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Research article

Non-linearities in the Phillips curve: Evidence from the euro area

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Abstract: Non-linearities in the inflation – output relationship at an aggregate or a sectoral level seems to be a particularly convincing explanation for the observed inflation dynamics in the post-pandemic period. Therefore, in this work, we tested the validity of cross-equation restrictions implied from an aggregate Phillips curve under linear and non-linear stochastic bivariate representations for core inflation and the output gap, using quarterly data from the euro area over the period 2000–2024. A novel feature of our approach was that we did not assume an expectations formation mechanism, but we restricted expectations to be consistent with the aggregate supply and a large information set that included the history of core inflation and the tightness of economic activity. The results provided strong support for the non-linearities argument in explaining the recent quick rise and the subsequent immaculate and rapid fall in inflation. An important policy implication is that the European Central Bank has rightfully not insisted on interest rate hikes, as the inflation episode appears to be mostly a supply side issue.

Keywords: Phillips curve; Markov switching regimes; vector autoregression; cross-equation restrictions

JEL Codes: E31, E32, E37

1. Introduction

The rapid increase in inflation following the covid-19 pandemic in many economies gave rise to two major approaches concerning the cost in terms of increased unemployment that would be necessary to curb inflationary pressures. The first came to be known as "team permanent" and held that, given the expansionary fiscal and monetary policies as well as the tightness of the labor market shown by the outward shift of the Beveridge curve, it would take a substantial increase in unemployment to rein in inflation. This approach is mostly influenced by the experience of the 1980s when the limited credibility of Central Bank anti-inflationary policies unanchored expectations and caused adverse shifts of a relatively flat Phillips curve. For a description of the major arguments of the "team permanent", see Domash and Summers (2022), Blanchard et al. (2022), Ball et al. (2022), Cecchetti et al. (2023).

The second approach, advanced by the so-called "team transitory" group, advocated a rather quick "soft landing", that is, a fast disinflation process without a noticeable negative impact on employment. The main theoretical underpinning here is a non-linear relationship between inflation and employment, which was proposed in the original Phillips (1958) paper and was revived in a New Keynesian (NK) setting by Benigno and Eggertsson (2023, 2024). However, there are two variants of the non-linearities story, which have quite different implications concerning the necessity for the pursuit of demand side policies. In the first variant, a tight labor market is associated with a steep segment of an economy-wide Phillips curve, which implies a quick rise in inflation after expansions in demand and/or negative supply shocks, but also an easy fall of inflation when a demand stimulus is eliminated. This variant seems to be a more plausible explanation of observed inflation dynamics when there is a substantial demand boost, as was the case over the pandemic period in the USA. However, in the absence of a fiscal stimulus, as has been the case in the euro area, similar inflation dynamics can be explained by non-linearities at a sectoral level, that is, kinks in sectoral supply relationships between price changes and employment induced by large shifts in consumer spending between durable goods and services after the covid-19 pandemic. This brings us to the second variant of the "team transitory" approach, which has been known as the sectoral shocks explanation and is described more analytically in Bernstein (2024) and Krugman (2024). According to this variant, the stressed sectors present steep segments in the relationship between price changes and employment as opposed to a flat corresponding relationship in other sectors and, therefore, the sudden change in the composition of consumer spending along with supply chain bottlenecks and rising energy prices contributed to extensive and quick price increases. Additionally, the sectoral shocks version suggests that the recent inflation episodes and the fast disinflation process were mostly due to supply side adjustments.

Regardless of the exact explanation for the "soft landing" of inflation, it appears that non-linearities in the inflation – employment or aggregate supply relationship hold a prominent place in reconciling observed dynamics with conventional theoretical predictions. That is, both a non-linear Phillips curve related to the economy as a whole and the sectoral shocks approach are predicated on the validity of non-linear relationships between price changes and employment. Therefore, in this work, we investigate whether a non-linear bivariate stochastic representation of the involved variables can generate forecasts compatible with the cross-equation restrictions implied by the Phillips curve and compare the performance of the non-linear process to that of a linear vector autoregressive model for the same variables. Moreover, we estimate a non-linear Markov switching regimes process using euro area data on core inflation and the output gap and rely on this information set to generate inflation expectations through the underlying stochastic representation instead of employing survey-based series on inflation forecasts. In other words, we let the data tell us whether there is a change in the slope of the inflation – output relationship as well as when such a change occurs. Then, the implied cross-equation restrictions on the parameters of the Markov process are tested through a Wald test and the same approach is repeated for a linear vector autoregressive process of the information variables. Thus, the novel feature of this approach is that we do not rely on an arbitrary expectations formation mechanism, but we use the model and the relevant information set to generate and restrict expectations. Furthermore, we enable linear or non-linear relationships between the involved variables through their representation by alternative linear and non-linear stochastic processes. The results reject the linear model and provide compelling evidence for the presence of non-linearities in the Phillips curve of the euro area over the period 2000–2024. These findings strongly suggest that the "team transitory" approach is a more promising explanation for the immaculate quick rise and fall of inflation in the eurozone, since detection of non-linearities at the aggregate level would certainly be the outcome of corresponding sectoral or country-specific relationships. Thus, given the absence of a substantial fiscal stimulus in the euro area over the post-covid19 period, the sectoral shocks variant takes prominence in describing inflation dynamics.

