance of monetary policy (the difference between the actual and the natural rates of interest) might have been correspondingly more stimulative for inflation than would appear otherwise.[28] By the same token, the deleveraging phase in the aftermath of the 2007-09 recession brings with it sustained "headwinds" to the short term natural rate. This might be capturing some of the headwinds that Janet Yellen, Chair of the US Federal Reserve, has referred to in recent speeches.[29] My model's estimates of such effects result in the short term r_t^* being on average 1 p.p. below its long-run trend from mid-2008 to end-2014, a period commonly associated with active deleveraging in the US economy (see Albuquerque et al. 2015).

The persistent headwinds on the natural rate of interest in the first few years after the GFC

[28] Interestingly, the departure between my long-run component of r_t^* and the LW's measures appears to take place around that extraordinarily long period of financial leveraging in the economy, during which time (up until the Great Recession) the LW measure seems to start tracking more closely my short-term natural rate.

[29] For instance, Yellen (2015) states, "In the wake of the financial crisis, the equilibrium real rate apparently fell well below zero because of numerous persistent headwinds. These headwinds include tighter underwriting standards and restricted access to some forms of credit; the need for households to reduce their debt burdens; [...]. [...] Fortunately, the overall force of these headwinds appears to have diminished considerably over the past year or so, allowing employment to accelerate appreciably even as the level of the federal funds rate and the volume of our asset holdings remained nearly unchanged."

might have hampered the effectiveness of aggressive interest rate cuts in providing stimulus to the economy and lifting inflation back to target. Figure 4 shows that the large reduction in the actual real funds rate by the Fed around 2008 did not necessarily translate into a stimulative stance of policy because during that initial stage, the short-term natural rate declined almost in parallel with the actual rate, remaining below it for some time. According to the narrative of my model, low-interest rate policy should have been gaining more traction as of late. This is because the effects of financial headwinds gradually dissipate towards the end of the sample, allowing the short-run natural rate to re-couple with its long-run counterpart by 2015.

The estimated path for the natural rate of interest presented here is surrounded by considerable uncertainty. Figure E.2 in Appendix E shows the 90% confidence bands around the smoothed (two-sided) estimates that are based on the full sample. For the long-run component of r_t^*, the degree of imprecision around the estimates is large but similar to the comparable r_t^* in the LW model. Exploring uncertainty from a different angle, Figure E.3 compares the smoothed estimates with the filtered (one-sided) estimates, where the latter are based only on current and past observations. The differences between the filtered and the smoothed measures highlight the limited usefulness of the estimates for practical decision making, as they are likely to provide poor guidance in real time.

An additional caveat is that the estimates presented here capture only conventional monetary policy as measured by the observed federal funds rate. Since December 2008, the nominal funds rate has been constrained by the zero lower bound (ZLB) and thus underestimates the additional amount of stimulus provided via unconventional monetary policies (UMP).[30] In principle, one could try to capture the effects of such policies by replacing the observed interest rate with a "shadow" rate, a counterfactual estimate of where the actual rate would have been in the absence of the ZLB constraint. Available estimates of such shadow rates for the US, however, are fraught with uncertainty (see Krippner 2013, Lombardi and Zhu 2014, Wu and Xia 2016). Hence employing such a measure here would "pollute" the results with an additional layer of measurement imprecision from external sources. Another complication is the arbitrariness of choosing a particular external estimate, as the available alternatives depict paths that are far from uniform.[31]

A final point to consider is the uncertainty around the estimated position of the financial cycle over history. My natural rate estimates rely on an endogenous measure of the credit cycle which turns out to be estimated rather imprecisely, as revealed by the large standard errors around c_t^* (see Table 1). I explore this issue in the next section.

[30] After maintaining the reference policy rate for 7 years at the zero lower bound, in December 2015 the Federal Open Market Committee raised the target for the federal funds rate by 0.25 p.p. to a range of 0.25-0.50 percent. The effects of this increase is fully reflected only in the last quarter of my sample period (2016Q1).

[31] Accounting for unconventional policies via such a shadow rate concept, Pescatori and Turunen (2016) report that their estimates of the natural rate of interest decline somewhat further and monetary accommodation is 1-3 p.p. larger during the GFC compared to the results based only on observed real rates. This suggests that for the post-2008 period, estimates that omit the effects from unconventional measures might be underestimating the true degree of policy accommodation and that the natural rate estimates might have an upward bias.

5 Sensitivity analysis

This section examines the sensitivity of the estimates with respect to alternative measures of the financial cycle. Rather than using the endogenous credit gap as done in the baseline, here I employ a set of alternative exogenous credit gaps estimated outside of the model by means of different detrending techniques or using different credit variables. These alternative gaps, treated here as "known" by the system, are then fed to the model in order to re-estimate the parameters and the unobservable variables which are compared to results from the baseline.

5.1 Alternative measures of the financial cycle

I explore alternative proxies across three dimensions: (1) changing the periodicity of the cycle; (2) using alternative detrending methods; and (3) changing the variables used.

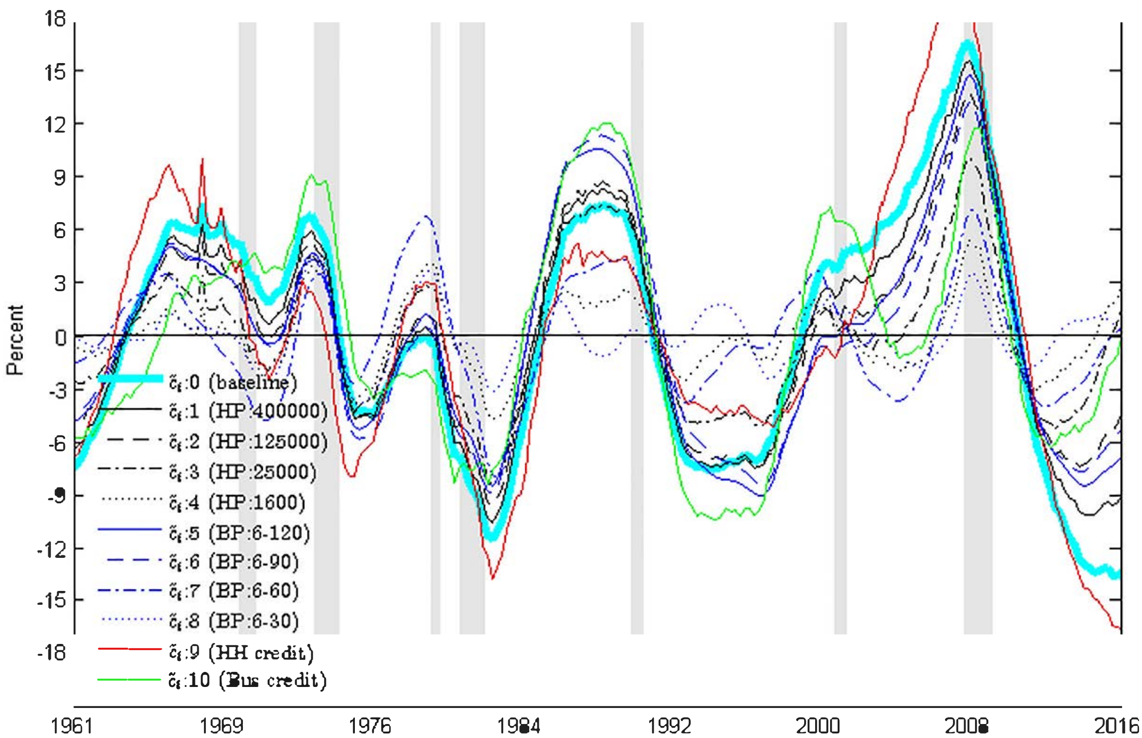
As regards (1), I start by estimating an exogenous financial cycle as proxied by real credit to the private non-financial sector (same variable as in the baseline), detrended with an HP filter using a smoothing parameter $\lambda = 4^4.1,600 \approx 400,000$ corresponding to a periodicity of about four times that of the business cycle. This choice is supported by empirical evidence that the financial cycle is considerably longer than the business cycle, which is typically assumed to have a length of up to about 8 years (corresponding to $\lambda = 1,600$ in the HP filter).[32] Then I decrease the periodicity of the financial cycle by detrending the baseline credit variable with three alternative smoothing parameters in the HP filter, namely $\lambda = 3^4.1,600 \approx 125,000$, $\lambda = 2^4.1,600 \approx 25,000$ and $\lambda = 1^4.1,600 \approx 1,600$. This corresponds to periodicities of three times, two times and one time the length of the business cycle. As for (2), I use the Christiano-Fitzgerald approximate band-pass (BP) filter as an alternative detrending method to the HP filter. The BP filter differs from the HP filter in that it excludes not only the low-frequency trend component from the cycle, but also high-frequency fluctuations that might reflect residual seasonality. I detrend the baseline credit measure by applying four different BP filters capturing periodicity in the range of 6-120, 6-90, 6-60 and 6-30 quarters. The upper bands correspond to periodicity of four, three, two and one-times the usual business cycle length, as with the four HP-detrended measures above. The main difference is that here, the high-frequency fluctuations in the series (with periodicity of less than 6 quarters) are also filtered out. This results in "smoother" gaps compared to those derived from the HP filter. Finally, in (3) I replace credit to the private non-financial sector with two alternative measures (in essence, its underlying components): credit to households and credit to the non-financial business sector.

