The Brexit Vote, Productivity Growth and Macroeconomic Adjustments in the United Kingdom*

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August 14, 2023

Abstract

The UK economy experienced significant macroeconomic adjustments following the 2016 referendum on its withdrawal from the European Union. To understand these adjustments, this paper presents empirical facts using novel UK macroeconomic data and estimates a small open economy model with tradable and non-tradable sectors. We demonstrate that the referendum outcome can be interpreted as *news about a future decline in productivity growth in the tradable sector*. An immediate fall in the relative price of non-tradable goods induces a temporary "sweet spot" for tradable producers. Economic activity in the tradable sector expands in the short run, while the non-tradable sector contracts. Aggregate output, consumption and investment growth decelerate.

JEL Classifications: E32, F17, F41, F43, O16.
Keywords: Brexit, Small open economy, Productivity, News shocks.

* The views expressed here are those of the authors, and not necessarily those of the Bank of England. We would like to thank the editor Veronica Guerreri and three anonymous referees for many helpful suggestions to improve this paper. We are grateful especially to Konstantinos Theodoridis for stimulating discussions and to Yunus Aksoy, Juan Antolin-Diaz, Tommaso Aquilante, James Bullard, Ambrogio Cesa-Bianchi, Meredith Crowley, Nikola Dacic, Pierre De Leo, Luca Fornaro, Marco Garofalo, Pierre-Olivier Gourinchas, Pete Kyle, Nuno Limao, Enrico Longoni, Ellen McGrattan, Riccardo Masolo, Michael McMahon, Francesca Monti, Dennis Novy, Ivan Petrella, Lukasz Rachel, Morten Ravn, Peter Sinclair, Greg Thwaites, Jan Vlieghe and Marija Vukotic for very helpful comments. Philip King, Oliver Ashtari Tafti and Mette Nielsen provided excellent research assistance. We also thank seminar and conference participants at the Bank of England, Banque de France, the 2021 & 2022 Barcelona Summer Forum (ADEMU and IFM), Birkbeck College, the Cambridge-INET Conference on the Economics of Brexit, the CEF 2021, the 15th Dynare Conference in Lausanne, Essex University, the EEA Annual Congress, the 23rd INFER Annual Conference, the International Conference on European Studies, the Leuven Summer Event, the 50th MMF Conference at LSE, the Peterson Institute for International Economics, the RES Annual Conference, the SED Annual Congress in Minneapolis, the Spanish Economics Association Annual Conference, University of Birmingham, University of Glasgow, University of Kent, University of Maryland Smith School of Business, University of Warwick, University of Southampton, and Washington University in St. Louis.

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1. Introduction

In the momentous referendum on 23 June 2016, voters decided that the United Kingdom (UK) should leave the European Union (EU). While the details regarding the UK's actual withdrawal ('Brexit') were far from clear, the period following the referendum was characterized by significant adjustments in the UK economy. A moderate slowdown in aggregate activity masked a substantial divergence in economic performance across sectors. Growth in the tradable sector remained resilient while the non-tradable sector stagnated, alongside a persistent drop in the relative price of non-tradables. This paper documents these empirical patterns using newly constructed UK macroeconomic data and provides an intuitive model-based narrative to explain them.

Our interpretation of the UK's adjustment to the referendum is motivated by the remarks of Broadbent (2017*a*), who conceptualizes the Brexit vote as the revelation of a *future slowdown in tradable sector productivity growth*. We formalize and assess this idea through the lens of an estimated small open economy (SOE) model with tradable and non-tradable sectors. Our model characterizes how firms and households respond to information about future productivity growth in the tradable sector by shifting resources across expenditure components, sectors and time. We demonstrate that the dynamics triggered by the anticipation of a tradable sector productivity slowdown are consistent with post-referendum UK data. In particular, our model captures the somewhat counter-intuitive effect of the referendum news on sectoral output: although the primary channel through which Brexit will eventually affect the UK economy is trade, it was growth in the non-tradable sector that experienced a pronounced slowdown after June 2016. In support of our interpretation of the referendum outcome, we provide new cross-country evidence on the link between EU membership and relatively higher productivity growth in tradable relative to non-tradable sectors. We also validate our interpretation using empirical patterns of hours, consumption, investment and wages, and show that other types of shocks cannot generate the observed adjustments.

The paper proceeds in four steps. First, we present motivating empirical facts about economic activity and relative prices across the UK tradable and non-tradable sector following the 2016 referendum. This is based on a novel quarterly macroeconomic data set we construct from industry-level data.[1]

[1]The construction of the data involves classifying industry data at the 2-digit level into tradable and non-tradable sectors and then constructing separate time series of macroeconomic aggregates for the two sectors. We make the data publicly available at http://econweb.umd.edu/~drechsel/files/BrexitPaperData.xlsx.