Some additional comments regarding the use of internally consistent expectations (also known as rational expectations), instead of survey-based expectations, are in order. Even though expectations consistent with the model in question may fail to account for broader factors that impinge on expectations, they are based on specific expectation functions in the history of the model's underlying variables, which can be used in deriving refutable parameter restrictions that can be tested against the data. The latter would be impossible if we use survey data or some other arbitrary expectation formation mechanism for which exact expectation functions are not known. Thus, the use of internally consistent expectations and the gain in terms of specifying exact refutable propositions comes at the expense of complete realism associated with survey-based forecasts. Nevertheless, it should be noted that lack of such an extensive degree of realism could be a major issue only if the restrictions derived from internally consistent expectations are rejected, as this would leave us with no alternative. As we shall see later, this is not the case in this work.

The paper is structured as follows: Some important related works are reviewed in the next section and then, in the third section, we outline the empirical methodology employed in econometric testing. In the fourth section, we describe the data and present our empirical findings. In the final section, we provide a synopsis and conclusions.

2. Related literature

Early empirical works following the pandemic era inflation suggested that a tight labor market would impose considerable costs in terms of increased unemployment in order to tame inflationary pressures. For example, Domash and Summers (2022) found that high vacancy rates in the USA have predictive power for wage inflation and concluded that the ensuing wage-inflation spiral would highly contribute to inflation for quite some time. Similarly, Blanchard et al. (2022) suggested that, given the observed economic activity and the characteristics of the labor market in the US, the Beveridge curve (the relationship between the vacancy rate and the unemployment rate) has shifted outward over the pandemic period, implying a very tight labor market which rather fades the hope for a "soft landing", that is, to curb inflation without substantial costs in unemployment. Additionally, Ball et al. (2022) attributed the rise in core inflation to a tight labor market and pass-through effects from past headline inflation shocks that seem to be related to energy prices and supply chain bottlenecks. Based on their findings about the tightness of the labor market, they suggested that the Fed's projections of the unemployment rate could hardly be reconciled with a low inflation target as this would require particularly favorable developments for inflationary expectations and the Beveridge curve.

Those in the "team transitory" camp advanced approaches compatible with a relatively quick round trip of inflation. For example, Benigno and Eggertsson (2023, 2024), in an effort to revive Phillips' (1958) original idea, put forward a New Keynesian (NK) model of the Phillips curve in which non-linearities arise from an imperfect labor market whose tightness is measured by the ratio of job vacancies to unemployed workers. In this setting, they introduce a Beveridge-type threshold, that is, a value of that ratio above which the labor market becomes very tight and the NK Phillips curve very steep. Such changes in slope may explain the sudden surge in inflation in response to demand and supply shocks, as well as the quick disinflation process, without considerable costs in increased unemployment when a demand stimulus recedes.

Krugman (2024) pointed out that even in the presence of non-linearities in the inflation-output relationship, there are two distinct explanations for the immaculate disinflation following the covid-19 pandemic. The first relies on a non-linear Phillips curve, the one advocated by Benigno and Eggertsson (2023, 2024), whose steep segment appears when the economy is running hot and implies an easy up – easy down inflation trajectory. The second involves sectoral shocks arising from shifts in consumer spending from services to durable goods which introduce non-linearities (kinks) in sectoral supply relationships. That is, steep segments of the supply curve appeared in some overheated sectors while others exposed a flat relationship between price changes and output. Thus, in the presence of fiscal and monetary stimuli, the stressed sectors contributed to a rapid increase in prices while sectors with loose demand did not experience considerable employment loss, which would have been the case without aggregate demand stimuli. Krugman (2024) suggested that the sectoral shocks approach is a more plausible explanation for the quick rise and fall of inflation since other economies, like the euro area, exhibited similar inflation dynamics in the absence of a generous fiscal expansion that characterized the US economy. Thus, the quick disinflation process seems to be more of a supply side story than a demand side policy.

