Economic Modelling 119 (2023) 106137

Contents lists available at ScienceDirect

Economic Modelling

journal homepage: www.journals.elsevier.com/economic-modelling

Monetary policy rules and inflation control in the US☆

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ARTICLE INFO

JEL classification:
C32
E52
E58

Keywords:
Monetary policy
Federal reserve
Taylor rule
Cointegration
VEC model

ABSTRACT

The interplay between policy-setting by the Federal Reserve and inflation is explored during a period with significant and diverse episodes from 1979 onwards. Our unrestricted estimates reveal a stable target path for the policy rate with a strong response to inflation and an effective control over it. We identify moments of discretionary and rule-based policy-making throughout three different chairmanships and quantify the degree of policy inertia. Including the 'great recession' and the first years after the crisis leaves the above-mentioned characteristics unchanged and shows that the adjustment to deviations from the target path becomes less gradual. Replacing the federal funds rate with a shadow rate yields ineffective inflation control, indicating that the dynamic behaviour of inflation is affected by the implementation of unconventional policy when the zero lower bound applies.

1. Introduction

The policymakers in the Federal Reserve (Fed henceforth) do consider the prescriptions of interest rate rules. For the first time ever in 2017 the Fed included in its Monetary Policy Report a section dedicated to "Monetary Policy Rules and Their Role in the Federal Reserve's Policy Process" (Board of Governors of the Federal Reserve, 2017), where we read the following: "FOMC policymakers discussed prescriptions from monetary policy rules as long ago as 1995 and have consulted them routinely since 2004. The materials that FOMC policymakers see also include forecasts of how the federal funds rate and key macro indicators would evolve, under each of the rules […]."[1] Thus, though much is said and written regarding monetary policy in the United States (US), the more accurate the information about the rules, the better the chance for proper decisions by the policymakers.

The present study delves into the properties of the variables entering one of these rules considered by the Fed – namely the Taylor rule (Taylor, 1993), a commonly consulted and frequently used interest rate rule – during a period with several interesting episodes: various chairmanship changes along with the 'great inflation' first, the 'great moderation' afterwards and more recently the 'great recession'. With historical data on the federal funds rate, an inflation measure and real output, we tackle the following issues: Does the Taylor rule describe a long-run bond between the involved time series? And if so, are the generated dynamics plausible and compatible with a reaction function? How stable is the outcome over the years?

With favourable answers to the above queries, we put on the table a target path for the federal funds rate and prove, for the first time to the best of our knowledge, that the three variables entering the Taylor rule share a common stochastic trend, i.e. they are cointegrated. This first finding is crucial because, given the non-stationarity of the series, if they are not cointegrated, each one follows its own path and conveys no information about the stance of the rest; in such case, the involved series are not linked over time and it makes no sense considering the prescriptions of a linear interest rate rule.

The cointegrating relation is estimated without any restrictions and it comes out that it resembles the Taylor rule. The federal funds rate is

☆ Earlier versions were presented at the 41st Annual Meeting of the Association of Southern European Theorists, Athens University of Economics and Business, 25–27 October 2019, the 19th European Economics and Finance Society (EEFS) Conference, City University, London 23–25 June 2021 and the 16th Conference on Research on Economic Theory and Econometrics, Island of Milos, 10–14 July 2017, and thanks are due to conference participants for many helpful comments and discussions. The paper has benefited from valuable comments by seminar participants at the Athens University of Economics and Business and IPAG Business School. We are grateful to Michael Argyrou, Dimitris Georgoutsos, Iftekhar Hasan, Alexandros Kontonikas, Francisco Nadal de Simone, George Tavlas, Chris Tsoumas and Ourania Dimakou for stimulating discussions on earlier drafts of the paper. We also thank the Editor Sushanta K. Mallick, the Guest Editor Joscha Beckmann and two anonymous referees for their thoughtful suggestions which improved the manuscript irrevocably.

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[1] FOMC stands for the Federal Open Market Committee that makes all the decisions and communications regarding monetary policy.

https://doi.org/10.1016/j.econmod.2022.106137
Received 10 November 2021; Received in revised form 25 November 2022; Accepted 28 November 2022
Available online 3 December 2022
0264-9993/

found to react to the estimated relation in a significant and equilibrium-correcting manner and, therefore, this linear combination of the three variables qualifies as a target path for the policy rate. This target path forms part of a model that generates dynamics consistent with the derived rule and the macroeconomic theory. What is more, the modelling structure contemplates deviations from the target path and adjustments towards it, and thus offers insights into how discretionary and rule-based policy-making complement each other.

Another fundamental finding is the stability of the cointegrating relation because a target path only seems right if it is maintained throughout various circumstances and changes in the leadership of the monetary authority. The reference period goes from 1979 until 2008 and, to explore the effect of the financial crisis, the sample is extended for a few years: thus, the analysis reveals a firm characteristic of policy-setting in the US and a modification due to the 'great recession'.

The rest of the paper is organised as follows. Section 2 reviews briefly the literature and Section 3 describes the properties of the data and the modelling framework. Section 4 reports and discusses the empirical evidence and Section 5 offers concluding remarks.

2. Literature review

The seminal paper by Taylor (1993) proposes a so-called 'simple' rule according to which the short-term interest rate shall be equal to one-and-a-half times the inflation rate plus one-half times the output gap plus one and becomes the starting point of a vast literature that builds, directly or indirectly, on this rule. Along with the academic appeal, recently even the Federal Reserve refers to the Taylor rule in its semi-annual Monetary Policy Reports and lists "key principles of good monetary policy" featured in it (Board of Governors of the Federal Reserve, 2017, 2018 and so on). According to this list, monetary policy shall be predictable and "accommodative when inflation is below the desired level and employment is below its maximum sustainable level [...]".[2] Another key principle of the same list is that "to stabilise inflation, the policy rate should be adjusted by more than one-for-one in response to persistent increases or decreases in inflation"; this characteristic is known as the Taylor principle and becomes central in what follows.

The above references acknowledge that the Taylor rule has been regularly consulted for policy-making decisions during the past decades; similarly, the current Chairman of the Fed declares to "find these rule prescriptions helpful" (Powell, 2018). Alongside, there is a vigorous debate on rule-based versus discretionary monetary policy that also situates the Taylor rule in its centre. In this context, Mishkin (2018) and Dellas and Tavlas (2021) offer comprehensive remarks and explanations on both standpoints, while Taylor (2021) argues that turbulent times – like the financial crisis, the ensuing 'great recession' and the recent pandemic – ask for predictability and criticises deviating from the directions of the rule. With regard to the response of the Fed to these downturns, Sims and Wu (2021) demonstrate how a 'simple' Taylor rule is a useful input for evaluating the effects of unconventional monetary policy; while for the sake of greater monetary policy transparency and accountability, Cecchetti and Schoenholtz (2019) call for better descriptions of policy rules and reaction functions. In general, Taylor (2016, 2021) vividly motivates the use of the Taylor rule for historical comparisons over time and across countries.[3]

The early writings on the rule are reviewed extensively by Taylor and Williams (2011) and Koenig (2013) among others. In the aftermath of the 2007–2009 turbulences, a branch of the literature discusses the nexus between monetary policy and financial stability. Fischer (2016) argues that, when monetary policy is concerned with financial stability, macroprudential tools may be more appropriate than adjustments in short-term interest rates. Furthermore, Caballero et al. (2016) propose a model that features, apart from the IS relationship and the Taylor rule, an equation describing the equilibrium in the market for safe assets in order to endogenously determine output, the interest rate, and the risk premium. In the same context, Verona et al. (2017) evaluate the stabilising performance of optimal Taylor-type interest rate rules and discover that, when monetary policy reacts to credit growth, the central bank improves its ability to achieve its objectives in the event of financial shocks. Despite these concerns, Taylor (2021) argues in favour of the simplicity of the interest rate rule turning down the inclusion of additional variables.

The empirical literature on the Taylor rule is complemented with a thorough examination of its (in)stability; what follows is a summary of a long list of studies where not only varies the outcome and the source of instability considered, but also the econometric approach and the employed data. Regarding the US, many authors, often inspired by Clarida et al. (2000), examine how the specifications of a Taylor rule vary through different Fed chairmanships and circumstances: for example, recently, Haque et al. (2021), Nikolsko-Rzhevskyy et al. (2019), Aguiar-Conraria et al. (2018), Ghiani et al. (2016), and formerly, Judd and Rudebusch (1998) offer different perspectives regarding the stability of the rule. Sims and Zha (2006) consider various sources of variability within a non-linear multivariate framework. Also concerned with non-linearities, Dolado et al. (2005) look into the interaction between inflation and the output gap, while Assenmacher-Wesche (2006) and Bunzel and Enders (2010) identify regime switches related to the deviations of inflation from its target. Lately, the literature analyses the consequences of the policy rate being constrained by the zero lower bound. In this context and applying the Taylor rule, early results for the US are provided by Kumar (2013) and for other countries by Belke and Klose (2013) and Drakos and Kouretas (2015), while recently Caporale et al. (2018), Steiner (2021) and Gross and Zahner (2021) employ alternative econometric approaches. Several of the above-mentioned studies are further discussed and juxtaposed to the results described in the present study.

The Taylor rule is indisputably the workhorse in a vast literature. However, a rather small part of the empirical literature is concerned with the fundamental problem reported in Granger and Newbold (1974) and Phillips (1986, 1989) that if variables integrated of order one are not cointegrated, a static regression in levels is spurious. The present study belongs to this strand of the literature because the Taylor rule seems to be directly affected. With US data, and as regards the integration order, Siklos and Wohar (2006) and Bunzel and Enders (2005) show that the variables involved are non-stationary while Österholm (2005) testifies instability and inconsistencies when non-stationarity is neglected. As for whether there is cointegration, there are a few studies with US data, the results of which vary depending on the period under study and the specification of the model: Bunzel and Enders (2005) do not find evidence in favour of a Taylor rule for the period 1954–2003; on the other hand, Christensen and Nielsen (2009) put forward a Taylor-type target for the interest rate spread with the unemployment gap and an insignificant effect from inflation for the period 1987–2006, while Ghiani et al. (2016) propose a Taylor-type rule with the unemployment rate and money growth for the period 1960–2012. With non-US data, Gerlach-Kristen (2003) improves the stability and predictability of the rule when non-stationarity is accounted for, and Eleftheriou (2009, 2017) explores the integration and cointegration properties of various monetary policy indicators.

The present study is motivated by the significance of the Taylor rule for policy-making in the US and its influence on macroeconomic research, holds a positive standpoint and is genuinely concerned with the econometric issues. Once the properties of the involved series are

[2] As explained in the report by the Board of Governors of the Federal Reserve (2017, p.36), the Fed, unlike the original Taylor rule, uses the unemployment gap because it captures better the FOMC's statutory goal.

[3] In this respect, for instance, Belke and Cui (2010) explore by means of the Taylor rule the interdependence between the Fed and the European Central Bank.