Altogether, the exercise described in (1)-(3) results in 10 alternative measures for the financial cycle gap relative to the baseline endogenous gap, as displayed in Figure 5. While these gaps

[32] Drehmann et al. (2010) argue that while business and financial cycles are interrelated, financial cycles are typically 3 to 4 times longer than the business cycle. The authors find that the financial cycle is well proxied by the private credit-to-GDP ratio detrended by an HP filter with a smoothing parameter λ of 400,000. The Basel Committee on Banking Supervision (BCBS) recommends using a credit-to-GDP gap computed along these lines as a reliable indicator for tracking excessive credit dynamics in the context of Basel III's implementation of countercyclical capital buffers (see Annex 1 of "Guidance for national authorities operating the countercyclical capital buffer" available at `http://www.bis.org/publ/bcbs187.pdf`). A similar approach is used by Borio and Lowe (2004) and Rungcharoenkitkul (2015). Nonetheless, one caveat of this method and similar detrending procedures is the poor reliability of estimates in real time (see Edge and Meisenzahl 2011).

differ substantially in magnitude, they share common features. One is that essentially all measures point to overheating in the financial cycle in the late 1980s and in the period prior to the Great Recession. Interestingly, both episodes were followed by systemic banking crises as tracked by the database of Laeven and Valencia (2013) – namely the savings and loans crisis initiated in 1988, and the subprime/GFC crisis which started in 2007-08. Another is that periods of recessions (shaded areas) typically correspond to downswings in the financial cycle.[33] This underlines the significance of the financial cycle for tracking resource utilisation gaps in the economy, as documented in the literature and confirmed by my estimates. It is interesting to note that the endogenous financial gap is rather persistent as it resembles the exogenous cycles estimated with the longest implied periodicity, such as the one derived from an HP filter with a smoothing parameter $\lambda = 400,000$.

Figure 5: The financial cycle: baseline and alternative measures



Note: HP and BP correspond to Hodrick-Prescott and Band-Pass filter, respectively. Credit to households (HH credit) and credit to the non-financial business sector (Bus credit) are detrended with an HP-filter using $\lambda = 4^4.1,600$.

Notwithstanding the similarities, one major disagreement between all measures is the position of the cycle at the end of the sample, which can be traced to the well-known end-point problem of filtering techniques. As of early 2016, the estimated financial gap ranges from -17% to +3%. One source of dispersion comes from the frequency of the cycle: filters with shorter implied periodicity show a more positive financial cycle gap at the end of the sample. However, cycles with the shortest periodicity (i.e. matching business cycle frequency; see dotted black and blue lines) go against the empirical evidence on financial cycle length and should be interpreted with

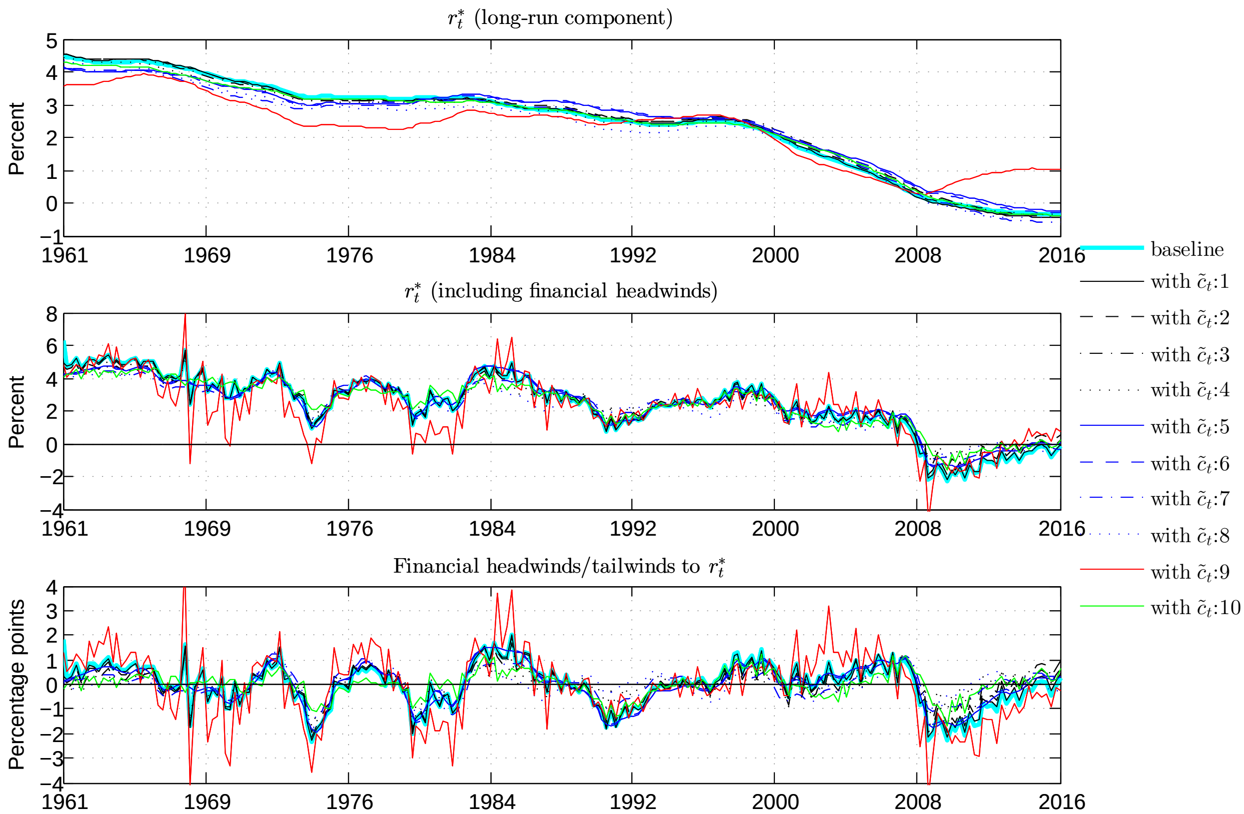
[33] A possible exception is the recession in the early 2000s, where several credit cycles also display a downturn, but others continue their upward swing.

caution as they are likely to contain "false cycles". Another source of dispersion is the underlying measure of credit: even with the same frequency and detrending method (HP filter), the cycle based on business credit indicates a much more positive gap (0%) than based on household credit (-17%) at the end of the sample. This could be explained by the fact that the swings in household indebtedness, both on the upside and on the downside, have been much more pronounced compared to those in corporate indebtedness during the last 15 years.

5.2 Sensitivity of the natural interest rate consistent with price stability

The estimates of the natural interest rate consistent with price stability r_t^* are generally robust with respect to the use of alternative financial cycle proxies in the model (see Figure 6).

Figure 6: The inflation-neutral rate: sensitivity to alternative financial cycle measures



Source: Two-sided estimates from the baseline model re-estimated with different proxies for the financial cycle from $\tilde{c}_t$:1 to $\tilde{c}_t$:10, as explained in the text.