The empirical relevance of the sectoral shocks approach was examined by Bernanke and Blanchard (2023) who estimated a simple dynamic model of prices, wages, and inflation expectations for the USA and reported evidence that the surge in the pandemic era inflation was mainly due to increases in commodity and sectoral goods prices, which resulted from drastic changes in the level and sectoral composition of demand along with substantial constraints on sectoral supply. Additionally, Bernanke and Blanchard (2024) reported estimates of the same model for ten other economies (including the Euro area, the UK, Japan, and Canada), which show similar results to those for the USA, namely that the initial inflation surge was driven by relative price shifts and sectoral shortages and only the relative importance of the contributing factors appears to differ across countries. In addition, the model traces varying degrees of labor market tightness in different economies, which may affect the speed of the disinflation process but, overall, the sectoral shocks seem to have rather transitory effects mainly due to firmly anchored inflation expectations.

Similarly, Gagnon and Rose (2025) argued that US pandemic-era inflation was the result of the confluence of three factors, namely sectoral shocks, energy price hikes, and aggregate demand stimuli. Moreover, recent inflation dynamics exhibited remarkable resemblance to those of the Korean war period, the differences being a shorter period of durables demand boom and limited supply disruptions in the former case. Based on such observations, these authors too attribute initial worries about a high unemployment cost of disinflation in the 2020s to a misconception regarding unanchored inflation expectations that characterized the 1980s disinflation process.

At the US state-level, the empirical findings regarding the slope of the Phillips curve are rather mixed. More precisely, Kumar and Orrenius (2016) reported strong evidence of non-linearity and convexity based on data over the period 1982–2013, while the results of Hazell et al. (2022) suggest that the slope of the Phillips curve was rather small in the 1980s and has remained small since, implying that the disinflation of the 80s was due to shifting expectations whereas the stability of inflation in the aftermath was the outcome of anchored expectations.

Almost all researchers performing empirical work use either survey-based inflation expectations or assume some mechanism of expectations formation, thus making the results dependent on such mechanisms. In this work, however, we use the model to generate expectations that are implicitly based on a large information set that includes not only the past inflation history but also a measure of the production activity tightness, as reflected in the history of output gap values. This distinct empirical approach is outlined in the next section.

3. Empirical methodology

Consider an expectations-augmented Phillips curve or aggregate supply:

$$\pi_t = kx_t + \nu_t + \beta E_t \pi_{t+1}, \tag{1}$$

where π_t is the inflation rate, E_t denotes expectations as of time t, $k > 0$ if x_t is the output gap or $k < 0$ if x_t is the employment gap, $\beta < 1$, and ν_t is a supply shock.

Forward iteration of (1) gives:

$$\pi_t = k \sum_{m=0}^{\infty} \beta^m E_t x_{t+m} + \sum_{m=0}^{\infty} \beta^m E_t \nu_{t+m}, \tag{2}$$

where the first term in the r.h.s. of (2) is the sum of expected future output gaps, and the second term is the sum of expected future supply shocks. However, supply shocks are unpredictable and, given that π_t is finite, it must be the case that $\sum_{m=0}^{\infty} \beta^m E_t \nu_{t+m} \to 0$ and that the sum $k \sum_{m=0}^{\infty} \beta^m E_t x_{t+m}$ must converge since the gap x_t is stationary. Hence, by updating equation (2) and taking expectation as of time t, we obtain:

$$E_t \pi_{t+1} = k \sum_{m=1}^{\infty} \beta^{m-1} E_t x_{t+m}, \tag{3}$$

which can alternatively be given as:

$$E_t\pi_{t+1} = kE_t x_{t+1} + \beta E_t\pi_{t+2}. \quad (4)$$

Now let the vector series $\boldsymbol{z}_t = [\pi_t \quad x_t]'$ follow a non-linear Markov switching process:

$$\boldsymbol{z}_t = \boldsymbol{\mu}_{h_t} + \boldsymbol{u}_t, \quad \boldsymbol{u}_t \sim N(\boldsymbol{0}, \boldsymbol{\Sigma}_{h_t}), \quad (5)$$

where h_t is an unobserved state variable taking values in the set $\{1, 2\}$. That is, states 1 and 2 can be thought of as regimes of low and high inflation, respectively. Note that the variance of z_t is also state dependent since the variance-covariance matrix of the vector error term $\boldsymbol{u}_t$ depends on the realized regime.[1]

If the state variable h_t is assumed to follow an irreducible Markov chain with transition probabilities $p_{ij} = pr(h_t{=}j|h_{t-1}{=}i)$, where i, j denote regimes 1 or 2, the stochastic representation (5) can be estimated via the EM algorithm (see Hamilton, 1990, 1993), which relies on iterations on the normal equations that involve non-linear functions of the data. This procedure provides non-linear estimates of the model's 12 parameters, which include the transition probabilities, the means, and the variance-covariance matrices (Σ) for each state.