Table 1
Summary statistics.

	is_t		y_t	
	1979Q1–2008Q2	1979Q1–2015Q1	1979Q1–2008Q2	1979Q1–2015Q1
Mean	0.064	0.053	9.188	9.270
Maximum	0.191 (1981Q2)		9.615 (2007Q4)	9.691 (2015Q1)
Minimum	0.009 (2003Q4)	0.0007 (2011Q4)	8.761 (1980Q3)	
Std. Dev.	0.037	0.042	0.272	0.299
	Δp_t		$issh_t$	
	1979Q1-2008Q2	1979Q1-2015Q1	1979Q1-2015Q1	
Mean	0.033	0.029	0.0506	
Maximum	0.096 (1981Q1)		0.191 (1981Q2)	
Minimum	0.011 (1998Q4)	0.002 (2009Q3)	−0.028 (2014Q2)	
Std. Dev.	0.020	0.019	0.045	

Table 2
Unit root tests for the period 1979Q1 to 2008Q2.

Variable	Deterministic			Test statistic
	Terms	Lag order	Test	Value
is_t	c	5 (AIC, HQ)	ADF	−1.82
	c, t	3 (AIC, HQ)	ADF	−2.99
	s81q3	4 (AIC)	LLS	−1.83
	s81q3	3 (HQ)	LLS	−2.37
	Level stationarity	5	KPSS	1.46**
	Trend stationarity	5	KPSS	0.18*
Δp_t	c	4 (AIC, HQ)	ADF	−2.92*
	c, t	4 (AIC, HQ)	ADF	−2.50
	s92q1	4 (AIC, HQ)	LLS	−2.82(*)
	t, s92q1	4 (AIC, HQ)	LLS	−2.19
	Level stationarity	4	KPSS	1.25**
	Trend stationarity	4	KPSS	0.36**
y_t	c, t	3 (AIC)	ADF	−3.01
	c, t	2 (HQ)	ADF	−3.05
	t, s81q2	3 (AIC)	LLS	−1.93
	t, s80q2	2 (HQ)	LLS	−2.26
	Trend stationarity	2	KPSS	0.13(*)
Δis_t	–	4 (AIC, HQ)	ADF	−4.98**
	c	4 (AIC, HQ)	ADF	−5.12**
	i80q4	3 (AIC, HQ)	LLS	−6.64**
	Level stationarity	5	KPSS	0.03
$\Delta^2 p_t$	–	4 (AIC, HQ)	ADF	−3.54**
	c	4 (AIC, HQ)	ADF	−3.69**
	i84q1	4 (AIC, HQ)	LLS	−3.38*
	Level stationarity	4	KPSS	0.13
Δy_t	c	1 (AIC, HQ)	ADF	−5.30**
	i80q4	1 (AIC, HQ)	LLS	−4.27**
	Level stationarity	1	KPSS	0.14

Note: see Appendix A.2 for details.

carefully explored, it is shown how the interest rate rule emerges as a cointegrating relation, i.e. a long-run target path, within a Vector Error Correction (VEC) model, the dynamics and stability of which are checked and explained thoroughly. The baseline model is estimated on the period 1979–2008, i.e. an era that starts when Paul Volcker takes office as Chair of the Board of Governors of the Fed and ends with the burst of the 'great recession'. The effects of this recession are studied by extending the sample period until the end of Ben Bernanke's chairmanship. As a robustness check, our findings are compared to the often-cited study by Clarida et al. (1998) who estimate Fed reaction functions in a one-equation framework.

3. Preliminary analysis

The time series employed are quarterly seasonally adjusted data on the short term interest rate measured by the federal funds rate, the inflation rate measured by the year-to-year difference of the log GDP deflator and the real output measured by the log GDP at constant prices and employed to capture the output gap, as explained below. In the Appendix, the first section contains a detailed description of the data, Table 1 reports the corresponding summary statistics and Fig. 7 plots the series in levels and first differences.

Regarding the timespan, the longest sample considered starts in 1979 Q1 and ends in 2015 Q1. Our main interest is on the period until the outburst of the financial crisis in the second quarter of 2008: as commented earlier, the focus of the paper is on the relationship of the federal funds rate with real output and inflation at times when this policy rate is the primary instrument of the Fed. The 'great recession' triggers adjustments to policy-making – as the federal funds rate approximates zero – that were not applied by the former chairmen of the Fed during the previous decades. Thus, the baseline model is run on times of "conventional" monetary policy that comprise 29 years (or 118 quarterly observations) and three chairmanships. As a robustness check, the sample period is extended to include the entire term of Ben Bernanke as Chair of the Board of Governors of the Fed during the 'great recession' and the first years after it. Additionally, the sample period is cut short to offer a comparison with the literature.

Extensive unit root and cointegration tests are implemented; the second section of the Appendix includes the methodological details and a series of tables with results. Let us mention here that in order to decide whether the series are stationary or not, three different unit root tests are carried out, with a combination of deterministic terms according to the characteristics of the series and the indications of the auxiliary regressions. As regards the cointegration rank, our decision is based on two different tests run on the three variables together and pairs of them; the bivariate cointegration tests are useful in revealing which variables share a common stochastic trend, i.e. which variables are tied together. In every case, the deterministic terms entering the cointegration tests depend on the properties of the series involved and the indications of the regressions accompanying the corresponding unit root tests. Let us point out that, in general, the integration and cointegration properties may vary due to the definition of the series and the period under study.

For the period from 1979 Q1 to 2008 Q2, the unit root tests (reported in Table 2) indicate that the three series are integrated of order one. The trivariate cointegration tests (Table 3) clearly indicate a cointegrating rank of one when the trend is restricted into the cointegrating relation. For the same deterministic terms, the bivariate cointegration tests reveal that the three series are linked stochastically.

For the period from 1979 Q1 to 2015 Q1, according to the unit root tests (Table 5), the three series are integrated of order one.[4] As for the cointegration tests, assuming one cointegration relation is not rejected by the data. The bivariate tests indicate that the three series are pairwise cointegrated, though the evidence depends on the deterministic terms. For the period from 1979 Q1 to 1994 Q4, the test results, which are not reported for brevity but are available upon request, deliver clear evidence of a unit root in the interest rate and the output series, while for inflation, the results are mixed, but the KPSS test (Kwiatkowski et al., 1992) clearly rejects stationarity. As for the cointegrating rank, the trivariate tests with the appropriate deterministic terms suggest one error correction term; and the bivariate tests corroborate that the three series are involved.

The finding that the variables in levels are integrated of order one is in accordance with the plot of the series (Fig. 7). This non-stationarity makes the spurious regression problem pertinent to an interest rate

[4] For the interest rate, let us note that the trend becomes insignificant when the outliers in the beginning of the period are considered. For the inflation series, the ADF and LLS tests indicate a unit root at the 5% level, and the KPSS clearly rejects the null of stationarity. Appendix A.2 provides information on these tests.

Table 3
Cointegration tests for the period 1979Q1 to 2008Q2.

Variables	H_0 Rank	Johansen trace Statistic	Pvalue	S&L test Statistic	Pvalue
$is_t, y_t, \Delta p_t$	0	53.30	0.002	34.92	0.006
	1	22.28	0.132	7.35	0.622
	2	9.21	0.171	0.90	0.818
	5 (AIC, HQ)	c,t, i80q4 i81q4		c,t, i80q4 i81q4	
	0	58.89	0.000		
	1	27.46	0.029		
	2	8.15	0.246		
	5 (AIC, HQ)	c,t			
	0	31.91	0.027		
	1	12.36	0.141		
	5 (AIC, HQ)	c,⊥t			
	0	27.99	0.081	21.76	0.038
	1	11.48	0.186	9.94	0.047
	5 (AIC, HQ)	c,⊥t, i80q4 i81q4		c,⊥t, i80q4 i81q4	

Note: see Appendix A.2 for details.

Table 4
Pairwise cointegration tests for the period 1979Q1 to 2008Q2.

Variables	H_0 Rank	Johansen trace Statistic	Pvalue	S&L test Statistic	Pvalue
is_t, y_t	0	23.36	0.098	16.78	0.036
	1	8.88	0.192	0.01	0.999
	5 (AIC, HQ)	c,t		c,t, i80q4 i81q4	
	0	14.88	0.060	8.57	0.085
	5 (AIC, HQ)	c,⊥t		c,⊥t, i80q4 i81q4	
$y_t, \Delta p_t$	0	12.33	0.142	4.87	0.351
	5 (AIC)	c,⊥t		c,⊥t, i80q4 i81q4	
	0	17.52	0.022	10.31	0.040
	2 (HQ)	c,⊥t		c,⊥t, i80q4 i81q4	
	0	29.50	0.014	14.35	0.084
	1	9.24	0.169	0.00	1.000
	5 (AIC)	c,t		c,t, i80q4 i81q4	
	0	35.73	0.001	18.16	0.019
	1	10.43	0.109	0.04	0.998
	2 (HQ)	c,t		c,t, i80q4 i81q4	
$is_t, \Delta p_t$	0	15.18	0.220	7.19	0.311
	1	4.48	0.357	0.77	0.433
	5 (AIC)	c		c, i80q4 i81q4	
	0	19.09	0.070	6.84	0.346
	1	4.40	0.368	0.44	0.568
	3 (HQ)	c		c, i80q4 i81q4	
	0	16.87	0.432	14.01	0.095
	1	4.92	0.614	1.92	0.556
	5 (AIC)	c,t		c,t, i80q4 i81q4	
	0	24.28	0.076	13.80	0.102
	1	10.49	0.107	0.90	0.819
	3 (HQ)	c,t		c,t, i80q4 i81q4	
	0	13.46	0.098	7.51	0.131
	5 (AIC)	c,⊥t		c,⊥t, i80q4 i81q4	
	0	17.58	0.022	7.36	0.139
	3 (HQ)	c,⊥t		c,⊥t, i80q4 i81q4	

Note: see Appendix A.2 for details.

rule (or any static regression) with these variables. Consequently, for the rule to be significant and useful, the existence of a cointegrating relation is necessary. The presence of a common stochastic trend among the series means that they are linked and move together; otherwise, each series follows its own course but gives no information on the course of the others. As far as we know, it is the first time that this necessary condition for the (trivariate according to the original formulation) Taylor rule to be relevant is established with data from the US economy.[5]

Once a common stochastic trend is verified, it is preserved invariant if further variables are considered, i.e. including additional variables may generate more cointegrating relations, without modifying the stationary relation in the original set of variables. Within the context of interest rate rules, this feature of cointegration allows exploring the relevance of rules augmented with any indicator.[6] The opposite experiment, i.e. reducing the number of the variables, stands for verifying the cointegration rank within a minimal set of variables and serves for checking whether a particular variable contributes to the common stochastic trend. In our case, the various bivariate cointegration tests indicate a rank of one, the same rank that indicate the tests on the three variables, a result that implies, as explained earlier, that all the series enter the cointegration relation.