Based on these facts, we develop our interpretation of the referendum result as news about lower future tradable sector productivity growth. We argue that this interpretation is consistent with the relatively strong performance of the tradable sector, and the relatively muted slowdown in aggregate activity, which had surprised many contemporary observers. We also present cross-country evidence for the link between EU membership and sectoral productivity growth. Since exits from trade agreements are very rare, we posit that leaving the EU should reverse the productivity effects of entering it, and show empirically that joining the EU is associated with a subsequent increase in tradable sector productivity growth, relative to the non-tradable sector. Second, we introduce our two-sector SOE model. The model exhibits differential trend growth rates across the tradable and non-tradable sector, making it possible to conduct the relevant experiments. Third, we estimate the model at business cycle frequency using our newly constructed data set. Estimating the model with information up to the time of the referendum enables us to pin down the structural parameters and initial balanced growth path around which we study Brexit scenarios. Fourth, we use the model to simulate the effects of the referendum outcome. The Brexit vote is a prime example of a news shock: at a well-identified point in time, firms and households receive new information about the future, but no actual changes materialize in the economy upon the announcement. Our main model experiment assesses the impact of the unanticipated news that the growth rate of productivity in the tradable sector will be persistently low in the future, calibrated to match the observed change in the relative price across sectors. We find that this experiment replicates key empirical patterns observed in the UK economy following the Brexit vote, including the change in relative sectoral performance that motivates our analysis, as well as post-referendum dynamics of additional sectoral and aggregate variables.

The mechanism that generates these macroeconomic adjustments works as follows. The Brexit news – conceptualized as a persistent drop in the growth rate of future productivity in the UK tradable sector – generates a temporary boom in tradable production. This expansion is driven by the response of the relative price of non-tradable output which shifts down when the news is revealed. Consequently, there is an opportunity to sell tradable output at a temporarily higher relative price before productivity growth in the sector actually falls, a temporary "sweet spot" for producers of tradables (Broadbent, 2017*a*,*b*). This generates a reallocation of labor towards the tradable sector, a rise in tradable output growth and an increase in exports, all of which reverse after the productivity growth decline in the tradable sector actually occurs. The

Brexit news also persistently reduces domestic interest rates relative to world interest rates. In addition, the news about slower productivity growth in the tradable sector triggers a material reduction in consumption and investment growth, while employment remains relatively stable. Aggregate output falls mildly in the short run. In the long run, our experiment predicts UK gross domestic product (GDP) to be 3.6% lower than in the no-Brexit counterfactual.[2]

Taken together, the narrative surrounding the UK economy's adjustment to the Brexit vote we develop in this paper not only informs one of the major policy debates in UK history, but also delivers general insights on the macroeconomic dynamics triggered by news about exiting an integrated economic area.

Our work contributes to several strands of academic research. First, there has been a surge in papers studying the impact of Brexit on the UK economy and beyond, from a variety of angles.[3] Similar to us, Born et al. (2019) and Vlieghe (2019) focus on the period immediately after the referendum from a macroeconomic perspective. Both of these studies apply a synthetic control method to gauge the effects of Brexit on UK economic growth. While the aggregate effects they find are similar to ours, the additional insights we provide on sectoral activity and relative prices contribute to understanding the nature of the adjustment mechanism. Other papers on the impact of Brexit focus on long-run trade (Dhingra et al., 2017; Sampson, 2017), foreign direct investment (McGrattan and Waddle, 2020), financial market volatility and stock returns (Davies and Studnicka, 2018), uncertainty (Steinberg, 2017; Bloom et al., 2018, 2019; Faccini and Palombo, 2020; Hassan et al., 2020), as well as exchange rate pass-through (Forbes et al., 2018; Breinlich et al., 2019).[4] Consistent with the notion of a "deglobalization shock" put forward by Gourinchas and Hale (2017), our work provides a narrative of the referendum impact as one fundamental economic shock. We provide a novel interpretation of this shock as negative news about productivity growth in the tradable sector. The suggested economic mechanism successfully matches the patterns observed in the newly constructed macroeconomic data that we present.

Second, our paper relates to research on the role of news shocks in business cycles, such as the work of Beaudry and Portier (2006), Jaimovich and Rebelo

[2] We explore the robustness of our results along several dimensions, including timing and profile of the news shock, and show that other shocks do not match the dynamics in the data.

[3] Other studies focus on the reasons for the outcome of the referendum rather than its economic impact. See for example Becker et al. (2017), Fetzer (2018).

[4] In particular the trade literature features many more studies that are helpful to understand Brexit and its effects. See for example Erceg et al. (2018) for an analysis of the short-run macroeconomic effects of specific trade policies such as tariffs, as well as Graziano et al. (2018) and Caldara et al. (2020) for recent papers on the effects of trade policy uncertainty.

(2009) and Schmitt–Grohe and Uribe (2012). We contribute in particular to the literature that studies the role of news shocks in open economies (Jaimovich and Rebelo, 2008; Kamber et al., 2017; Siena, 2020) as well as in multi-sector models (Gortz and Tsoukalas, 2018; Vukotić, 2019). The Brexit vote is perhaps the archetype of a news shock, given that we can precisely pinpoint its time of arrival, and given its economy-wide scope. From the perspective of understanding news shocks, the Brexit referendum thus takes the role of a large quasi-natural experiment, which we exploit to show that news shocks have important consequences for macroeconomic dynamics in an open economy.