Forecasts of $\boldsymbol{z}_{t+m}$, based on time-t information, are given by

$$E(\boldsymbol{z}_{t+m}|I_t) = E_t\boldsymbol{z}_{t+m} = \boldsymbol{\delta}'_t\boldsymbol{P}^m\boldsymbol{\mu}_h, \quad (6)$$

where I_t is the available information set that includes the histories of $\boldsymbol{z}$ and h through time t, $\boldsymbol{\delta}'_t$ is the vector of state probabilities at time t, $\boldsymbol{\delta}'_t = [pr(h_t = 1|I_t) \quad pr(h_t = 2|I_t)]$ (also known as filter inferences as they obtain from a non-linear filter in the estimation process), $\boldsymbol{P}$ is the transition probability matrix

$$\boldsymbol{P} = \begin{bmatrix} p_{11} & p_{12} \\ p_{21} & p_{22} \end{bmatrix}, \quad (7)$$

and $\boldsymbol{\mu}_h = [\boldsymbol{\mu}_{h=1} \quad \boldsymbol{\mu}_{h=2}]'$ is a 2×2 matrix of state means.

Then, we can use equation (6) to generate non-linear forecasts of π_{t+1} and x_{t+1}, included in (3), and disentangle them by post-multiplying (6) by vector $\boldsymbol{e}_1 = [1 \quad 0]'$ for π_{t+1} and by vector $\boldsymbol{e}_2 = [0 \quad 1]'$ for x_{t+1}. That is, equations (4) and (6) give:

$$\boldsymbol{\delta}'_t\boldsymbol{P}\boldsymbol{\mu}_h\boldsymbol{e}_1 = k\boldsymbol{\delta}'_t\boldsymbol{P}\boldsymbol{\mu}_h\boldsymbol{e}_2 + \beta\boldsymbol{\delta}'_t\boldsymbol{P}^2\boldsymbol{\mu}_h\boldsymbol{e}_1. \quad (8)$$

These restrictions must hold for general probability vector $\boldsymbol{\delta}'_t$ and, therefore, the Phillips curve places the following cross-equation constraints on the parameters of the Markov switching process:

[1] A linear autoregressive part is not included in the Markov process because the focus is intentionally on the source of non-linearity, which comes from changes in regime, leaving the linear effect to the VAR process discussed later. Our main concern here is to distinguish non-linear and linear forecasting functions in the history of relevant variables, and we do not really use a variable of expected inflation to estimate a Phillips curve. Instead, we focus on cross-equation restrictions implied by the underlying aggregate supply relationship.

$$\boldsymbol{P}(\boldsymbol{I}-\beta\boldsymbol{P})\boldsymbol{\mu}_h\boldsymbol{e}_1 = k\boldsymbol{P}\boldsymbol{\mu}_h\boldsymbol{e}_2. \tag{9}$$

Note that even though k is not included in the switching parameters, and is thus taken as prespecified in econometric testing, the Markov process implies a switching slope of the Phillips curve since core inflation and the output gap are allowed to vary between regimes. Indeed, if we solve equation (4) for k, we have:

$$k = \frac{E_t\pi_{t+1} - \beta E_t\pi_{t+2}}{E_t x_{t+1}}, \tag{10}$$

which, under the switching representation (5), shows that k is state-dependent because expectations depend on the regime at time t. Thus, to explore the effect of small or big changes in the slope, we examine several values for k in testing the cross-equation restrictions in equation (9). Additionally, as in Hazell *et al*. (2022), parameter β is set at $\beta = 0.99$.[2]