The presence of cointegration does not imply that the cointegrating relation is interesting- or, more specifically, that it is an interest rate rule, or that the variables enter with the right sign or with the expected coefficient value. In other words, the presence of a common stochastic trend is a necessary but not a sufficient condition for a cointegrating relation to be interpreted in any way; for an interpretation to be valid, it has to produce appropriate coefficient estimates and be combined with the appropriate dynamics within a model. The rest of this section describes the employed procedure, and the next section presents the estimations and the generated dynamics that allow us to interpret the common stochastic trend as a target path for the federal funds rate.

Modelling framework. In view of the integration and cointegration properties described above, the interaction between the short-term interest rate, is_t, and the two economic indicators, namely inflation, Δp_t, and output, y_t, is analysed by means of Vector Error Correction models of the following form:

$$\Delta X_t = \Pi \begin{bmatrix} X_{t-1} \\ Trend_{t-1} \end{bmatrix} + \sum_{j=1}^{k-1} \Gamma_j \Delta X_{t-j} + \Xi D_t + u_t, \quad (1)$$

where X_t is the vector with the endogenous variables, Δ refers to the differencing operator, Π, Γ and Ξ are coefficient matrices, D_t contains the deterministic terms (that are not restricted in the cointegration space), and u_t is white noise with zero mean and non-singular covariance matrix Σ_u. The endogenous variables are is_t, Δp_t and y_t –in this order, unless otherwise indicated– and the model is composed by the corresponding three equations (Δis_t, $\Delta^2 p_t$ and Δy_t). The lag order k is chosen according to the information criteria and the cointegration rank is set according to the outcome of the corresponding cointegration tests.[7] Furthermore, $\Pi = \alpha\beta'$, where α contains the loading coefficients and β the coefficients of the cointegration relationship. To identify β,

[5] Bunzel and Enders (2005) with quarterly data and the output gap estimated exogenously find evidence of non-stationarity but not of cointegration. Christensen and Nielsen (2009) and Ghiani et al. (2016) with monthly data and the unemployment as their economic activity indicator, only find cointegration when a fourth variable is included in the rule (the bond rate in the former study, money supply in the later).

[6] Eleftheriou (2009) expands on this feature.

[7] The model selection criteria are calculated with a maximum lag order of 8, a choice that is refined by the information criteria, if necessary. For the baseline model the maximum lag order is reduced to 6 by the criteria and then the Akaike criterion suggests a lag order of 5. Let us underline that

Table 5
Unit root tests for the period 1979Q1 to 2015Q1.

Variable	Deterministic terms	lag order	test	Test statistic value
is_t	c	5 (AIC, HQ)	ADF	−1.79
	c, t	6 (AIC, HQ)	ADF	−4.51**
	s82q3	5 (AIC, HQ)	LLS	−1.69
	Level stationarity	5	KPSS	1.97**
	Trend stationarity	5	KPSS	0.14*
Δp_t	c	1 (AIC, HQ)	ADF	−2.76(*)
	s10q2	4 (AIC, HQ)	LLS	−2.62(*)
	Level stationarity	4	KPSS	1.49**
	Trend stationarity	4	KPSS	0.37**
y_t	c, t	2 (AIC)	ADF	−1.08
	c, t	1 (HQ)	ADF	−0.78
	t, s80q2	2 (AIC)	LLS	−1.72
	t, s80q2	1 (HQ)	LLS	−1.35
	Trend stationarity	2	KPSS	0.80**
Δis_t	–	4 (AIC, HQ)	ADF	−5.51**
	c	4 (AIC, HQ)	ADF	−5.71**
	i81q2	4 (AIC)	LLS	−3.65**
	Level stationarity	4	KPSS	0.03
$\Delta^2 p_t$	–	4 (AIC, HQ)	ADF	−4.07**
	c	4 (AIC, HQ)	ADF	−4.25**
	i07q1	4 (HQ)	LLS	−4.13**
	Level stationarity	4	KPSS	0.10
Δy_t	c	1 (AIC)	ADF	−5.64**
		0 (HQ)	ADF	−7.72**
	i82q1	1 (AIC, HQ)	LLS	−5.59**
	Level stationarity	0	KPSS	0.00

Note: see Appendix A.2 for details.

the first part is set to be an identity matrix, i.e. $\beta' = [I_r : \beta'_{(M-r)}]$, where r is the cointegrating rank, M is the number of the variables and $\beta'_{(M-r)}$ is a $((M-r)\times r)$ matrix. Regarding the vector D_t, the models have a constant and may contain impulse dummies.[8] For each model, the specific information on the deterministic terms, the lag order and the cointegrating rank is given in the respective section.

As for the trend restricted to the cointegrating relation of model (1), it is related with the evolution of the real output series – the graphic representation and the integration and cointegration tests (in the Appendix) corroborate its relevance – and approximates potential output. Provided that the estimated β_y and β_{Trend} have the expected sign, the difference between y_t and the trend accounts for the output gap and $-\frac{\hat{\beta}_{Trend}}{\hat{\beta}_y}$ offers an estimation of the average real output growth per quarter; the estimated growth is juxtaposed to the observed one for the period analysed to check the accuracy of the results.[9] This mode of measuring the output gap within the model is an alternative to the exogenous measures.[10]

Model (1) is estimated employing the Johansen reduced rank procedure without any restrictions for the estimation of the cointegration vector β. Then a system testing procedure is applied to detect possible zero restrictions among the coefficients contained in the α vector and the matrices Γ and Ξ.[11] As these restrictions are not rejected (p-value reported for each model respectively), the analyses presented in the next section (discussion of α, impulse responses, stability and residual analysis, etc.) refer to the restricted models.

As argued earlier, for the established cointegrating relation to be interpreted as a target path for the interest rate, it must be accompanied by appropriate dynamics within the model. Thus, before we proceed to the empirical evidence, a few aspects of the modelling framework need to be explained within the specific context of interest rate rules. To start with, the β coefficients describe the long-run relation, or the common stochastic trend, which as shown in the next pages, fulfils the characteristics of a target path for the federal funds rate. Then, the loading coefficients describe the built-in adjustment mechanism towards the long-run relation: more specifically, the α coefficient corresponding to the Δis_t equation, $\alpha_{\Delta is}$, describes the adjustment of the policy rate towards the target path, and captures what is known in the literature as interest rate smoothing.[12] For the cointegrating relation to be interpreted as an interest rate rule, $\alpha_{\Delta is}$ must be negative and statistically significant, so that when the interest rate is above (below) its target path, this rate is reduced (increased) so as to approach the target. Similarly, when the cointegrating relation enters the equations of $\Delta^2 p_t$ and Δy_t in an equilibrium adjusting manner (i.e. when $\alpha_{\Delta^2 p}$ and $\alpha_{\Delta y}$ are negative and statistically significant), policy-setting produces a corrective effect on these indicators. In this way, the employed framework captures a hint of the transmission mechanism of monetary policy-setting — the full picture is obtained with the impulse responses generated by the model.

And lastly, an advantage of the modelling structure is that it encompasses various versions of the rule (forward or backward looking, or contemporaneous) proposed in the literature. This is because cointegration between any variables (is_t, Δp_t and y_t in this case) implies cointegration between any occurrence of these (for example, is_t, Δp_{t+1} and y_{t-4}).

4. Empirical evidence

4.1. Baseline model

The focus here is on monetary policy in the US since 1979, i.e. the year that chairman Volcker took office in the Federal Reserve, and until the outset of the 'great recession' in 2008.[13] The presented cointegration tests reveal that during these three decades the federal funds rate is tied together with real output and the inflation rate in a long-run equilibrium. How does this long-run path look like? How do the federal funds rate and the economic indicators react to it? Is the path stable over time? These are the main questions covered in what follows.

As explained in the previous section, a VEC model, described by Eq. (1), is estimated with one cointegrating relation. The lag order k is set equal to 5 quarters and the deterministic terms are enriched with

the cointegrating rank tests are performed considering the same lag order as it coincides with the indication of the criteria reported in Table 3. The multivariate lag order may vary from the lags in the univariate unit root analysis.

[8] An impulse dummy named for instance "I80q4" takes the value 1 in the last quarter of 1980, and similarly for "I81q4" and "I84q4". "I80q4" and "I81q4" capture the sharp rise in the US interest rate and the inflation rate following the oil shock and the start of the Volcker disinflation. "I84q4" is related to the start of the 'great moderation' and the fall in the interest rate. The selection of the dummies is based on the following: the descriptive statistics of the series (summarised in Table 1 in the Appendix); the suggestion of the Lanne et al. (2002) unit root test (reported in Tables 2 and 5) for which the software JMulti offers a search for the break date that is complemented with a residual analysis; and the statistical significance of the corresponding coefficient within the estimated VEC model.

[9] We expect $\hat{\beta}_y > 0$ and $\hat{\beta}_{Trend} < 0$, with $\hat{\beta}$ indicating the estimated cointegration coefficient of the respective variable.

[10] Among others, the following studies opt for the same method (and interpretation): Johansen and Juselius (2001), Brüggemann (2003) and Eleftheriou (2009, 2017).

[11] The software employed is JMulTi and is available at www.jmulti.com In the system testing procedure the threshold value is set equal to 2.

[12] This interpretation is shared by Judd and Rudebusch (1998), Brüggemann (2003) and Christensen and Nielsen (2009) among others.

[13] Recently Haque et al. (2021) and Bachmann et al. (2021) also examine the pre-crisis period (and both assume monetary policy is described by the Taylor rule).

Table 6
Cointegration tests for the period 1979Q1 to 2015Q1.

Variables	H_0	Johansen trace		S&L test	
	Rank	Statistic	Pvalue	Statistic	Pvalue
$is_t, y_t, \Delta p_t$	0	41.39	0.069	37.93	0.002
	1	20.86	0.188	14.04	0.094
	2	6.41	0.420	0.08	0.995
	5 (AIC)	c,t		c,t, i84q4, i81q4	
	0	47.52	0.014	27.33	0.070
	1	20.62	0.199	9.77	0.359
	2	7.08	0.346	0.02	0.999
	3 (HQ)	c,t		c,t, i84q4, i81q4	
	0	35.48	0.009	29.98	0.002
	1	16.28	0.036	12.60	0.014
	5 (AIC)	c,⊥t		c,⊥t, i84q4 i81q4	
	0	43.44	0.000	23.80	0.019
	1	16.78	0.030	12.15	0.018
	3 (HQ)	c,⊥t		c,⊥t, i84q4 i81q4	

Note: see Appendix A.2 for details.

Table 7
Pairwise cointegration tests for the period 1979Q1 to 2015Q1.