For instance, the smoothed (two-sided) estimates of the trend component of r_t^* (upper panel in Figure 6) fall within a range that is never wider than one percentage point from the beginning of the sample in 1961 up to 2011. This is not surprising, since the inflation-neutral interest rate is meant to close, over time, a conventional output gap which by construction excludes the contribution from the financial cycle ($\gamma\tilde{c}_t$). Towards the end of the sample, the somewhat larger dispersion in the range of estimates is due exclusively to a stronger recovery of the trend component of r_t^* estimated using household credit as a proxy for the financial cycle. As regards the importance of the financial cycle in informing the broader business cycle, the estimates of the loading parameter γ are always positive and fall within a range of 0.11-0.34. They remain highly statistically significant in all specifications except when using the proxy for the financial cycle based on business credit ($\tilde{c}_t$:10), where the estimate is statistically significant only at the 10% level (see Table E.2 in Appendix E).[34] The relative stability of the estimates for the trend component of r_t^* is partly due to the fact that the median unbiased estimates (MUE) of the signal-to-noise ratios λ_g and λ_z, do not appear to be overly sensitive to alternative financial cycle proxies as shown in Table E.3 in Appendix E.

A larger dispersion is displayed for the short-run estimates of r_t^*, shown in the middle panel of Figure 6, as they incorporate financial headwinds and tailwinds ($c\gamma\Delta\tilde{c}_t$) being directly linked with the different proxies for the financial cycle. Nonetheless, the 10 alternative paths for r_t^* look qualitatively similar and fall in a range of -0.75% to +0.75% at the end of the sample.

Interestingly, looking at the pre-GFC period 2001-07, all measures of the long-run component of r_t^* point to a steady decline, while most short-run estimates are relatively stable hovering in a range of approximately 1% to 2%. This could be ascribed to financial tailwinds to r_t^* building as the financial cycle leverages up (see bottom panel of Figure 6). Around 2008, the financial cycle turned from a leveraging into a deleveraging phase. This appears not to affect the long-run r_t^*, which continues its smooth declining path.[35] However, the short-run r_t^* moves abruptly down to negative territory in 2009-10. This occurs because the tailwinds in 2006-07 are quickly reversed into headwinds over 2009-10. Subsequently, as financial deleveraging eases, headwinds gradually subside and become largely neutral by early 2016.[36]

6 Concluding remarks

This paper offers an interpretation and measurement of the natural rate of interest in a constellation where large swings in the financial cycle may affect the business cycle without necessarily destabilising inflation. Financial factors that affect activity may distort the link between interest rate gaps and output gaps and hence bias estimates of the natural rate of interest. By extending the model of Laubach and Williams (2003) to incorporate the financial cycle – arguably an omitted variable from the system – I find that the plausibility of business cycle estimates improves, and the link between resource utilisation gaps and price dynamics is better identified.

One caveat is the high degree of uncertainty around the estimates of the unobservable variables, which limits their usefulness for practical policy applications. This is particularly the case for the endogenous trend-cycle decomposition of the financial cycle, which calls for further research on developing the modelling approach of the financial block and its links with monetary policy.

[34] Using a house prices-based measure of the financial cycle (not reported here) resulted in estimates for the loading parameter of the financial cycle onto the output gap being close to zero and insignificant. This is not surprising as one would expect the explanatory power of the credit gap for the business cycle to be much stronger than the one of the house price gap.

[35] Again, this is the case for the estimates based on all alternative financial cycle proxies but the one using household credit.

[36] More specifically, at present most estimates point to mildly positive tailwinds ranging from 0.25 p.p. to 1.00 p.p. The exceptions are the two scenarios with $\tilde{c}_t$:8 and $\tilde{c}_t$:9, which suggest slightly negative headwinds at the end of the sample (range: -0.25 p.p. to -0.30 p.p.).

Appendix

A The model in state space form

Assume:

$$y_t = y_t^{*fn} + \underbrace{\tilde{y}_t + \gamma\tilde{c}_t}_{\tilde{y}_t^{fn}}; \qquad \tilde{y}_t \sim AR(2)$$

$$r_t^* = cg_t^{in} + z_t = \underbrace{cg_t + z_t}_{r_t^{*lr}} + \underbrace{c\gamma\Delta\tilde{c}_t}_{headwinds}$$

Measurement equations:

$$\tilde{y}_t^{fn} - \gamma\tilde{c}_t = a_1(\tilde{y}_{t-1}^{fn} - \gamma\tilde{c}_{t-1}) + a_2(\tilde{y}_{t-2}^{fn} - \gamma\tilde{c}_{t-2}) + \frac{a_3}{2}(r_{t-1} - r_{t-1}^*) + \frac{a_3}{2}(r_{t-2} - r_{t-2}^*) + \varepsilon_{1t}$$

$$\pi_t = b_1\pi_{t-1} + \frac{b_2}{3}\sum_{j=2}^{4}\pi_{t-j} + (1 - b_1 - b_2)E_t\pi^{lr} + b_3(\tilde{u}_{t-1}) + b_4(\pi_{t-1}^o - \pi_{t-1}) + b_5(\pi_t^i - \pi_t) + \varepsilon_{2t}$$

$$\tilde{c}_t = c_1\tilde{c}_{t-1} + \frac{c_2}{3}\sum_{j=2}^{4}\tilde{c}_{t-j} + \frac{c_3}{2}(r_{t-1} - r_{t-1}^{*lr} + s_{t-1}) + \frac{c_3}{2}(r_{t-2} - r_{t-2}^{*lr} + s_{t-2}) + \varepsilon_{6t}$$

$$\tilde{u}_t = f_0(\tilde{y}_t^{fn} - \gamma\tilde{c}_t) + f_1(\tilde{y}_{t-1}^{fn} - \gamma\tilde{c}_{t-1}) + d_1\tilde{u}_{t-1} + d_2\tilde{u}_{t-2}$$

Transition equations:

$$z_t = z_{t-1} + \varepsilon_{3t}$$

$$y_t^{*fn} = y_{t-1}^{*fn} + g_{t-1} + \varepsilon_{4t}$$

$$g_t = g_{t-1} + \varepsilon_{5t}$$

$$c_t^* = 2c_{t-1}^* - c_{t-2}^* + \varepsilon_{7t}$$

$$u_t^* = u_{t-1}^* + \varepsilon_{8t}$$

where

y_t - log of real GDP

y_t^{*fn} - finance-neutral trend output

$\tilde{y}_t^{fn} = 100(y_t - y_t^{*fn})$ - finance-neutral output gap

$\tilde{y}_t = \tilde{y}_t^{fn} - \gamma\tilde{c}_t$ - conventional (inflation-neutral) output gap

$y_t^* = y_t^{*fn} + \gamma\tilde{c}_t$ - conventional (inflation-neutral) trend output

u_t - unemployment rate

$\tilde{u}_t = u_t - u_t^*$ - unemployment gap

u_t^* - non-accelerating inflation rate of unemployment (NAIRU)

z_t - captures other determinants of the natural interest rate (such as rate of time preference)

$\tilde{c}_t = 100(c_t - c_t^*)$ - credit gap

c_t - log of real credit to the private non-financial sector, deflated with GDP deflator

c_t^* - trend in real credit

g_t - growth rate of finance-neutral trend output

$g_t^{in} = g_t + \gamma \Delta \tilde{c}_t$ - growth rate of inflation-neutral trend output

r_t^* - short-run natural interest rate including financial headwinds/tailwinds (the natural rate that closes non-inflationary output gap $\tilde{y}_t$, or the portion of the finance-neutral output gap which excludes the contribution from the credit cycle ($\tilde{y}_t^{fn} - \gamma \tilde{c}_t$)

r_t^{*lr} - long-run natural interest rate (excluding financial headwinds/tailwinds)

π_t - core PCE price inflation (annualised quarterly growth rate in the PCE deflator ex food and energy)

$E_t \pi^{lr}$ - survey-based measure of long run inflation expectations

π_t^o - crude imported oil price inflation

π_t^i - core import (ex petroleum, computers and semiconductors) price inflation

$r_t = i_t - E_t \pi_{t+1}$- ex-ante real fed funds rate

i_t - annualised nominal fed funds rate

$E_t \pi_{t+1}$ - expectation of average inflation over the four quarters ahead from a univariate AR(3) of inflation estimated over the 40 quarters prior to the date at which expectations are being formed