The validity of these restrictions can be tested through a Wald test based on deviation $\boldsymbol{\lambda} = \boldsymbol{P}(\boldsymbol{I} - \beta\boldsymbol{P})\boldsymbol{\mu}_h\boldsymbol{e}_1 - k\boldsymbol{P}\boldsymbol{\mu}_h\boldsymbol{e}_2$, and the relevant statistic is:

$$W = \boldsymbol{\lambda}'\left[\frac{\partial\lambda}{\partial\boldsymbol{b}'}Var(\boldsymbol{b})\frac{\partial\lambda}{\partial\boldsymbol{b}}\right]^{-1}\boldsymbol{\lambda} \rightarrow \chi^2(r), \tag{11}$$

where $\boldsymbol{b}$ is the vector of model parameters (12×1 in the case of the bivariate model) with variance-covariance matrix Var($\boldsymbol{b}$), and $\chi^2(r)$ is a chi-square distribution with r degrees of freedom, r being the number of constraints. Under the Markov process, $\boldsymbol{\lambda}$ is a 2×1 vector, so $r = 2$, and the partial derivatives in equation (11) can be computed numerically.

Next, consider an alternative linear stochastic representation for the vector series $\boldsymbol{z}_t = [\pi_t \quad x_t]'$, specifically a vector autoregressive model with p lags [VAR(p)]:[3]

$$\boldsymbol{z}_t = \sum_{i=1}^{p}\boldsymbol{B}_i\boldsymbol{z}_{t-i} + \boldsymbol{u}_t, \tag{12}$$

whose first-order companion form is:

$$\boldsymbol{y}_t = \boldsymbol{A}\boldsymbol{y}_{t-1} + \boldsymbol{\xi}_t, \tag{13}$$

and $\boldsymbol{y}_t$ is the $2p$×1 vector $\boldsymbol{y}_t = [\pi_t \,..\, \pi_{t-p+1} \; x_t \,..\, x_{t-p+1}]'$, $\boldsymbol{A}$ is a $2p$×$2p$ matrix of coefficients, and $\boldsymbol{\xi}_t$ is a $2p$×1 vector of residuals.

Using the companion form (13), we can generate expectations of $\boldsymbol{y}_{t+m}$ as:

$$E(\boldsymbol{y}_{t+m}|I_t) = E_t\boldsymbol{y}_{t+m} = \boldsymbol{A}^m\boldsymbol{y}_t, \tag{14}$$

and disentangle expectation of π and x by pre-multiplying (14) by the $2p$×1 vectors $\boldsymbol{e}_1$ and $\boldsymbol{e}_2$ with unity in rows 1 and p+1, respectively, and zeroes elsewhere. Thus, equations (3) and (14) imply:

[2] Hazell et al. (2022) have argued that in a New Keynesian setting with transitory supply shocks, inflation expectations affect current inflation one-for-one.

[3] It should be noted that in the empirical estimations of the next section, all variables enter the VAR in deviations from their means to account for potential effects of constant terms.

$$e_1' A y_t = k \sum_{m=1}^{\infty} \beta^{m-1} e_2' A^m y_t,$$

$$e_1' A y_t = \frac{k}{\beta} \sum_{m=1}^{\infty} \beta^{m} e_2' A^m y_t,$$

$$e_1' A y_t = k e_2' A (\mathbf{I} - \beta A)^{-1} y_t, \tag{15}$$

where the infinite sum converges when y_t is stationary.

Then, under a linear VAR representation of inflation and output gap dynamics, the Phillips curve implies the following set of 2p restrictions on the VAR parameters:

$$e_1' A = k e_2' A (\mathbf{I} - \beta A)^{-1}. \tag{16}$$

These can also be tested via the Wald statistic given in equation (11), only with $\lambda = e_1' A - k e_2' A (\mathbf{I} - \beta A)^{-1}$ and a limiting distribution $\chi^2(2p)$, i.e., with 2p degrees of freedom. Again, following Hazell et al. (2022), parameter β is set at $\beta = 0.99$.

4. Data and results

Quarterly data on harmonized core inflation[4] for the euro area are drawn from the OECD's statistical database (https://data-explorer.oecd.org/), economic outlook section, and they cover the period from 2000Q1 to 2024Q4 (100 observations). Additionally, the euro area output gap, measured as percentage of potential output, is computed using quarterly data on real GDP and potential output (chain-linked volume) drawn from the same OECD database and for the same period. Summary statistics of these variables are given in Table 1, and the series are depicted in Figure 1.

Table 1. Summary statistics for euro area variables.

	Harmonized Core Inflation	Output Gap
Mean	1.68	−0.36
Standard Deviation	1.05	2.41
Max	5.51	3.75
Min	0.25	−14.96
Observations	100	100

Notes: Quarterly data from 2000Q1 to 2024Q4. Core inflation in percentage and output gap in percentage of potential output.