Variables	H_0	Johansen trace		S&L test	
	Rank	Statistic	Pvalue	Statistic	Pvalue
is_t, y_t	0	16.64	0.450	13.01	0.134
	1	4.73	0.640	2.32	0.467
	5 (AIC, HQ)	c,t, i81q4 i84q4		c,t, i81q4 i84q4	
	0	16.50	0.033	11.79	0.021
	5 (AIC, HQ)	c,⊥t, i81q4 i84q4		c,⊥t, i81q4 i84q4	
	0	19.86	0.237		
	1	6.82	0.374		
	5 (AIC)	c,t			
	0	19.27	0.011		
	5 (AIC)	c,⊥t			
	0	14.14	0.078		
	4 (HQ)	c,⊥t			
$y_t, \Delta p_t$	0	14.60	0.066	14.06	0.007
	2 (AIC, HQ)	c,⊥t, i81q4 i84q4		c,⊥t, i81q4 i84q4	
	0	20.03	0.008		
	2 (AIC, HQ)	c,⊥t			
	0	22.19	0.135		
	1	6.15	0.452		
	2 (AIC, HQ)	c,t			
	0	16.78	0.439	15.64	0.052
	1	4.95	0.609	0.65	0.884
	2 (AIC, HQ)	c,t, i81q4 i84q4		c,t, i81q4 i84q4	
$is_t, \Delta p_t$	0	16.71	0.145	6.33	0.402
	1	4.36	0.373	0.14	0.766
	5 (AIC, HQ)	c		c, i81q4 i84q4	
	0	21.26	0.170	19.63	0.010
	1	6.22	0.444	1.02	0.788
	5 (AIC, HQ)	c,t		c,t, i81q4 i84q4	
	0	13.69	0.091	5.74	0.2586
	5 (AIC, HQ)	c,⊥t		c,⊥t, i81q4 i84q4	

Note: see Appendix A.2 for details.

two impulse dummies – one for the fourth quarter of 1980 and the other for the same quarter of 1981 – to cope with the acute rise in the inflation rate after an oil shock and the hike in the US interest rate mainly due to the restrictive policy stance adopted by chairman Volcker.

Table 8
Residual analysis for the 1979–2008 model.

PORT (16-20)	144.5(0.09)- 185.1(0.08)		
LM (1-2-3)	14.57(0.10)- 19.64(0.35)- 26.85(0.47)		
VARCHLM(2-4-8)	85.08 (0.13)- 154.84(0.25)- 318.47(0.10)		
	$u_{\Delta is}$	$u_{\Delta y}$	$u_{\Delta^2 p}$
PORT (2)	4.06 (0.13)	0.43 (0.80)	0.67 (0.71)
PORT (4)	5.09 (0.27)	2.73 (0.60)	4.07 (0.39)
PORT (8)	7.25 (0.50)	7.46 (0.48)	19.31 (0.01)
ARCH(2)	1.55 (0.45)	9.11 (0.01)	1.44 (0.49)
ARCH(4)	2.48 (0.65)	9.29 (0.05)	7.56 (0.11)
JB	19.84 (0.00)	0.51 (0.77)	2.72 (0.26)

Note: see Appendix A.2 for details.

Table 9
Residual analysis for the 1979–2015 model.

PORT (16-20)	137.9(0.17)–167.7(0.30)		
LM (2)	23.39(0.17)		
VARCHLM(2-8)	194.94(0.00)–409.76(0.00)		
	$u_{\Delta is}$	$u_{\Delta y}$	$u_{\Delta^2 p}$
PORT (4)	8.78 (0.07)	4.96 (0.29)	1.51 (0.82)
ARCH(4)	37.87 (0.00)	0.56 (0.97)	10.87 (0.03)
JB	244.8 (0.00)	3.76 (0.15)	1.51 (0.47)

Note: see Appendix A.2 for details.

The (unrestrictedly) estimated cointegrating relationship, with the coefficient of the short-term rate normalised to 1, turns out to be (the standard errors are reported in curly brackets and the t-statistics in parentheses):

$$is_t = \underset{\substack{\{0.163\}\\(5.249)}}{0.86}y_t + \underset{\substack{\{0.235\}\\(4.752)}}{1.116}\Delta p_t - \underset{\substack{\{0.001\}\\(-5.536)}}{0.007}Trend_t \qquad (2)$$

or $is_t = 0.86(y_t - 0.0081Trend_t) + 1.116\Delta p_t$.

This long-run relationship between the policy rate and the two indicators that describe the state of the US economy bears a marked resemblance to a Taylor-like rule for the interest rate. The inflation rate enters with the expected sign and its coefficient is larger than unity, a value that ensures a rise in the real rate when inflation increases. The coefficient of the trend adjusted real output has the expected sign and is a bit higher than the output gap coefficient suggested by Taylor (1993). As explained above the output gap is not calculated exogenously but is captured through the specification of the model: the average real output growth per quarter is estimated to be 0.81% (or 3.24% per year).[14]

Hence, Eq. (2) establishes that the common stochastic trend connecting the series qualifies as an interest rate rule. What is more, this estimated path for the interest rate complies with the Taylor principle and is accommodative, both features being in accordance with the "key principles of good monetary policy" pointed out in the Fed reports. The obtained coefficients are like those found by other authors but are derived within an error correction term which is a unique outcome.[15]

[14] These values are close to the observed average real output growth for the corresponding period, i.e. 0.72% quarterly and 2.9% annually.

[15] Kumar (2013) for the period 1954 to 2008 reports an identical inflation coefficient and a positive, though significantly higher, output gap coefficient; the employed dataset is similar, but the output gap is measured exogenously and the modelling procedure differs, as the series are found to be stationary. For the Greenspan era (1987 to 2006), Christensen and Nielsen (2009) find a cointegrating relationship in which the inflation coefficient is either statistically insignificant or, in the case of core inflation, bears the wrong sign and thus cannot be interpreted as a monetary policy rule; the econometric procedure is similar to ours, but the data is monthly and includes unemployment, core inflation or the change in the consumer price index and the market bond yield.

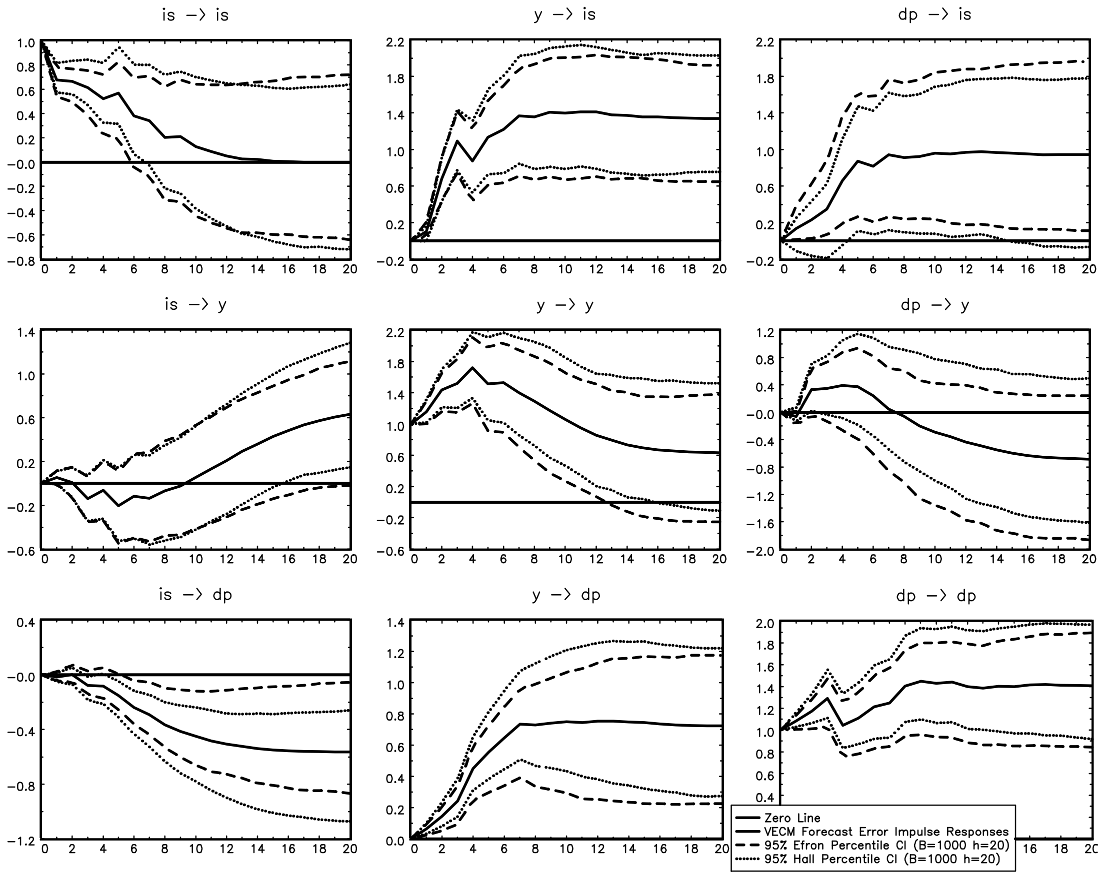

Fig. 1. Impulse responses for the 1979–2008 model.

Within our modelling framework, Eq. (2) describes just the target rate path; whether and how the variables react to this path is captured by $\alpha_{\Delta is}$, $\alpha_{\Delta y}$ and $\alpha_{\Delta^2 p}$. These loading coefficients, as explained in the preliminary analysis, correspond to the subset restricted model and are reported below (with the t-statistics in parentheses):[16]

$\alpha_{\Delta is}$	$\alpha_{\Delta y}$	$\alpha_{\Delta^2 p}$
−0.121 (−3.613)	0.053 (2.336)	−0.076 (−7.926)

So, does the estimated cointegrating relationship behave as a reaction function? Yes, it does, because $\alpha_{\Delta is}$ is statistically significant and negative. Moreover, as argued earlier, this loading coefficient captures the gradual adjustment of the interest rate towards the desired level (i.e. interest rate smoothing); its magnitude here suggests that a negative one percentage point deviation (of the interest rate from the implied target path described by Eq. (2)) triggers an increase by 12 base points in the policy rate in the next quarter. In other words, it takes almost two years to return to the target path. As for the other two equations, the cointegrating relationship enters in an equilibrium-correcting manner in the equation corresponding to the inflation rate. This implies that if the interest rate is above its target path inflation drops, meaning that monetary policy is effective.[17]

To get a complete picture of the generated dynamics an impulse response analysis is carried out. As the residual correlation matrix, reported below, contains off-diagonals that are significantly different from zero, both the forecast error and the orthogonal impulse responses (with appropriate ordering of the variables) are computed together with 95% confidence intervals based on two bootstrap procedures. The differences are qualitatively insignificant and, thus, just forecast error impulse responses are plotted and commented in detail.[18]

$$\begin{bmatrix} 1 & & \\ 0.262 & 1 & \\ 0.029 & 0.024 & 1 \end{bmatrix} \begin{matrix} \Delta is_t \\ \Delta y_t \\ \Delta^2 p_t \end{matrix}$$

By means of these impulse responses, the relevance of the Taylor rule can be explored by observing the adjustment of the short-term rate to shocks hitting the non-policy variables, namely, real output and inflation. These responses are illustrated in the first row of Fig. 1: very clearly, and in line with the predictions of the rule, a positive shock to output or inflation leads to a long-lasting and significant increase in the short-term interest rate.

Additionally, it is of interest the first column of Fig. 1 which illustrates the transmission of a shock to the interest rate. A rise in the federal funds rate has a positive impact on itself that becomes insignificant after a year and a half. This monetary policy contraction does not have a significantly negative impact on real output, but it

[16] The restrictions of the reduced model are not rejected with a p-value of 0.58 in a $\chi^2(27)$ distribution.