State space representation:

$$\mathbf{y}_t = \mathbf{Z}\alpha_t + \mathbf{B}\mathbf{x}_t + \mathbf{u}_t \qquad \mathbf{u}_t \sim NID(0, H)$$

$$\alpha_t = \mathbf{T}\alpha_{t-1} + \mathbf{c} + \mathbf{v}_t \qquad \mathbf{v}_t \sim NID(0, Q)$$

$$
\underbrace{\begin{bmatrix} y_t \\ \pi_t \\ c_t \\ u_t \end{bmatrix}}_{\mathbf{y}_t} = \underbrace{\begin{bmatrix}
1 & -a_1 & -a_2 & -\frac{ca_3}{2} & -\frac{ca_3}{2} & -\frac{a_3}{2} & -\frac{a_3}{2} & \begin{matrix} -\gamma \\ +\frac{ca_3}{2}\gamma \end{matrix} & a_1\gamma & \begin{matrix} a_2\gamma \\ -\frac{ca_3}{2}\gamma \end{matrix} & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & -b_3 & 0 \\
0 & 0 & 0 & -\frac{cc_3}{2} & -\frac{cc_3}{2} & -\frac{c_3}{2} & -\frac{c_3}{2} & 1 & -c_1 & -\frac{c_2}{3} & -\frac{c_2}{3} & -\frac{c_2}{3} & 0 & 0 & 0 \\
-f_0 & -f_1 & 0 & 0 & 0 & 0 & 0 & f_0\gamma & f_1\gamma & 0 & 0 & 0 & 1 & -d_1 & -d_2
\end{bmatrix}}_{\mathbf{Z}} \underbrace{\begin{bmatrix} y_t^{*fn} \\ y_{t-1}^{*fn} \\ y_{t-2}^{*fn} \\ g_{t-1} \\ g_{t-2} \\ z_{t-1} \\ z_{t-2} \\ c_t^* \\ c_{t-1}^* \\ c_{t-2}^* \\ c_{t-3}^* \\ c_{t-4}^* \\ u_t^* \\ u_{t-1}^* \\ u_{t-2}^* \end{bmatrix}}_{\alpha_t}
$$

$$
+ \underbrace{\begin{bmatrix}
0 & a_1 & a_2 & \frac{a_3}{2} & \frac{a_3}{2} & 0 & 0 & 0 & 0 & 0 & \begin{matrix} \gamma \\ -\frac{ca_3}{2}\gamma \end{matrix} & -a_1\gamma & \begin{matrix} -a_2\gamma \\ +\frac{ca_3}{2}\gamma \end{matrix} & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & b_1 & b_2 & \begin{matrix} 1 \\ -b_1 \\ -b_2 \end{matrix} & b_4 & b_5 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & b_3 & 0 \\
0 & 0 & 0 & \frac{c_3}{2} & \frac{c_3}{2} & 0 & 0 & 0 & 0 & 0 & 0 & c_1 & \frac{c_2}{3} & \frac{c_2}{3} & \frac{c_2}{3} & \frac{c_3}{2} & \frac{c_3}{2} & 0 & 0 \\
f_0 & f_1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & -f_0\gamma & -f_1\gamma & 0 & 0 & 0 & 0 & 0 & d_1 & d_2
\end{bmatrix}}_{\mathbf{B}} \underbrace{\begin{bmatrix} y_t \\ y_{t-1} \\ y_{t-2} \\ r_{t-1} \\ r_{t-2} \\ \pi_{t-1} \\ \pi_{t-2,4} \\ E_t\pi^{lr} \\ \pi_{t-1}^o - \pi_{t-1} \\ \pi_t^i - \pi_t \\ c_t \\ c_{t-1} \\ c_{t-2} \\ c_{t-3} \\ c_{t-4} \\ s_{t-1} \\ s_{t-2} \\ u_{t-1} \\ u_{t-2} \end{bmatrix}}_{\mathbf{x}_t}
$$

$$
+ \underbrace{\begin{bmatrix} \varepsilon_{1t} \\ \varepsilon_{2t} \\ \varepsilon_{6t} \\ 0 \end{bmatrix}}_{\mathbf{u}_t}, H = \begin{bmatrix} \sigma_1^2 & 0 & 0 & 0 \\ 0 & \sigma_2^2 & 0 & 0 \\ 0 & 0 & \sigma_6^2 & 0 \\ 0 & 0 & 0 & 0 \end{bmatrix}
$$

$$
\underbrace{\begin{bmatrix} y_t^{*fn} \\ y_{t-1}^{*fn} \\ y_{t-2}^{*fn} \\ g_{t-1} \\ g_{t-2} \\ z_{t-1} \\ z_{t-2} \\ c_t^* \\ c_{t-1}^* \\ c_{t-2}^* \\ c_{t-3}^* \\ c_{t-4}^* \\ u_t^* \\ u_{t-1}^* \\ u_{t-2}^* \end{bmatrix}}_{\alpha_t}
=
\underbrace{\begin{bmatrix}
1 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 2 & -1 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0
\end{bmatrix}}_{\mathbf{T}}
\underbrace{\begin{bmatrix} y_{t-1}^{*fn} \\ y_{t-2}^{*fn} \\ y_{t-3}^{*fn} \\ g_{t-2} \\ g_{t-3} \\ z_{t-2} \\ z_{t-3} \\ c_{t-1}^* \\ c_{t-2}^* \\ c_{t-3}^* \\ c_{t-4}^* \\ c_{t-5}^* \\ u_{t-1}^* \\ u_{t-2}^* \\ u_{t-3}^* \end{bmatrix}}_{\alpha_{t-1}}
+
\underbrace{\begin{bmatrix} \varepsilon_{4t} + \varepsilon_{5,t-1} \\ 0 \\ 0 \\ \varepsilon_{5,t-1} \\ 0 \\ \varepsilon_{3,t-1} \\ 0 \\ \varepsilon_{7t} \\ 0 \\ 0 \\ 0 \\ 0 \\ \varepsilon_{8t} \\ 0 \\ 0 \end{bmatrix}}_{\mathbf{v}_t}
$$

$$
Q = \begin{bmatrix}
(1+\lambda_g)\sigma_4^2 & 0 & 0 & \lambda_g^2\sigma_4^2 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
\lambda_g^2\sigma_4^2 & 0 & 0 & \lambda_g^2\sigma_4^2 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 2(\lambda_z \frac{\sigma_1}{a_3})^2 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & \frac{2(\lambda_k\sigma_6)^2}{1+c_1^2+c_2^2/3} & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & \sigma_8^2 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0
\end{bmatrix}
$$

In order to deal with the pile-up problem, the following ratios of variances are fixed in the last estimation stage (having been estimated in earlier stages):

$\lambda_g = \sigma_5/\sigma_4$

$\lambda_z = a_3\sigma_3/\sigma_1\sqrt{2}$

$\lambda_k = \sigma_7\sqrt{1 + c_1^2 + c_2^2/3}/\sigma_6\sqrt{2}$

Parameters to be estimated (22):

$$\theta = [a_1, a_2, a_3, \gamma, b_1, b_2, b_3, b_4, b_5, c, c_1, c_2, c_3, f_0, f_1, d_1, d_2, \sigma_1, \sigma_2, \sigma_4, \sigma_6, \sigma_8]$$

B Data description and sources

The model is estimated on quarterly data for 1961Q1-2016Q1 available as of 30 June 2016. The series (1)-(5) are the same as in the Laubach and Williams model dataset, updated until 2016Q1. The remaining series are new.

(1) y - log of real GDP in billions of chained 2009 dollars. Source: Bureau of Economic Analysis (BEA). Haver code: GDPH@USECON

(2) π - core PCE price inflation as measured by the annualised quarterly growth rate in the PCE deflator excluding food and energy. Source: BEA. Haver code: JCXFE@USECON[37]

(3) π^o - crude imported oil price inflation as measured by the annualised quarterly growth rate in the price deflator for petroleum imports. Source: BEA. Haver code: JMMP@USNA[38]

(4) π^i - core import (ex petroleum, computers and semiconductors) price inflation. Annualised quarterly growth rates of the implicit price deflator for imports of nonpetroleum goods, which after 1967Q1 also excludes the prices of computers and semiconductors[39]

(5) i - nominal federal funds rate expressed as effective annual yield (daily compounded). Source: FRB/US dataset (series code: RFFE) available at https://www.federalreserve.gov/econresdata/frbus/us-models-package.htm[40]

(6) c - log of real credit to the private non-financial sector. Nominal credit to the private non-financial sector is measured by the sum of liabilities of Households and Nonprofit Organizations (Haver code: XL15TCR5@FFUNDS) and liabilities of the Nonfinancial Business sector (Haver code: XL14TCR5@FFUNDS). Source for both series: Federal Reserve Board. Nominal credit is deflated with the GDP deflator from BEA (Haver code: JGDP@USECON)

(7) u - civilian unemployment rate. Source: Bureau of Labor Statistics. Haver code: LR@USECON

(8) $E_t\pi^{lr}$ - 10-year expected PCE price inflation (Survey of Professional Forecasters). Source: FRB/US dataset (series code: PTR)

(9) s - Moody's Baa corporate bond spread over 10-Year Treasury constant maturity. Source: FRED database, Federal Reserve Bank of St. Louis.