[4] We use core inflation to capture the fundamental relationship between the tightness of economic activity and inflation, which might be obscured by the use of headline inflation. Indeed, headline inflation includes transitory price changes related to food and energy prices, which operate as supply shocks that shift aggregate supply without necessarily changing its slope. Additionally, recent evidence reported by Ball et al. (2022) with data from the US suggests that transitory headline inflation shocks do not pass through to core inflation. The use of headline inflation then would only make it hard to distinguish the effects of transitory supply shocks and those due to economic slack.

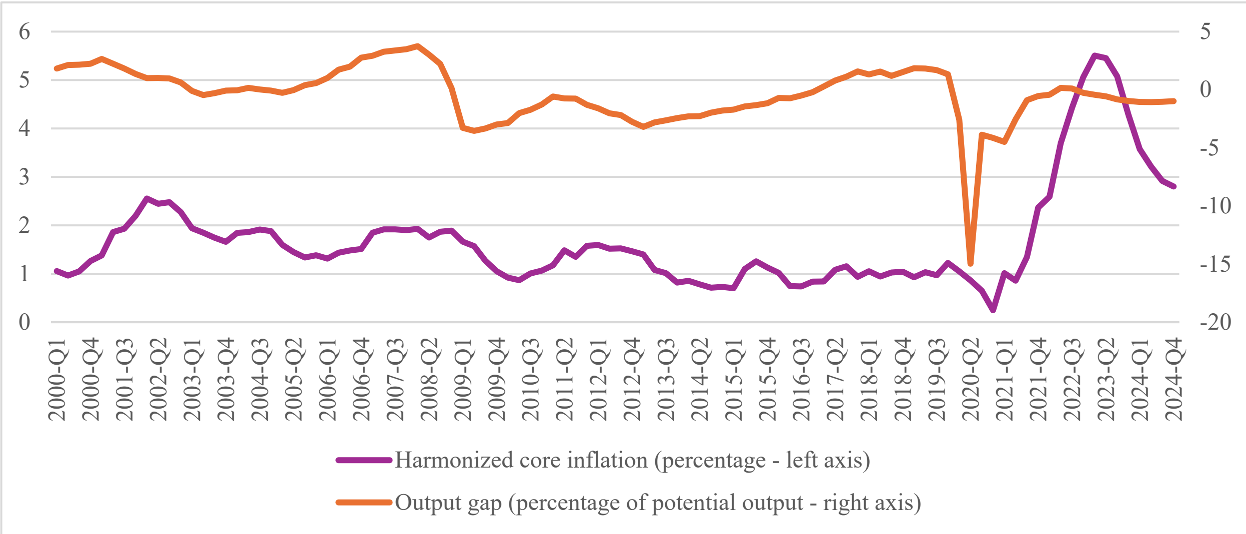

Figure 1. Euro area series.

To avoid biased test procedures, the representations in equations (5) and (12) must be estimated on stationary variables. Therefore, in Table 2, we report two tests for unit roots, which provide solid evidence that the levels of the harmonized core inflation and the output gap series are stationary. The KPSS test (Kwiatkowski et al., 1992) is appropriate for the null that a series is stationary, whereas the null for the augmented Dickey-Fuller (ADF) test is that a series has a unit root (Dickey and Fuller, 1979). The reason we include the ADF test with a break is the sudden jump that both variables presented over the covid-19 pandemic, as can be seen in Figure 1. Thus, in the following estimations, we use the levels of the series.

Table 2. Unit root tests for euro area variables.

	Core Inflation (levels)	Output Gap (levels)
KPSS test	0.218 *	0.384*
ADF test with break	−4.592*	−5.373*

Notes: Quarterly data (2000Q1–2024Q4, 100 observations). The null hypothesis for the KPSS test is that the series is stationary, whereas for the ADF with a break test, the null hypothesis is that the series has a unit root. Critical values at the 5% significance level are 0.463 for the KPSS and −4.443 for the ADF with a break test. A * shows stationarity of the series.

Estimates of the Markov switching regimes model are reported in Table 3 and are derived via the EM algorithm, which maximizes the logarithm of the sample likelihood function through iterations on the normal equations. The algorithm relies on an initial guess of the parameter vector, which is used in a non-linear filter to calculate smoothed inferences, that is, the probabilities that the process is in a particular state at each point in time based on the full sample. These inferences are then fed into the normal equations to recalculate the parameter vector, and this process goes on until a convergence criterion is satisfied. The final parameter vector corresponds to a local maximum of the likelihood surface and, for this reason, several starting parameter sets are considered to select a vector that gives the highest value of the likelihood function.[5]

Table 3. Estimated Markov switching parameters for the euro area.