[17] The interest rate equation contains lags of the three endogenous variables, thus there is considerable dynamic feedback. The same happens with the inflation equation while the output equation is dominated by its own history with just a couple of lags of the other two variables being significant.

[18] The impulse response analysis of the VEC models is based on their vector autoregressive (VAR) form in levels. The forecast error impulse responses are generated with a unit innovation. In the orthogonal impulse responses, the usual ordering of the variables is real output first, inflation second, and the policy interest rate third (Christiano et al. (1999) propose this ordering to break the contemporaneous relationship). We check that the conclusions remain unaltered if instead of the subset model, the unrestricted one is employed. Additional plots are available upon request.

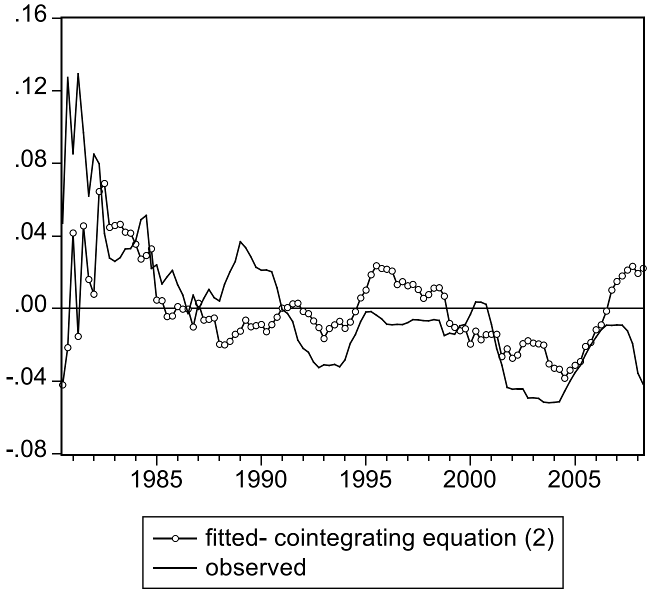

Fig. 2. Fit of the cointegrating equation for the 1979–2008 model.

does make inflation drop significantly after a bit more than a year. The responses of an impulse on output are displayed in the second column: it has a positive effect on itself (that lasts for three years) and also on the inflation rate. And in the third column are displayed the responses of an impulse on inflation: there is a long-term effect on inflation itself and an insignificant response of the output. Overall, the dynamics described in Fig. 1 corroborate the well-functioning of the proposed model and, more specifically, confirm the relevance of the estimated interest rate rule and its effectiveness in controlling inflation.[19]

Regarding stability, various tests are carried out and presented in Figs. 8–11 in the Appendix. To start with, the Chow Forecast test is implemented on every second datapoint and the null hypothesis of constant coefficients is not rejected. Then, the loading coefficients are estimated recursively (with the cointegrating relation fixed at the full sample estimate, i.e. the one reported above): in the case of the interest rate and inflation equations, the recursive estimates confirm that Eq. (2) enters in an equilibrium-correcting manner as they are always negative and significant; in the case of the output equation, the loading coefficient is positive at all times, though insignificant until roughly 2002. A third check of stability is through the recursive eigenvalue and the tau statistic: these indicators build on a recursive estimation of the long-run part of the model and neither rejects stability.[20]

The residual analysis is completed with the tests reported in Table 8 in the Appendix. Evidently the residuals of the subset restricted model do not suffer neither from autocorrelation nor autoregressive conditional heteroskedasticity, though non-normality is not rejected.[21]

As a final step in the exploration of the fit of a rule, it is usual in the literature employing one-equation frameworks, and also in the Fed reports, to plot the estimated target rate series together with the historical interest rate values. Accordingly, within the present framework, Fig. 2 depicts the observed interest rate series together with the fitted values of the cointegrating relationship, both as deviations from their mean; the former series is shown as a solid line, and the latter with circular patterns. Remember that according to Eq. (2), the trend is restricted into the error correction term and therefore the plotted series contains the output gap measure; on the other hand, neither the dummies, nor the loading coefficients, nor any other short-run dynamics are represented. By and large, the fitted path is close to the historical values with the correlation coefficient being equal to 0.63. Still, bear in mind that the sketched rule is just the long-run relation; there are dynamics excluded from the picture but present in the model, like for instance, the spikes in the beginning of the sample and, most importantly, interest rate smoothing, an established practice of the Fed that is left out from the plot.

The deviations displayed in Fig. 2 are in line with the evidence reported in the literature and are associated with various episodes, such as the oil crises in the beginning of the sample period, or the Asian financial crisis around 1998. As regards the divergence in the later part of the sample, with the Fed funds rate being below the prescription of the estimated target rule at all times except in 2006, it is consistent with the plot included in the report by the Board of Governors of the Federal Reserve (2017, p. 39) and the findings in Belongia and Ireland (2016) and it is central in the discussion offered by Taylor (2011). In any case, these deviations reveal the moments and size of a discretionary monetary policy.[22]

To conclude, this section reveals that the long-run link among the variables under study is an interest rate rule: the estimated (without prior assumptions) relation is similar to the Taylor rule and behaves as a reaction function. The dynamics generated by the model are in line with such a rule and demonstrate that inflation is effectively brought down after a policy contraction. What is more, despite the chairmanship changes and the diverse circumstances, the target path is stable throughout almost three decades, this being an essential feature for a rule to be instructive.

4.2. Model with post-2008 data

Let us now see how this path copes with the turmoil around 2008. The sample period is prolonged to include the financial crisis and the subsequent 'great recession' and ends in 2015, i.e. just after the conclusion of Bernanke's chairmanship in the Federal Reserve. This extension covers an extraordinary period where the Fed and other central banks drive their policy rates to zero and experiment with (the implementation and later containment of) unconventional policy interventions.

As commented in the preliminary analysis, there is evidence of one common stochastic trend connecting the federal funds rate, real output and the inflation rate during this period, which includes the mandates of Paul Volcker, Alan Greenspan, Ben Bernanke and the first year of Janet Yellen. Leaving aside the concerns over the binding zero lower bound and the complexity of real time decision making, our objective

[19] In relation with the effects of a contractionary monetary policy shock, Bachmann et al. (2021, p. 2), by means of an original identification of monetary policy shocks and assuming the Fed observes the Taylor rule with error, confirm that "… [it] has a limited negative effect on output but a persistent negative impact on prices" for the period 1987 to 2008 and using the same series for real output and prices as we do. As regards the output response in specific, let us stress that with the 68% confidence interval it turns out to be significantly negative in the third and fifth quarter. Similarly, Arias et al. (2019), with US data and an alternative approach, also find that an increase in the federal funds rate induces a contraction in output, which, when accompanied with 95% bands is in fact insignificant.

[20] The Chow Forecast test reports bootstrapped p-values over 1000 replications. The recursive loading coefficients are plotted together with two-standard error bands in the following order: $\alpha_{\Delta is}$, $\alpha_{\Delta^2 p}$ and $\alpha_{\Delta y}$. The recursive eigenvalue is plotted together with the estimated confidence interval using full sample estimates of the standard errors. The tau statistic is plotted together with the 5% critical value. For further details, the reader is referred to Lütkepohl and Krätzig (2004).

[21] The no rejection of non-normality concerns just the residuals of the interest rate equation, and, as discussed in Lütkepohl and Krätzig (2004), it is neither rare nor troubling.

[22] A similar interpretation is put forward by Christensen and Nielsen (2009) within a comparable framework.

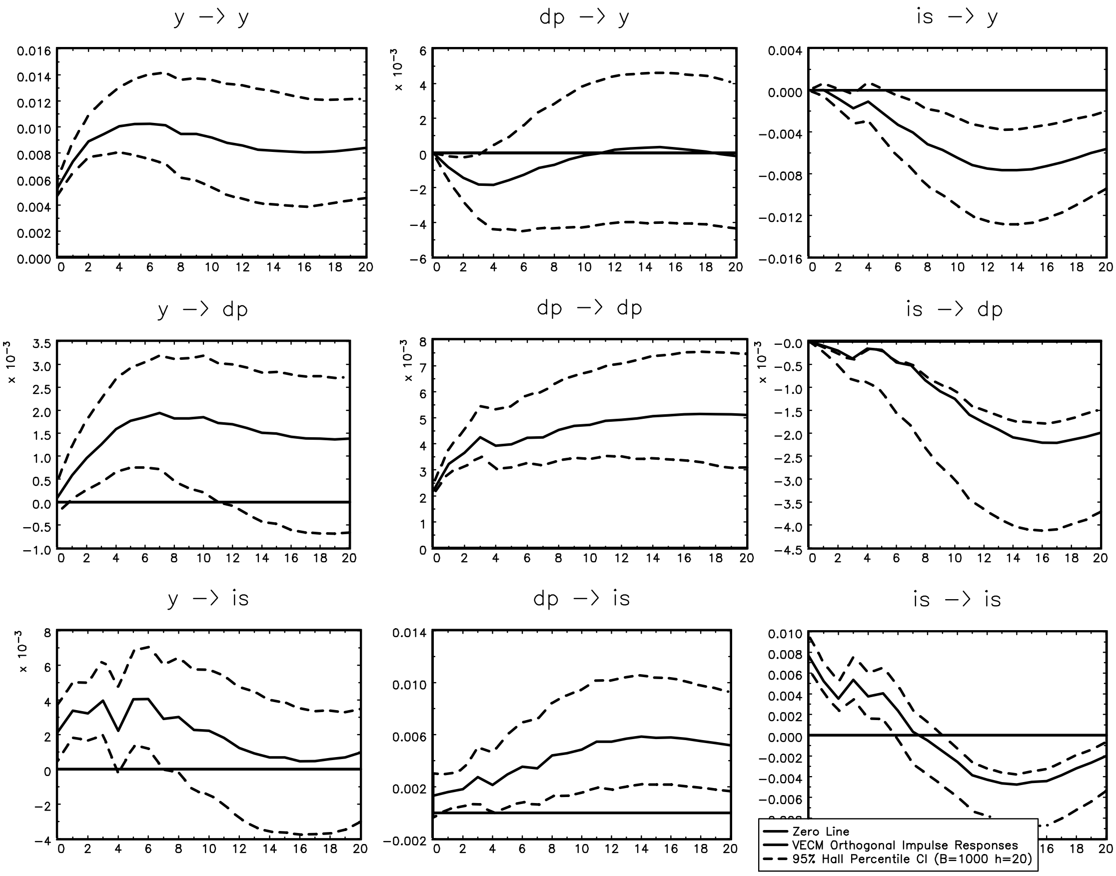

Fig. 3. Impulse responses for the 1979–2015 model.

here is to uncover what the equilibrium relation connecting the three variables looks like and whether it is different from the target path described for the pre-2008 period.

The employed VEC model includes one cointegrating relationship and a lag order of 5 quarters. As for the deterministic terms, two impulse dummies are incorporated; the first for the fourth quarter of 1980 and the second for the same quarter of 1984. All the clarifications regarding the specification of the model are provided in the previous section.