[37] Available from 1951Q1. In order to construct the ex-ante real federal funds rate, average expected inflation over the four quarters ahead is computed from a univariate AR(3) model of inflation estimated over the 40 quarters prior to the date at which expectations are being formed. For this purpose, prior to the start of the PCE core inflation series in 1952Q2, inflation data is extended further back in time based on the overall PCE deflator (Source: BEA; Haver code: JC@USECON). The computation of the inflation series and of expected inflation is identical to the one in Laubach and Williams (2003).

[38] Prior to 1968Q1, imported crude oil price inflation is based on the FRB/US index for crude oil imports as this series extends further back in history than the BEA series. Available from the FRB/US model dataset at https://www.federalreserve.gov/econresdata/frbus/us-models-package.htm (series code: POIL).

[39] This series comes from the original Laubach and Williams model dataset (available until 2014Q1). In my sample I update the series for the remaining eight quarters up to 2016Q1 using the growth rates of a proxy for core import prices constructed from publicly available information. This is done by subtracting the implicit deflator for "Imports of goods: Capital goods, except automotive: Computers, peripherals, and parts" (HAVER code: JMMKXP@USNA) from the implicit deflator for nonpetroleum imports (HAVER code: JMMXP@USNA), using a Fisher-ideal chain-type formula to take into account the appropriate weights.

[40] As in Laubach and Williams (2003), I use the Federal Reserve Bank of New York's discount rate (Haver code: FDWB@USECON) instead of the federal funds rate prior to 1965.

C Dynamic responses to unanticipated and anticipated components of a risk shock in the CMR (2014) DSGE model

Figure C.1: Baseline model with nominal rigidities and financial frictions

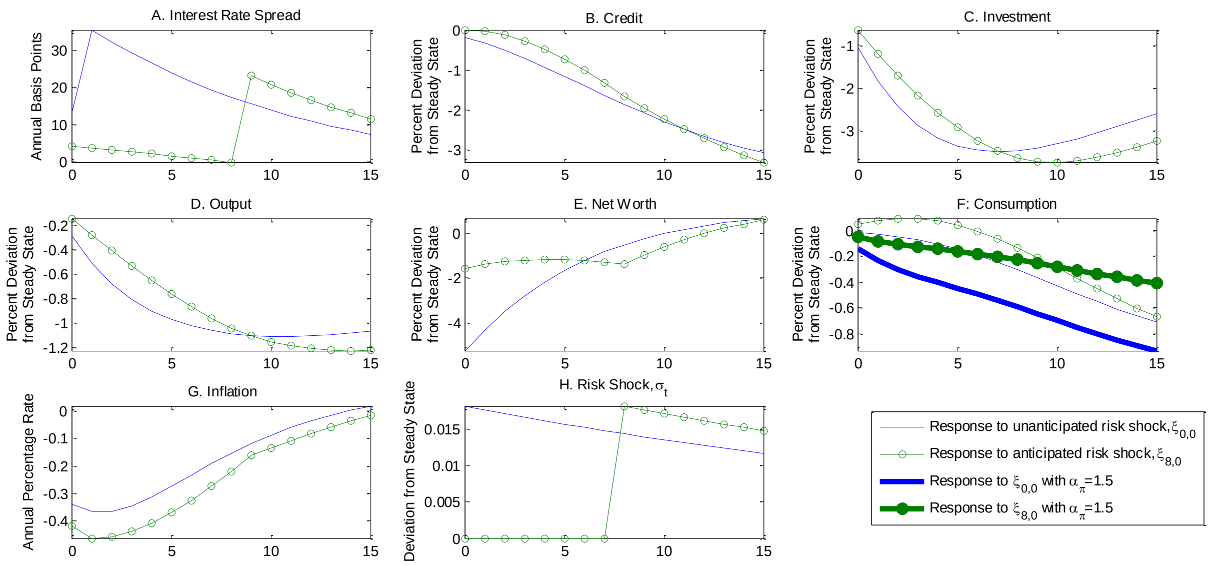
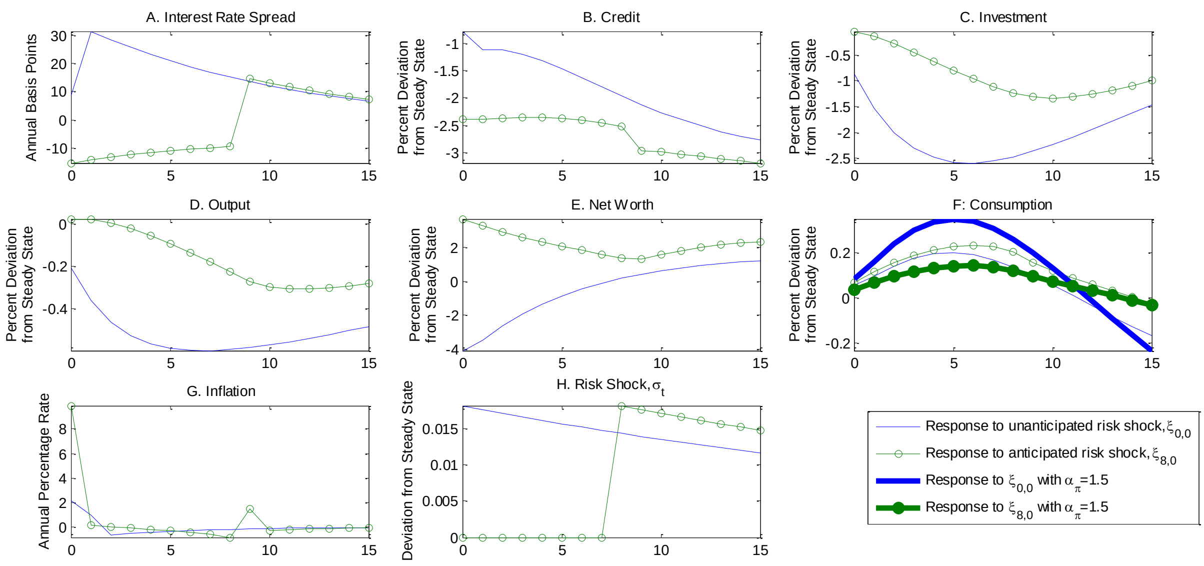


Figure C.2: Baseline, with flexible prices and wages



D Is the credit gap inflationary?

Identifying the credit gap contribution to the output gap via the γ parameter rests on the assumption that this contribution is exogenous to the inflationary component of the output gap. Here I test empirically this assumption by augmenting, compared to the baseline, the Phillips curve equation (eq. 10 in the main text) to include the lagged credit gap as follows:

$$\pi_t = b_1\pi_{t-1} + \frac{b_2}{3}\sum_{j=2}^{4}\pi_{t-j} + (1-b_1-b_2)E_t\pi^{lr} + b_3\tilde{u}_{t-1} + b_4(\pi^o_{t-1} - \pi_{t-1}) + b_5(\pi^i_t - \pi_t) + \varphi\tilde{c}_{t-1} + \varepsilon_{2t}$$

I am interested in the significance of the φ parameter.

I investigate this through a set of exercises, the results from which are reported in Table D.1. First, in Column (2) I extract the two-sided estimates for the unemployment gap $\tilde{u}_{t-1}$ and the credit gap $\tilde{c}_{t-1}$ and, together with the other exogenous variables, I estimate a single-equation Phillips curve as specified above. Second, in Column (3) I augment inside my state space model the Phillips curve with a lagged credit gap. This allows for consistent re-estimation of all parameters and unobserved variables within the system.