	Core Inflation	Output Gap
Parameter		
μ_1	1.219 (0.046)	−0.440 (0.325)
μ_2	2.915 (0.252)	−0.162 (0.134)
σ_1^2	0.146 (0.025)	7.680 (1.282)
σ_2^2	1.536 (0.419)	0.435 (0.131)
cov_1	0.452 (1.135)	
cov_2	−0.283 (0.170)	
p_{11}	0.977 (0.017)	
p_{22}	0.949 (0.040)	
L^*	100.462	

Notes: Based on quarterly data from 2000Q1 to 2024Q4. Numbers in parentheses next to the estimated parameters are standard errors. L^* is the value of the log likelihood function.

Note that the relatively high values of the transition probabilities p_{11} and p_{22} show that states are persistent, but this does not mean that they are permanent. Indeed, the smoothed probability of the state of high inflation conditional for the full sample of observations T, i.e., $pr(h_t=2|z_1, z_2, \ldots, z_T)$, is depicted in Figure 2 and shows that the data detect three turning points of the process. Given that the smoothed probability reflects agents' perception of the state based on the largest available information set, that is the full sample, our estimates reveal that states are not perceived as permanent. At any rate, the high inflation state has a smaller expected duration of $(1\text{-}p_{22})^{-1}=(1\text{-}0.949)^{-1}=19.6$ quarters compared to the expected duration of the low inflation state of $(1\text{-}p_{11})^{-1}=(1\text{-}0.977)^{-1}=43.5$ quarters. Additionally, it is worth noting that the regime changes traced by the Markov process are remarkably close to the actual turning points of inflation.

[5] For analogous estimation of the Markov specification in the context of monetary policy evaluation, see Kirikos (2020, 2021, 2022, 2024).

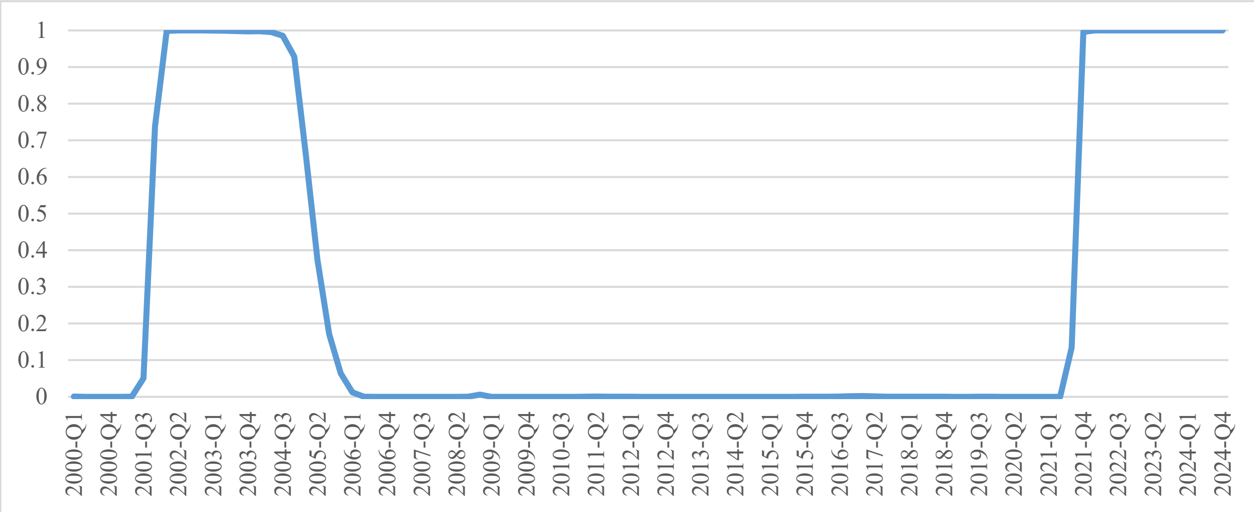

Figure 2. Smoothed probability of a high inflation state.