The cointegrating relationship (with the coefficient of the short-term rate normalised to 1, the standard errors reported in curly brackets and the t-statistics in parentheses) is estimated as follows:

$$is_t = \underset{\substack{\{0.058\} \\ (0.018)}}{0.001} y_t + \underset{\substack{\{0.239\} \\ (4.157)}}{0.992} \Delta p_t - \underset{\substack{\{0.000\} \\ (-1.542)}}{0.001} Trend_t \qquad (3)$$

or $is_t = 0.992 \Delta p_t$.

The coefficient accompanying output is insignificant and the trend adjusted real output drops out of the target rule. Like in the baseline model, the inflation rate enters with the expected sign and its coefficient is practically equal to unity and is not statistically different from the one reported in Eq. (2).[23]

As regards the loading coefficients, they are negative and highly significant meaning that the above cointegrating relationship enters in each of the three equations in an equilibrium-correcting manner.[24] In

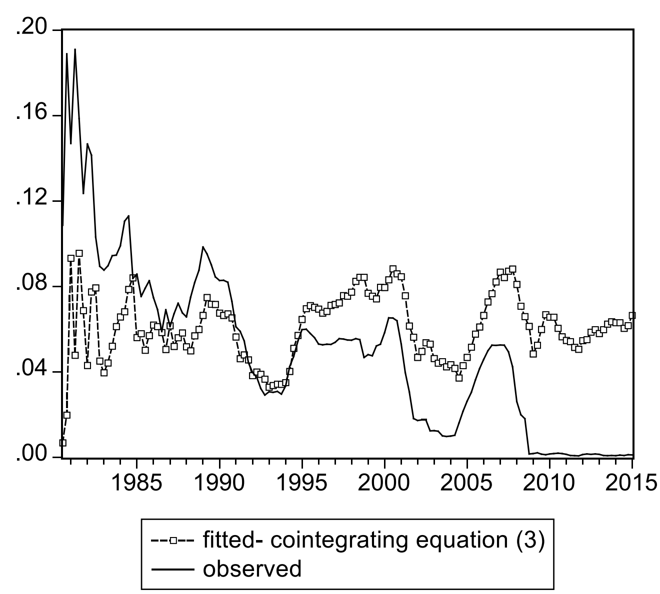

Fig. 4. Fit of the cointegrating equation for the 1979–2015 model.

[23] With data until 2011, Kumar (2013) reports an inflation coefficient not statistically different from ours; at the same time, and contrary to our findings, he argues that the weight on the output gap increased after the crisis. Belke and Klose (2013) also find a higher response to the output gap during the crisis (with data until 2010).

[24] The loading coefficients correspond to the reduced model, the restrictions of which are not rejected with a p-value of 0.61 in a $\chi^2(30)$ distribution.

the case of the interest rate equation, this implies that Eq. (3) serves as a policy reaction function. The coefficient is almost threefold in comparison with the baseline model, and thus, when a deviation arises, it takes only 10 months to return to the target path (described by Eq. (3)). This evidence of less smoothing in the policy rate is in line with Mishkin (2009, 2010) who argues that during atypical circumstances the central bank ought to be flexible and show less inertia and gradualism.[25] As for output and inflation, a say positive deviation from the target path causes both to go down.[26]

Since the residual correlation matrix contains at least two significant off-diagonals, the orthogonal impulse responses are computed (with the adequate ordering of the variables) and are plotted in Fig. 3 with the 95% confidence interval determined by the Hall bootstrap procedure.[27] Within the context of an interest rate rule, the third row displays that an impulse in output or inflation induces a significant increase in the short-term rate, a reaction that is consistent with such rule. Additionally, the third column displays how an impulse in the policy rate induces a significant and long-lasting fall both in output and the inflation rate. Overall, the generated dynamics are correct and as expected.

As in the case of the baseline model, stability is explored with a battery of tests presented in Figs. 12–15 in the Appendix.[28] The Chow Forecast test is run over every second datapoint and does not reject parameter constancy, despite the shift around 2008. With the cointegrating relation fixed and equal to (3), the loading coefficients are estimated recursively, and as shown in Fig. 13, they are negative and significant all the way through. Then, with the short-term parameters of the model fixed to their estimated values, the cointegrating relation is estimated recursively: Fig. 14 shows the recursive eigenvalue and Fig. 15 the tau statistic and both reveal that the cointegrating relation remains stable.

As for the residual analysis, the tests reported in Table 9 (in the Appendix) indicate that the residuals are free of autocorrelation, but not of autoregressive conditional heteroskedasticity. In particular, the residuals of the interest rate equation are characterised not only by ARCH effects, but also by autocorrelation and non-normality.

Fig. 4 depicts the observed interest rate series (solid line) together with the fitted values of the cointegrating relation (dashed line with rectangular patterns). Keep in mind that neither the dummies, nor the loading coefficients, nor the constant or any other short-run dynamics are included in the cointegrating relation and therefore their effect is left out of the picture. In this context, Eq. (3) replicates well the fluctuations of the historical values at least since 1988, i.e. from the Greenspan chairmanship onwards, which is quite an achievement for a rule with a sole indicator.[29] However, since 1995, its prescriptions fail to approximate the level of the funds rate as they are persistently above it.

It is worth highlighting that, despite some failings, the present model is run over thirty-five years of heterogeneous economic conditions and reveals the firm characteristics of policy-setting in the US. To start with, the long-run relation establishes that there is always a strong response of the policy rate to inflation.[30] Furthermore, the impulse response analysis validates that a contraction of the policy rate effectively reduces inflation and shows how the policy rate reacts to shocks in real output and inflation.

Employing the shadow rate. Now the federal funds rate is replaced with the Wu and Xia (2016) shadow rate from the third quarter of 2008, when the zero lower bound comes into effect, and until the end of the sample.[31] As the cointegration tests again indicate one common stochastic trend, a VEC model is estimated (with the same lag order and impulse dummies as before) and the cointegrating vector turns out as follows ($issh_t$ indicates the combined interest rate series, the standard errors are reported in curly brackets and the t -statistics in parentheses):

$$issh_t = \underset{\substack{\{0.061\} \\ (1.607)}}{0.098} y_t + \underset{\substack{\{0.248\} \\ (4.266)}}{1.058} \Delta p_t - \underset{\substack{\{0.000\} \\ (-3.289)}}{0.001} Trend_t \tag{4}$$

or $issh_t = 1.058\Delta p_t - 0.001 Trend_t$.

It is noteworthy that this (unrestrictedly estimated) vector shares the same inflation rate coefficient as the cointegrating relationship featuring is_t for the same period. Its main difference with Eq. (3) is that the trend enters significantly, to capture the downward tendency in the combined $issh_t$ series.

As for the loading coefficients, they are identical to the ones of Eq. (3), except for $\alpha_{\Delta^2 p}$ which is insignificant. This finding implies that inflation does not react to Eq. (4) and informs of a modification in the dynamics of inflation when unconventional policy is brought into play. In line with this, the impulse response analysis indicates that an impulse in the combined interest series induces a shift in inflation in the same (and not the opposite) direction.

The impulse responses describing the reaction of the combined interest rate series to real output and inflation are as depicted previously, i.e. in accordance with an interest rate rule. The conclusions of the stability and residual analysis also remain unaltered.

4.3. A robustness exercise

To contrast the findings of our multivariate modelling approach, the sample period is now cut short to coincide with the one considered in Clarida et al. (1998, CGG henceforth) who employ a one-equation framework, use monthly data and assume stationarity. To be more specific, the sample contains 64 quarters and finishes in 1994. With a lag order of 5 quarters and no dummies, the estimated cointegrating relationship (as previously, with the coefficient of the short-term rate normalised to 1, the standard errors reported in curly brackets and the t-statistics in parentheses) is

$$is_t = \underset{\substack{\{0.106\} \\ (4.052)}}{0.43} y_t + \underset{\substack{\{0.181\} \\ (6.196)}}{1.122} \Delta p_t - \underset{\substack{\{0.001\} \\ (-5.385)}}{0.004} Trend_t \tag{5}$$

or $is_t = 0.43(y_t - 0.0093 Trend_t) + 1.122\Delta p_t$.

Once again, the cointegrating relationship between the policy rate and the two indicators that describe the state of the US economy is similar

[25] Belke and Klose (2013) also find a lower degree of monetary policy inertia both for the Fed and the European Central Bank during the 2008 crisis.

[26] Unlike us, Ghiani et al. (2016) report that inflation does not react to a cointegrating relation between the short-term interest rate, inflation, unemployment and money supply growth (with data until 2012).

[27] Note that the orthogonal impulse responses are based on an innovation of size one standard deviation. As explained in a previous footnote, output is placed first, followed by inflation and finally the interest rate. An additional reference on the recursive ordering within the impulse response analysis is Breitung et al. (2004).

[28] Footnote 20 contains additional information on the stability tests.

[29] The correlation coefficient between 1989 and 2008 equals 0.55.

[30] Similarly, Aguiar-Conraria et al. (2018) report a strong and stable preference for inflation stability within the Taylor rule, employing real-time data from 1965 to 2017. For the same period as in our extended model, Laubach and Williams (2016) argue that a strong response to inflation in the context of a Taylor rule is a way to cope with the uncertainty in measuring the natural rate of interest.

[31] We owe this addition to an anonymous referee whom we thank. For the sake of brevity, we summarise the main findings and make the detailed results available upon request. As for the choice of the Wu and Xia (2016) shadow rate, it is backed by its popularity within the literature (for example, Aguiar-Conraria et al. (2018), Nikolsko-Rzhevskyy et al. (2019), Bachmann et al. (2021), Gross and Zahner (2021), Kumar et al. (2022)). The Appendix offers additional information on the series.