Table D.1: Phillips curve parameter estimates (dependent variable: π_t)

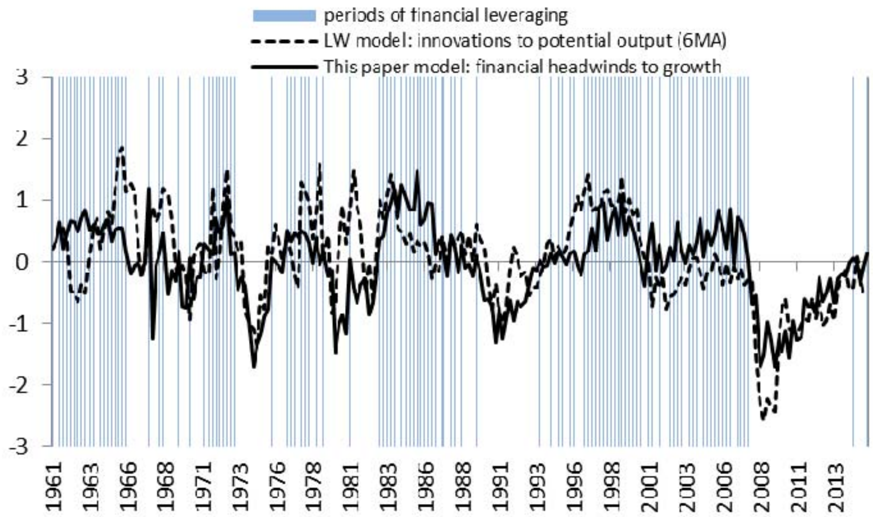
Parameter	Loading on:	(1) Model baseline	(2) Single PC equation	(3) Model altern. spec.
b_1	π_{t-1}	0.502	0.490	0.502
		(10.02)	(7.33)	(9.91)
b_2	$\sum_{j=2}^{4}\pi_{t-j}/3$	0.310	0.300	0.310
		(5.42)	(4.06)	(5.32)
b_3	$\tilde{u}_{t-1}$	-0.134	-0.155	-0.139
		(3.27)	(4.01)	(3.20)
b_4	$\pi^o_{t-1} - \pi_{t-1}$	0.003	0.003	0.003
		(3.09)	(2.52)	(3.12)
b_5	$\pi^i_t - \pi_t$	0.031	0.030	0.032
		(3.83)	(2.95)	(3.82)
φ	$\tilde{c}_{t-1}$		-0.002	-0.003
			(0.23)	(0.28)

Note: The table reports coefficients for the baseline and augmented Phillips curve equations. Absolute value t-statistics in parenthesis. Column (1) is the baseline model specification. Column (2) is a single-equation Phillips curve estimated outside of the model augmented with a lagged credit gap, using two-sided estimates for the unemployment gap and the credit gap from the baseline. Column (3) shows results from a re-estimated model where, compared to the baseline, the Phillips curve equation has been modified to include also a lagged credit gap.

T-statistics in Table D.1 (in brackets) show that the credit gap alone has no influence on inflation and hence is not connected in a statistically significant way with the inflation-relevant cycle - see last row of Columns (2) and (3). This result is confirmed by additional specifications (not reported here) when the credit gap enters either contemporaneously or with two lags in the Phillips curve; when the unemployment gap is excluded; or when the unemployment gap is replaced by the output gap in the Phillips curve. The estimates for the other parameters are robust to these alternative specifications. Overall, the lack of statistical significance of the parameter loading on the credit gap in the Phillips curve is supportive for my assumption that the contribution from the credit gap to the output gap is non-inflationary.

E Additional tables and figures

Figure E.1: Innovations to potential output vs financial headwinds to growth



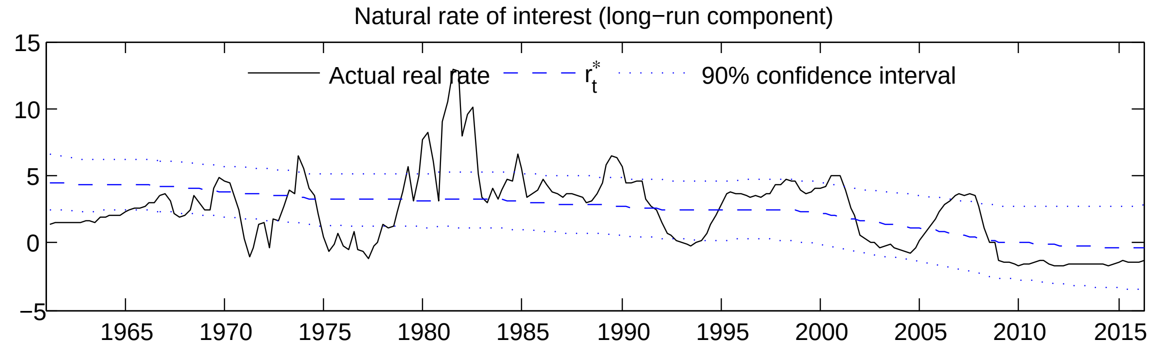
Note: Computations based on smoothed (two-sided) estimates of unobservable variables. Innovations and contributions to growth variables in annualised terms. The blue shaded area represents periods of financial leveraging, i.e. periods in which changes in the credit gap ($\Delta\tilde{c}_t$), as defined in this paper, are positive. LW model estimates from the FRB of San Francisco website available as of 30 June 2016.

Table E.1: Innovations to potential output vs financial headwinds to growth

Period	quarters	lev=1, delev=0	LW model: innovations to y_t^* $(\Delta y_t^* - g_{t-1}) \equiv \varepsilon_{y^*t}$	This paper model: financial headwinds $(g_t^{in} - g_t) \equiv \gamma\Delta\tilde{c}_t$	This paper model: innovations to y_t^{*fn} $(\Delta y_t^{*fn} - g_{t-1}) \equiv \varepsilon_{4t}$
1961Q2-1966Q2	21	1	0.56	0.51	0.33
1971Q3-1973Q3	9	1	0.17	0.41	0.11
1973Q4-1975Q4	9	0	-0.39	-0.90	0.00
1983Q2-1987Q3	18	1	0.43	0.76	-0.19
1990Q1-1993Q4	16	0	-0.28	-0.65	0.16
1997Q1-2000Q4	16	1	0.90	0.52	0.25
2004Q1-2006Q4	12	1	-0.22	0.44	-0.46
2008Q2-2014Q4	27	0	-1.02	-0.86	0.10
Full sample	220		0.06	-0.02	0.02

Note: Computations based on smoothed (two-sided) estimates of unobservable variables. Average quarterly values reported for every period. Growth variables are in annualised terms. Leveraging (lev) and deleveraging (delev) cycles are defined on the basis of 8 consecutive quarters of either positive (for lev) or negative (for delev) changes in the credit gap ($\Delta\tilde{c}_t$) as defined in this paper. LW model estimates from the FRB of San Francisco website available as of 30 June 2016.

Figure E.2: Uncertainty around the estimates of the natural rate of interest



Note: Smoothed (two-sided) estimates from the model.

Figure E.3: Filtered (one-sided) vs smoothed (two-sided) estimates of the natural rate of interest

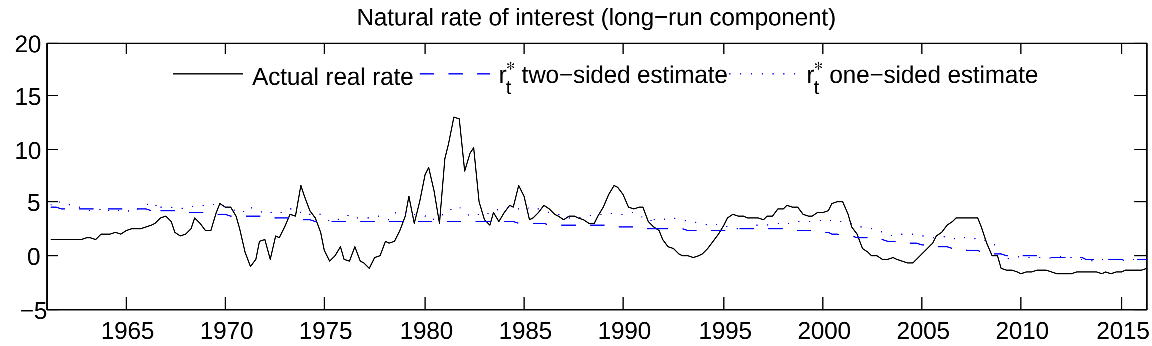
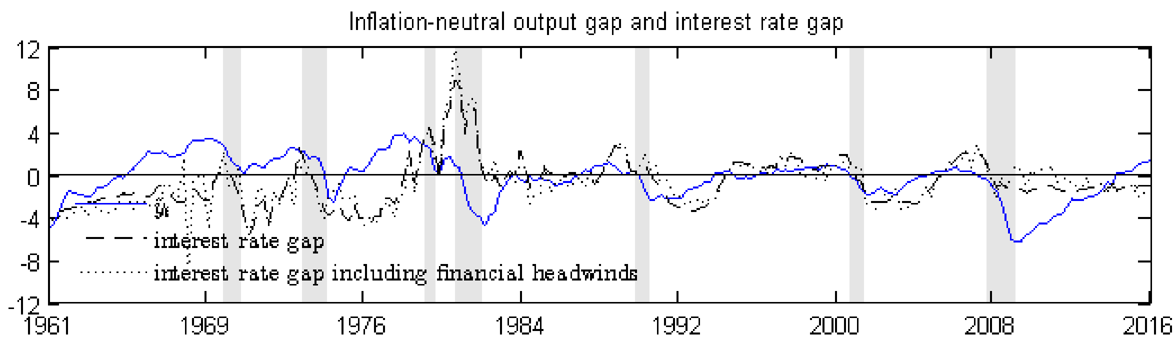