Specification tests for the Markov process are given in Table 4. More precisely, we test the hypothesis of equal means across states and the hypothesis that the probability of going to any state does not depend on the probability of the previous state. The validity of these hypotheses would imply that the data are not characterized by the Markov property. The relevant Wald statistics are:

$$(\boldsymbol{\ell b})'[\boldsymbol{\ell \Omega \ell}']^{-1}(\boldsymbol{\ell b}) \sim \chi_r^2, \tag{17}$$

where $\boldsymbol{\ell}$ is an r×12 matrix of restriction coefficients, $\boldsymbol{b}$ is the 12×1 vector of parameters, and $\boldsymbol{\Omega}$ is the 12×12 variance-covariance matrix of the parameters. The χ^2distribution has r degrees of freedom, with r=2 for the joint hypothesis H$_o$: $\boldsymbol{\mu}_1 = \boldsymbol{\mu}_2$ (equal mean vectors in regimes 1 and 2) and r=1 for the simple hypothesis H$_o$: $p_{11} = 1 - p_{22}$. Apparently, the values of the test statistics in Table 4 show strong rejections of both null hypotheses and imply a good fit of the Markovian dynamics.

Table 4. Wald tests of Markov specification.

H$_o$: $\boldsymbol{\mu}_1 = \boldsymbol{\mu}_2$	H$_o$: $p_{11} = 1 - p_{22}$
46.162 (0.000)	407.39 (0.000)

Note: Numbers in parentheses are *p*-values.

Turning now to the linear VAR specification (12), the Akaike and Schwarz criteria, reported in Table 5, suggest 5 lags for the autoregressive process. Therefore, in testing the cross-equation restrictions under a VAR representation for inflation and the output gap, we use this lag length.

Table 5. Information criteria for VAR lag.

VAR lags	1	2	3	4	5
Akaike	0.37	0.16	−0.15	−0.14	−0.53*
Schwarz	0.42	0.27	0.01	0.07	−0.26*

Note: A * shows selected lags.

The values of the Wald statistic (11) for testing the cross-equation restrictions implied by the Phillips curve under both a non-linear Markov switching regimes specification (equation 9) and a linear VAR model (equation 16) are presented in Table 6 for different values of the parameter k, while, as discussed, parameter β is set at $\beta = 0.99$ in all cases.[6] It appears that the restrictions are statistically significant under the non-linear Markov process for a wide range of values for k, whereas the corresponding restrictions under a linear VAR representation are strongly rejected. These results suggest that there are non-linearities in the data, which are compatible with a shifting relationship between core inflation and the output gap in the euro area. Thus, our findings lend support to either a non-linear Phillips curve for the whole economy or sectoral non-linear relationships between inflation and employment, which seem to be plausible explanations for the observed immaculate and rapid disinflation process. Additionally, the sectoral shocks variant takes prominence, given that non-linearities at the aggregate level reflect sectoral non-linearities in the supply relationships along with the lack of a substantial fiscal expansion in the post-pandemic period in the euro area.

Table 6. Wald test for cross-equation restrictions.

	Non-linear Markov process	Linear VAR(5)
$k = 0.05$	3.503 (0.173) *	311.63 (0.000)
$k = 0.2$	4.984 (0.083) *	56.02 (0.000)
$k = 0.5$	5.306 (0.070) *	32.26 (0.000)
$k = 0.8$	4.963 (0.084) *	33.71 (0.000)
$k = 1$	4.748 (0.093) *	34.98 (0.000)
$k = 1.2$	4.571 (0.102) *	36.05 (0.000)
$k = 1.5$	4.367 (0.112) *	37.28 (0.000)

Notes: VAR(5) corresponds to a vector autoregressive process with 5 lags. A * shows significance at 5% and numbers in parentheses are p-values.

5. Conclusions

Non-linearities in the inflation – output relationship at an aggregate or a sectoral level seems to be a particularly convincing explanation for the observed inflation dynamics in the post-pandemic period. Therefore, in this work, we have tested the validity of cross-equation restrictions implied from an aggregate Phillips curve under linear and non-linear stochastic bivariate representations for core inflation and the output gap, using quarterly data from the euro area over the period 2000–2024. A novel feature of our approach is that we do not assume an expectations formation mechanism but generate expectations consistent with the aggregate supply and a large information set that includes the history of core inflation and the tightness of economic activity. The results provide strong support for the non-linearities argument in explaining the quick rise and subsequent immaculate and rapid fall

[6] In conventional estimates of the Phillips curve, based on inflation expectations from surveys of professional forecasters, parameter k takes on small values, implying a relatively flat Phillips curve. For example, Ball and Mazumder (2021) estimated k close to 0.2 using quarterly data from the euro area over the period 1999-2018, whereas Eser et al. (2020) reported a median value of 0.18 for the same period.

in inflation. An important policy implication is that the European Central Bank has rightfully not insisted on interest rate hikes since the inflation episode appears to be mainly a supply side issue.

Use of AI tools declaration

No AI tools were used in this work.

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Conflict of interest

The author declares no conflicts of interest in this paper

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