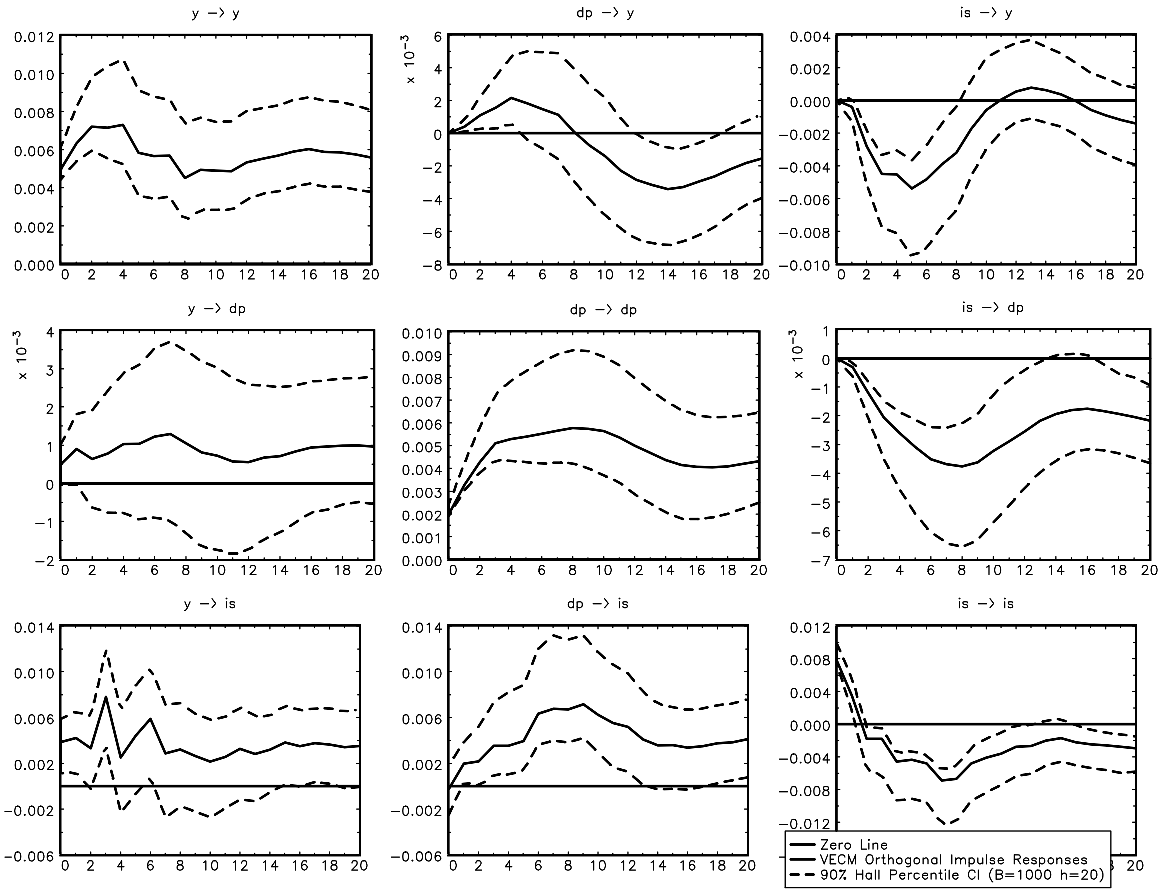

Fig. 5. Impulse responses for the 1979–1994 model.

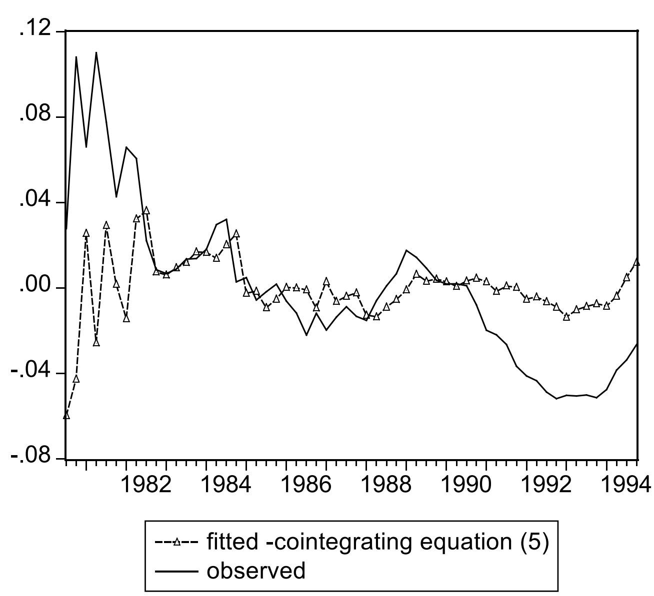

Fig. 6. Fit of the cointegrating equation for the 1979–1994 model.

to a Taylor type rule. The inflation rate enters with the expected sign and its coefficient is larger than unity — this is a characteristic shared with Taylor (1993) and CGG. This inflation coefficient is identical to the one reported in Eq. (2) and is not statistically different from the one reported in Eq. (3). Regarding output, and unlike CGG where the output gap enters insignificantly, the coefficient of the trend adjusted real output has the expected sign and is remarkably close to the output gap coefficient suggested by Taylor (1993). The average real output growth per quarter is estimated to be 0.9% (i.e., 3.6% per year).[32]

CGG consider various specifications of the rule and argue that the Fed is forward-looking; our modelling structure embraces all possible specifications through the cointegrating relation. CGG modify the rule specifically for the Fed to capture interest rate smoothing in a sufficient way; in our modelling structure the rule forms part of a dynamic model with an integrated adjustment mechanism. In this sense, the loading coefficients indicate that the cointegrating relationship enters the three equations of the model in an equilibrium-correcting manner and Eq. (5) can indeed be interpreted as a policy reaction function.[33] In comparison with the values reported for the other sample periods, here $\alpha_{\Delta is}$ is high (equal to 0.92 in absolute terms) and this means that throughout the years 1979 to 1994 there is not much interest rate smoothing. To be more specific, a negative 1 percentage point deviation (of the interest rate from the target path described by Eq. (5)) triggers an increase of 92 base points in the policy rate in the next quarter; thus it takes less than four months to return to the target path.[34]

The residual correlation matrix contains a relatively large off-diagonal and for this reason the dynamics of the model are explored by means of orthogonal impulse responses. These are derived with the endogenous variables ordered as described in a previous footnote

[32] The observed average real output growth for the corresponding period is 0.7% quarterly and 2.8% annually.

[33] As earlier, the subset restricted model is considered, with the p-value of the restrictions being 0.99 in a $\chi^2(24)$ distribution.

[34] In relation with interest rate smoothing, Bunzel and Enders (2010) also inform of less inertia when inflation is high (from 1979 to 1991) than when inflation is low (between 1991 and 2007).

and are plotted in Fig. 5 together with the 90% confidence interval based on the Hall bootstrap procedure. On the one hand, the third row shows that an impulse in output or inflation produces an increase in the interest rate, confirming the relevance of the proposed rule. And, on the other hand, the third column shows that a policy tightening produces the expected negative effects on output and inflation.[35]

As regards the fitting of the model, the results are good: the Chow Forecast test does not reject parameter constancy; the recursive loading coefficients remain negative and significant; the recursive estimation of the long-run part of the model indicates stability; and the residuals of the model are free of autocorrelation and of autoregressive conditional heteroskedasticity and also seem to be normally distributed.[36]

To conclude, Fig. 6 plots the observed interest rate together with the fitted values generated by Eq. (5), both as deviations from their means; the former is depicted as a solid line and the latter as a dashed line with triangular patterns. Despite the deviations, that are partly attributed to the exclusion of the short-run dynamics from the picture, the correlation coefficient of the two series goes up to 0.73 for the central period.

5. Conclusions

The challenges for monetary policy nowadays are multiple and diverse in nature: the slowdown due to the pandemic and the uncertainty, together with rising prices in the short term; the crave for central banks independence; the prospect of central-bank digital currencies; and the here to stay international interdependence. At this juncture monetary policy-making in the US is examined during various decades that are characterised by remarkable occasions such as the ‘great inflation’, the ‘great moderation’, and the ‘great recession’ along with four chairmanship changes.

A common stochastic trend between the federal funds rate, the inflation rate and real output is brought to light. This contribution is novel and fundamental; without such long-run bond it would be senseless to continue considering the prescriptions of an interest rate rule. Besides, it is shown that this equilibrium relation indeed qualifies as a target path for the federal funds rate and, in this sense, manifests a rule-based policy-making. On the other hand, by contemplating deviations from the path, the employed dynamic framework reveals moments of discretionary monetary policy and quantifies the dynamic adjustment to the benchmark rule. Thus, the two standpoints regarding policy-making are brought together and are appropriately modelled.

The estimated long-run target path for the US rate bears resemblance to the well-known Taylor rule and for all the periods under study it delivers a strong response to inflation. This means that the Fed, always, and no matter what, seeks to stabilise the inflation rate. The generated impulse responses put forward other solid outcomes, according to which, the federal funds rate reacts to shocks in real output and inflation in line with the rule and, as regards the transmission of monetary policy-setting, a contraction of the policy rate effectively reduces inflation.

These characteristics survive the inclusion of the ‘great recession’ and the first years after it, and the same happens with the evidence in favour of a common stochastic trend between the three time series. The model with post-2008 data delivers a target path where only the inflation rate enters significantly and produces a much less gradual adjustment to deviations from it. Replacing the federal funds rate with a shadow rate, reproduces a similar target path and, as previously, captures a flexible and swift reaction of the combined interest rate series to the atypical circumstances. It is of interest though that this model brings forth ineffective inflation control, indicating that the dynamic behaviour of inflation is affected by the implementation of unconventional policy when the zero lower bound applies.

All in all, our findings enrich the description of policy-making of a major central bank, and thus contribute to the accountability and predictability of its decisions. Cross-checking the target paths of other central banks and their interdependence remain open questions. As regards future research, considering the different sources of inflation and an even longer sample shall cast light on what it takes to achieve and maintain control over inflation.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

Appendix

A.1. Data description

The time series are quarterly observations of seasonally adjusted data extracted from the FRED database. The codes and detailed information are as follows:

- GDPC1 — Real Gross Domestic Product, Billions of Chained 2009 Dollars, Quarterly, Seasonally Adjusted Annual Rate. Link: https://fred.stlouisfed.org/series/GDPC1. Transformation: natural log of the original series. Notation: y_t (y or Y in the figures), Δy_t (or Y_D1) when referring to its first difference.

- GDPDEF — Gross Domestic Product: Implicit Price Deflator, Index 2009 = 100, Quarterly, Seasonally Adjusted. Link: https://fred.stlouisfed.org/series/GDPDEF. Transformation: natural log of the original series and year-to-year difference. Notation: Δp_t (dp or DP in the figures), $\Delta^2 p_t$ (or DP_D1) when referring to its first difference.

- IRSTFR01USQ156N — Immediate Rates: Less than 24 h: Federal Funds Rate for the United States (Organization for Economic Co-operation and Development, Release: Main Economic Indicators), Quarterly, Not Seasonally Adjusted. Link: https://fred.stlouisfed.org/series/IRSTFR01USQ156N. Transformation: original series divided by 100. Notation: is_t (is or IS in the figures), Δis_t (or IS_D1) when referring to its first difference.

The Wu and Xia (2016) shadow rate is extracted from the web page of the Federal Reserve Bank of Atlanta. Link: https://www.atlantafed.org/cqer/research/wu-xia-shadow-federal-funds-rate. The original shadow rate is divided by 100 and is combined with the is_t series above (the is_t is used until the second quarter of 2008 and the shadow rate afterwards). The notation for the combined series is: $issh_t$.

A.2. Tables

Note on Tables 2 and 5 with the unit root tests: “c” stands for constant, “t” for linear time trend, “s81q3” for a shift dummy that equals 1 after 1981 third quarter, “i80q4” for an impulse dummy that equals 1 in 1980 fourth quarter (similarly for the other dummies), “Δ” for the first difference of the series; “AIC” and “HQ” refer to the Akaike and the Hannan–Quinn criterion respectively for the choice of the lag order with various maximum lags; “ADF” denotes the Augmented Dickey–Fuller test, “LLS” the Lanne et al. (2002) test and “KPSS” the Kwiatkowski et al. (1992) test. Asterisks $^{(*)}$, * and ** indicate that the null hypothesis (of a unit root for the ADF and LLS tests and of

[35] The qualitative findings remain unaltered if the forecast error impulse responses are computed.