Figure E.4: Output gap, credit gap and corresponding interest rate gaps



Note: Based on filtered (one-sided) estimates from the model. In the panel, $\tilde{y}_t$ is the inflation-neutral output gap; "interest rate gap" refers to $r_t - (cg_t + z_t)$, where $cg_t + z_t$ is the long-run component of the inflation-neutral natural rate of interest r_t^*; "interest rate gap including financial headwinds" is $r_t - r_t^*$, where r_t^* is the short-term inflation-neutral natural rate of interest as defined in the paper.

Table E.2: Sensitivity analysis: estimates of γ parameter

Proxy for the financial cycle	Estimated value	Standard error	T-statistic
$\tilde{c}_t$:0 (baseline)	0.185	0.050	3.72
$\tilde{c}_t$:1 (HP:400000)	0.184	0.053	3.46
$\tilde{c}_t$:2 (HP:125000)	0.182	0.055	3.30
$\tilde{c}_t$:3 (HP:25000)	0.180	0.060	2.99
$\tilde{c}_t$:4 (HP:1600)	0.174	0.076	2.29
$\tilde{c}_t$:5 (BP:8-120)	0.210	0.060	3.48
$\tilde{c}_t$:6 (BP:8-90)	0.208	0.062	3.37
$\tilde{c}_t$:7 (BP:8-60)	0.198	0.066	2.99
$\tilde{c}_t$:8 (BP:8-30)	0.222	0.088	2.53
$\tilde{c}_t$:9 (HH credit)	0.341	0.081	4.18
$\tilde{c}_t$:10 (Bus credit)	0.109	0.056	1.93

Note: Maximum likelihood estimates, standard errors and T-statistics for the γ parameter from the baseline model re-estimated with different proxies for the financial cycle from $\tilde{c}_t$:1 to $\tilde{c}_t$:10, as explained in Section 5. HP and BP correspond to Hodrick-Prescott and Band-Pass filter, respectively. Credit to households (HH credit) and credit to the non-financial business sector (Bus credit) are detrended with an HP filter using $\lambda = 4^4.1,600$.

Table E.3: Sensitivity analysis: signal-to-noise ratios

Proxy for the financial cycle	Signal-to-noise ratios	
	λ_g	λ_z
$\tilde{c}_t$:0 (baseline)	0.050	0.020
$\tilde{c}_t$:1 (HP:400000)	0.052	0.021
$\tilde{c}_t$:2 (HP:125000)	0.052	0.019
$\tilde{c}_t$:3 (HP:25000)	0.052	0.017
$\tilde{c}_t$:4 (HP:1600)	0.051	0.014
$\tilde{c}_t$:5 (BP:8-120)	0.053	0.019
$\tilde{c}_t$:6 (BP:8-90)	0.053	0.018
$\tilde{c}_t$:7 (BP:8-60)	0.053	0.015
$\tilde{c}_t$:8 (BP:8-30)	0.051	0.016
$\tilde{c}_t$:9 (HH credit)	0.047	0.023
$\tilde{c}_t$:10 (Bus credit)	0.052	0.016

Note: Median unbiased estimates for the signal-to-noise ratios λ_g, λ_z and λ_r re-estimated with different proxies for the financial cycle in the model from $\tilde{c}_t$:1 to $\tilde{c}_t$:10, as explained in Section 5.

References

Adalid, R. and Detken, C. (2007), 'Liquidity Shocks and Asset Price Boom/Bust Cycles', *ECB Working Paper* **732**.

Albuquerque, B., Baumann, U. and Krustev, G. (2015), 'US household deleveraging following the great recession a model-based estimate of equilibrium debt', *The B.E. Journal of Macroeconomics* **15**(1), 255–307.

Amato, J. D. (2005), 'The Role of the Natural Rate of Interest in Monetary Policy', *CESifo Economic Studies* **51**(4), 729–755.

Arseneau, D. M. and Kiley, M. T. (2014), 'The Role of Financial Imbalances in Assessing the State of the Economy', *Board of Governors of the Federal Reserve System, FEDS Notes* **2014-04-18**.

Barsky, R., Justiniano, A. and Melosi, L. (2014), 'The Natural Rate of Interest and Its Usefulness for Monetary Policy', *American Economic Review* **104**(5), 37–43.

Basistha, A. and Startz, R. (2008), 'Measuring the NAIRU with Reduced Uncertainty: A Multiple-Indicator Common-Cycle Approach', *Review of Economics and Statistics* **90**(4), 805–811.

Benigno, P., Eggertsson, G. and Romei, F. (2014), 'Dynamic Debt Deleveraging and Optimal Monetary Policy', *NBER Working Paper* **20556**.

Berger, H., Dowling, T., Lanau, S., Lian, W., Mrkaic, M., Rabanal, P. and Sanjani, M. T. (2015), 'Steady as She Goes – Estimating Potential During Financial "Booms and Busts"', *IMF Working Paper* **15/233**.

Beyer, R. C. M. and Wieland, V. (2017), 'Instability, imprecision and inconsistent use of equilibrium real interest rate estimates', *CEPR Discussion Paper* **11927**.

Blanchard, O., Cerutti, E. and Summers, L. (2015), 'Inflation and Activity – Two Explorations, and Their Monetary Policy Implications', *NBER Working Paper* **21726**.

Borio, C. and Disyatat, P. (2014), 'Low interest rates and secular stagnation: Is debt a missing link?', VoxEU, 25 June 2014.

Borio, C., Disyatat, P. and Juselius, M. (2017), 'Rethinking potential output: Embedding information about the financial cycle', *Oxford Economic Papers* **69**(3), 655–677.

Borio, C., Kharroubi, E., Upper, C. and Zampolli, F. (2016), 'Labour reallocation and productivity dynamics: financial causes, real consequences', *BIS Working Paper* **534**.

Borio, C. and Lowe, P. (2004), 'Securing sustainable price stability: should credit come back from the wilderness?', *BIS Working Paper* **157**.

Christiano, L., Ilut, C., Motto, R. and Rostagno, M. (2008), 'Monetary Policy and Stock Market Boom-Bust Cycles', *ECB Working Paper* **955**.

Christiano, L., Ilut, C., Motto, R. and Rostagno, M. (2010), 'Monetary Policy and Stock Market Booms', Proceedings - Economic Policy Symposium - Jackson Hole, Federal Reserve Bank of Kansas City, 85-145.

Christiano, L., Motto, R. and Rostagno, M. (2014), 'Risk Shocks', *American Economic Review* **104**(1), 27–65.

Claessens, S., Kose, M. A. and Terrones, M. E. (2012), 'How do business and financial cycles interact?', *Journal of International Economics* **87**(1), 178–190.

Clark, T. E. and Kozicki, S. (2005), 'Estimating equilibrium real interest rates in real time', *The North American Journal of Economics and Finance* **16**(3), 395–413.

Cukierman, A. (2016), 'Reflections on the Natural Rate of Interest, its Measurement, Monetary Policy and the Zero Lower Bound', *CEPR Discussion Paper* **11467**.

Cúrdia, V., Ferrero, A., Ng, G. C. and Tambalotti, A. (2015), 'Has U.S. monetary policy tracked the efficient interest rate?', *Journal of Monetary Economics* **70**(March), 72–83.

De Fiore, F. and Tristani, O. (2013), 'Optimal Monetary Policy in a Model of the Credit Channel', *Economic Journal* **123**(571), 906–931.

Del Negro, M., Giannoni, M. P. and Schorfheide, F. (2015), 'Inflation in the Great Recession and New Keynesian Models', *American Economic Journal: Macroeconomics* **7**(1), 168–196.

Drehmann, M., Borio, C., Gambacorta, L., Jiminez, G. and Trucharte, C. (2010), 'Countercyclical capital buffers: exploring options', *BIS Working Paper* **317**.

Drehmann, M., Borio, C. and Tsatsaronis, K. (2012), 'Characterising the financial cycle: don't lose sight of the medium term!', *BIS Working Paper* **380**.

Edge, R. M., Kiley, M. T. and Laforte, J.-P. (2008), 'Natural rate measures in an estimated DSGE model of the U.S. economy', *Journal of Economic Dynamics and Control* **32**(8), 2512–2535.

Edge, R. M. and Meisenzahl, R. R. (2011), 'The Unreliability of Credit-to-GDP Ratio Gaps in Real Time: Implications for Countercyclical Capital Buffers', *International Journal of Central Banking* **7**(4), 261–298.

Eggertsson, G. and Krugman, P. (2012), 'Debt, Deleveraging, and the Liquidity Trap: a Fisher-Minsky-Koo Approach', *The Quarterly Journal of Economics* **127**(3), 1469–1513.

Furlanetto, F., Gelain, P. and Sanjani, M. T. (2014), 'Output Gap in Presence of Financial Frictions and Monetary Policy Trade-offs', *IMF Working Paper* **14/128**.

Galí, J. (2008), *Monetary Policy, Inflation, and the Business Cycle: An Introduction to the New Keynesian Framework*, Princeton University Press, Princeton, N.J.

Garnier, J. and Wilhelmsen, B.-R. (2009), 'The natural rate of interest and the output gap in the euro area: a joint estimation', *Empirical Economics* **36**(2), 297–319.

Grintzalis, I., Lodge, D. and Manu, A.-S. (2017), 'The implications of global and domestic credit cycles for emerging market economies: Measures of finance-adjusted output gaps', *ECB Working Paper* **2034**.

Hamilton, J. D. (1986), 'A standard error for the estimated state vector of a state-space model', *Journal of Econometrics* **33**(3), 387–397.

Harvey, A. C. (1989), *Forecasting, Structural Time Series Models and the Kalman Filter*, Cambridge University Press, Cambridge, U.K.

Holston, K., Laubach, T. and Williams, J. C. (2017), 'Measuring the natural rate of interest: International trends and determinants', *Journal of International Economics* **108**(S1), 59–75.

Johannsen, B. K. and Mertens, E. (2016), 'A Time Series Model of Interest Rates With the Effective Lower Bound', *Board of Governors of the Federal Reserve System, Finance and Economics Discussion Series* **33**.

Juselius, M., Borio, C., Disyatat, P. and Drehmann, M. (2017), 'Monetary Policy, the Financial Cycle and Ultra-Low Interest Rates', *International Journal of Central Banking* **13**(3), 55–89.

Kiley, M. T. (2015), 'What Can the Data Tell Us About the Equilibrium Real Interest Rate?', *Board of Governors of the Federal Reserve System, Finance and Economics Discussion Series* **77**.

Krippner, L. (2013), 'A tractable framework for zero lower bound Gaussian term structure models', *Reserve Bank of New Zealand Discussion Paper* **2013-02**.

Laeven, L. and Valencia, F. (2013), 'Systemic Banking Crises Database', *IMF Economic Review* **61**(2), 225–270.

Laubach, T. (2001), 'Measuring the NAIRU: Evidence from Seven Economies', *Review of Economics and Statistics* **83**(2), 218–231.

Laubach, T. and Williams, J. C. (2003), 'Measuring the Natural Rate of Interest', *Review of Economics and Statistics* **85**(4), 1063–1070.

Laubach, T. and Williams, J. C. (2016), 'Measuring the Natural Rate of Interest Redux', *Board of Governors of the Federal Reserve System, Finance and Economics Discussion Series* **2016-11**.

Lombardi, M. J. and Zhu, F. (2014), 'A shadow policy rate to calibrate US monetary policy at the zero lower bound', *BIS Working Paper* **452**.

Lubik, T. A. and Matthes, C. (2015), 'Calculating the Natural Rate of Interest: A Comparison of Two Alternative Approaches', *Richmond Fed Economic Brief* (Oct), 1–6.

Manrique, M. and Marqués, J. M. (2004), 'An empirical approximation of the natural rate of interest and potential growth', *Banco de España Working Paper* **0416**.

Mendoza, E. and Terrones, M. (2008), 'An Anatomy Of Credit Booms: Evidence From Macro Aggregates And Micro Data', *NBER Working Paper* **14049**.

Mésonnier, J.-S. and Renne, J.-P. (2007), ‘A time-varying “natural” rate of interest for the euro area’, *European Economic Review* **51**(7), 1768–1784.

Moazzami, B. and Dadgostar, B. (2009), ‘Okun’s Law Revisited: Evidence From OECD Countries’, *International Business and Economics Research Journal* **8**(8), 21–24.

Neiss, K. S. and Nelson, E. (2003), ‘The Real-Interest-Rate Gap As An Inflation Indicator’, *Macroeconomic Dynamics* **7**(2), 239–262.

Ordoñez, G. and Gorton, G. (2015), ‘Good Booms, Bad Booms’, Society for Economic Dynamics, 2015 Meeting Papers, No 292.

Pescatori, A. and Turunen, J. (2016), ‘Lower for Longer; Neutral Rates in the United States’, *IMF Economic Review* **64**(4), 708–731.

Rungcharoenkitkul, P. (2015), ‘Bank Competition and Credit Booms’, *BIS Working Paper* **488**.

Rünstler, G. and Vlekke, M. (2018), ‘Business, Housing, and Credit Cycles’, *Journal of Applied Econometrics* **33**(2), 212–226.

Smets, F. and Wouters, R. (2003), ‘An Estimated Dynamic Stochastic General Equilibrium Model of the Euro Area’, *Journal of the European Economic Association* **1**(5), 1123–1175.

Stock, J. H. (1994), ‘Unit Roots, Structural Breaks and Trends’, *in* R. F. Engle and D. McFadden, eds, ‘Handbook of Econometrics’, Vol. IV, Elsevier, Amsterdam.

Stock, J. H. and Watson, M. W. (1998), ‘Median Unbiased Estimation of Coefficient Variance in a Time Varying Parameter Model’, *Journal of the American Statistical Association* **93**, 349–358.

Taylor, J. B. and Wieland, V. (2016), ‘Finding the Equilibrium Real Interest Rate in a Fog of Policy Deviations’, *Business Economics* **51**(3), 147–154.

Weber, A., Lemke, W. and Worms, A. (2008), ‘How useful is the concept of the natural real rate of interest for monetary policy?’, *Cambridge Journal of Economics* **32**(1), 49–63.

Wicksell, K. (1898), *Interest and Prices*, Mcmillan, London, 1936. Translation of the 1898 edition by R. F. Kahn.

Woodford, M. (2003), *Interest and Prices: Foundations of a Theory of Monetary Policy*, Princeton University Press, Princeton, N.J.

Wu, J. C. and Xia, F. D. (2016), ‘Measuring the Macroeconomic Impact of Monetary Policy at the Zero Lower Bound’, *Journal of Money, Credit and Banking* **48**(2-3), 253–291.

Yellen, J. (2015), ‘Normalizing Monetary Policy: Prospects and Perspectives’. Remarks at the ”The New Normal Monetary Policy,” a research conference sponsored by the Federal Reserve Bank of San Francisco, San Francisco, California (http://www.federalreserve.gov/newsevents/speech/yellen20150327a.pdf).

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Georgi Krustev
European Central Bank, Frankfurt am Main, Germany; email georgi.krustev@ecb.europa.eu

Postal address 60640 Frankfurt am Main, Germany
Telephone +49 69 1344 0
Website www.ecb.europa.eu

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