[36] The employed tests are the same as before and the detailed results are available upon request.

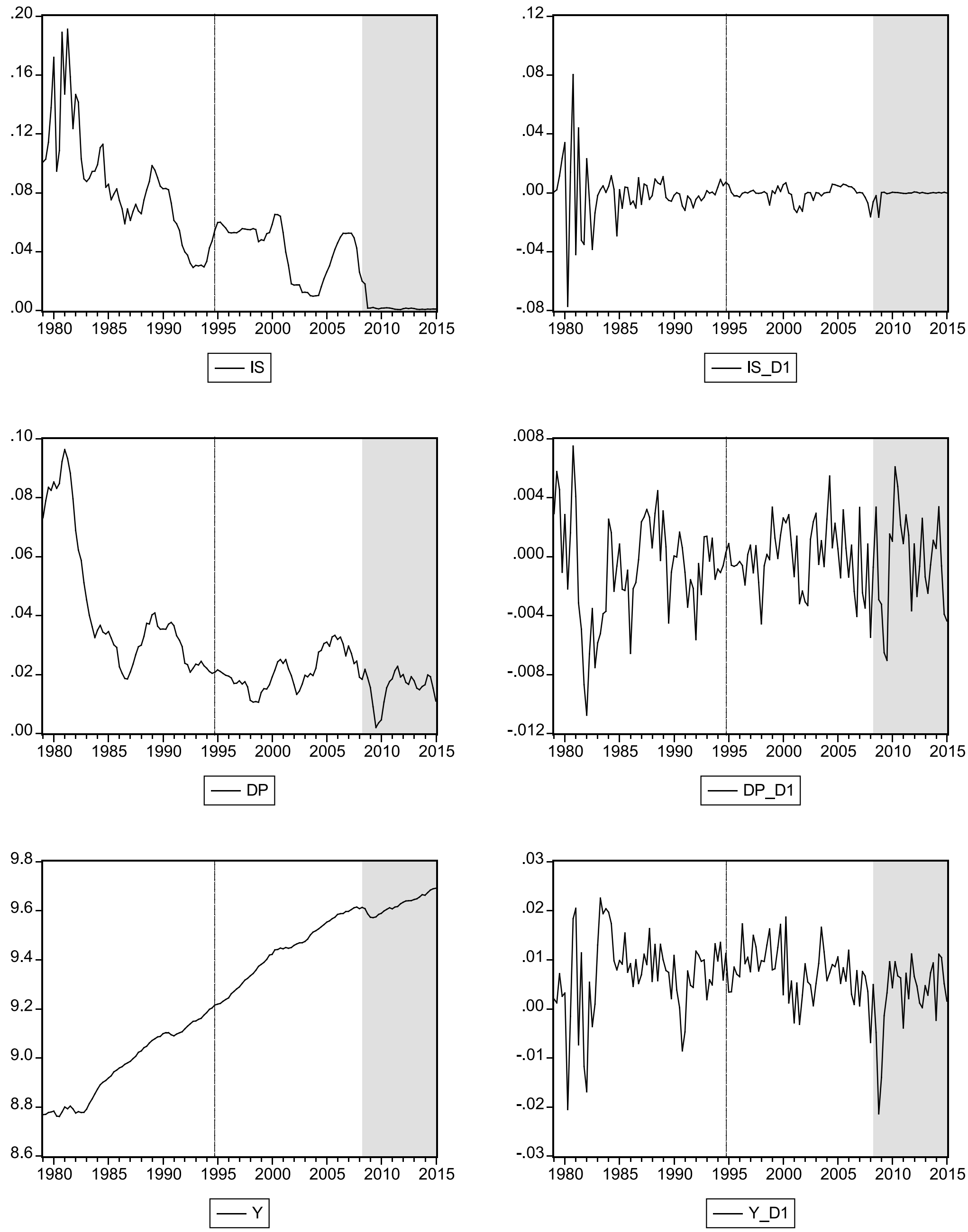

Fig. 7. Time-series in levels and first differences.

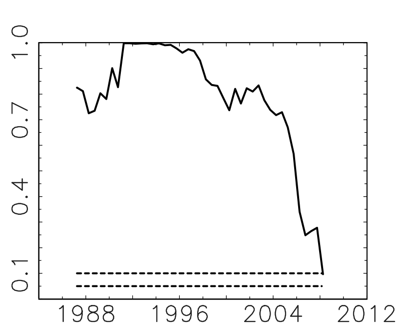

Fig. 8. Chow Forecast test for the 1979–2008 model.

stationarity for the KPSS test) is rejected at the 10%, 5% and 1% levels respectively. The date in the dummies is chosen by means of the search mechanism incorporated in the LLS test in JMulTi.

Note on Tables 3, 4, 6 and 7 with the cointegration tests: "c" stands for constant, "t" for linear time trend, "⊥" for orthogonal to cointegration relation, "i80q4" for an impulse dummy that equals 1 in 1980 fourth quarter (similarly for the other dummies); "AIC" and "HQ" refer to the Akaike and the Hannan–Quinn criterion respectively for the choice of the lag order with various maximum lags. The "statistic" and "pvalue" are obtained with JMulTi and correspond to Johansen (1995) for the Johansen trace test and to Saikkonen and Lütkepohl (2000) for the S&L test.

Note on Tables 8 and 9 with the residual analysis: PORT (k) is the Portmanteau test for kth order residual autocorrelation, LM(k) is a Lagrange multiplier test for kth order residual autocorrelation, ARCH

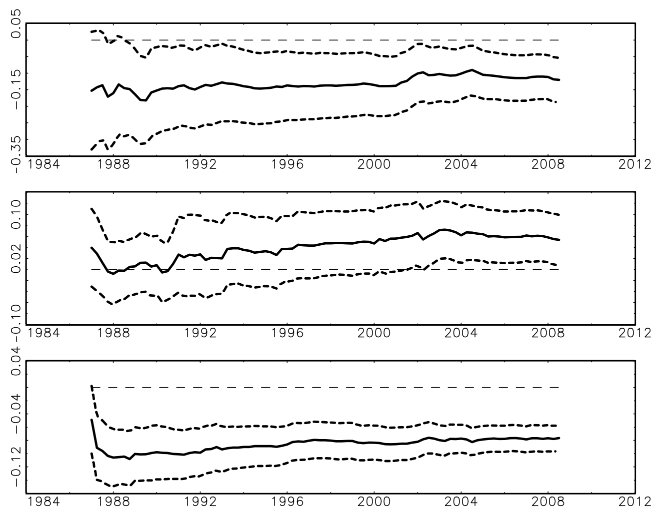

Fig. 9. Recursive loading coefficients for the 1979–2008 model.

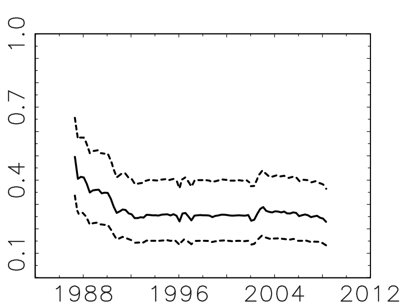

Fig. 10. Recursive eigenvalue for the 1979–2008 model (long-run part only)

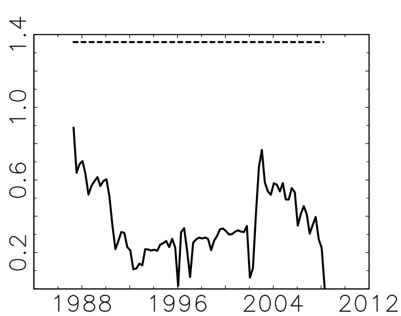

Fig. 11. Tau statistic for the 1979–2008 model (long-run part only)

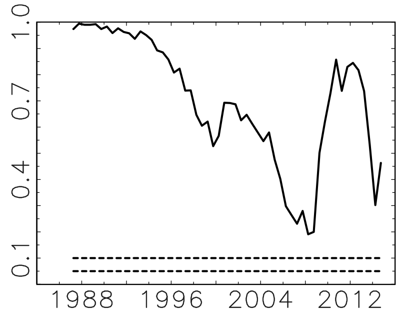

Fig. 12. Chow Forecast test for the 1979–2015 model.

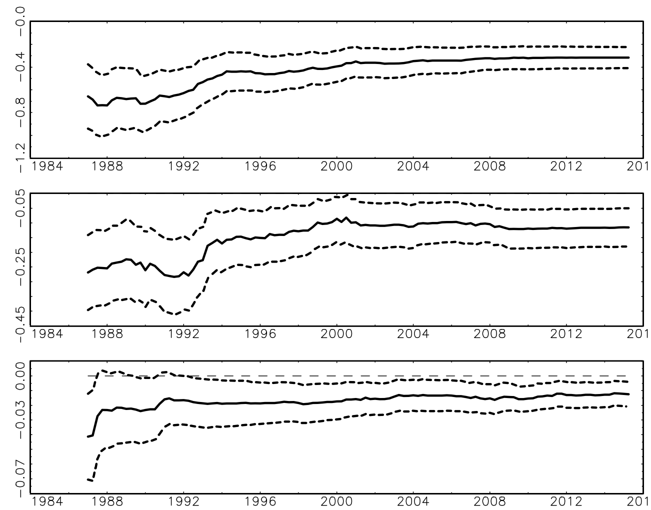

Fig. 13. Recursive loading coefficients for the 1979–2015 model.

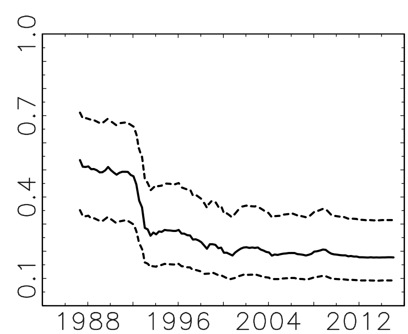

Fig. 14. Recursive eigenvalue for the 1979–2015 model (long-run part only)

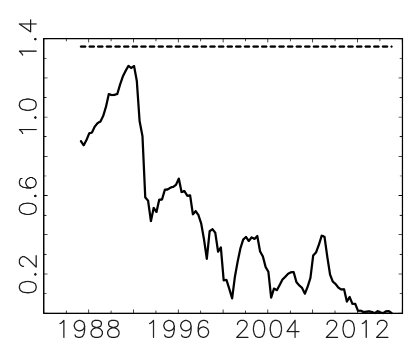

Fig. 15. Tau statistic for the 1979–2015 model (long-run part only)

(k) is a Lagrange multiplier test for kth order autoregressive conditional heteroskedasticity, JB is the Jarque–Bera test for non-normality. The values in parentheses besides the test statistics are the corresponding p-values. The top panel of the tables reports tests on the residuals of the model and the lower panel on those of the individual equations.

A.3. Figures

See Figs. 7–15.

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