Third, our paper relates to work that has undertaken a serious calibration of models with tradable and non-tradable sectors, such as De Gregorio et al. (1994), Betts and Kehoe (2006) and Lombardo and Ravenna (2012). Similar to this line of research, we allocate 2-digit SIC industry level data into tradable and non-tradable categories. To the best of our knowledge, we are the first to do so for the UK and the first to use such a classification to construct time series aggregates to estimate, rather than calibrate, a structural model. The importance of sectoral reallocation in response to unprecedented macroeconomic shocks has recently also been stressed by Guerrieri et al. (2021, 2022).

Finally, we contribute to the broader SOE literature, which follows the classic work of Mendoza (1991). We build on the contribution of Drechsel and Tenreyro (2018) by allowing for productivity growth differentials between sectors.[5] While Drechsel and Tenreyro (2018) focus on emerging economies, this paper demonstrates that structural shocks to sectoral productivity growth are also a useful modeling device for advanced economies.[6]

The remainder of the paper is structured as follows. Section 2 documents stylized facts about the UK economy following the referendum, as well as an empirical motivation for the link between EU membership and productivity growth across sectors. Section 3 introduces our two-sector SOE model, and previews its main economic forces. Section 4 presents the data and discusses the estimation. Section 5 simulates our Brexit scenario and provides a comprehensive description of the results. Section 6 concludes.

[5] Stockman and Tesar (1995) is an earlier example of an open economy model with sectoral productivity differences. Their framework features only stationary shocks. Other contributions to broader the SOE literature include, but are not limited to, Kose (2002), Schmitt-Grohe and Uribe (2003), Aguiar and Gopinath (2007) and Garcia-Cicco et al. (2010). Gourinchas and Rey (2014) survey research on both small open economy and large open economy models.

[6] Modeling different growth rates in technologies across sectors also relates to the literature that studies investment-specific alongside neutral technology, such as Greenwood et al. (2000) and Justiniano et al. (2011). See also Acemoglu and Guerrieri (2008) for a model of differential productivity growth across sectors based on different factor proportions.

2. Brexit and Sectoral Productivity Expectations

This section presents empirical facts about economic activity and relative prices across the UK tradable and non-tradable sector following the referendum. It argues that these patterns are consistent with an economic adjustment to news about the future prospects for productivity in the tradable sector. To support this interpretation, we discuss theoretical and empirical motivations for the link between EU membership and productivity in the tradable sector. In particular, we present new empirical evidence that the productivity growth differential between tradable and non-tradable sectors increases after countries join the EU.

2.1. The Surprising Resilience of the UK Tradable Sector

Before the referendum, there was substantial debate over the consequences for the UK economy of a decision to leave the EU. A number of studies predicted that increasing trade barriers with the UK's largest trading partner would lead to long-term reductions in trade and GDP (Ebell and Warren, 2016; Kierzenkowski et al., 2016). Many economists and policy-makers highlighted that a vote to leave could also weaken growth, potentially triggering a recession, in the short term.[7] However, in the immediate aftermath of the referendum, contemporary accounts noted that strong performance in the tradable sector had moderated the slowdown in overall growth, prompting a former policy-maker to express "surprise" at the relatively "robust" economic performance (Lea, 2018).[8]

Our novel UK quarterly macroeconomic data set, built by classifying industry data at the 2-digit level into tradable and non-tradable sectors and computing sectoral real gross value added (GVA), hours worked, productivity and relative prices over time, can shed light on the contemporary debate.[9] Figure 1 presents key patterns in UK data before and after referendum, where the shaded area marks the period after the June 2016 Brexit vote. Panel A presents our newly constructed real GVA in the tradable and non-tradable

[7] The Managing Director of the IMF noted that a leave vote "could lead to a recession" in the UK (Lagarde, 2016). Presenting estimates of the UK Treasury, a month before the referendum, Chancellor George Osborne stated that: "... a vote to leave would represent an immediate and profound shock to our economy. That shock would push our economy into a recession." (UK Government, 2016). While such analysis was contested by some (e.g. Minford, 2016), there was a general consensus among economists that a vote to leave the EU would have negative short-term consequences for the UK. On 12 May 2016, *The Times* newspaper published a letter signed by 196 economists predicting both long-term and short-term economic costs ('Economists warn against Brexit vote', Philip Aldrick, Thursday 12 May 2016).

[8] See also "UK growth upgrade could 'dwarf' Brexit hit", BBC News, 22 January 2018.

[9] Details on the construction of the sectoral data are provided in Section 4.1.

sectors, as well as aggregate real GDP.[10] It is evident that the relatively modest GDP slowdown in the UK after June 2016 masked divergent responses in the tradable and non-tradable sectors. While the non-tradable sector stagnated relative to its pre-referendum path, growth in the tradable sector increased following the Brexit vote.

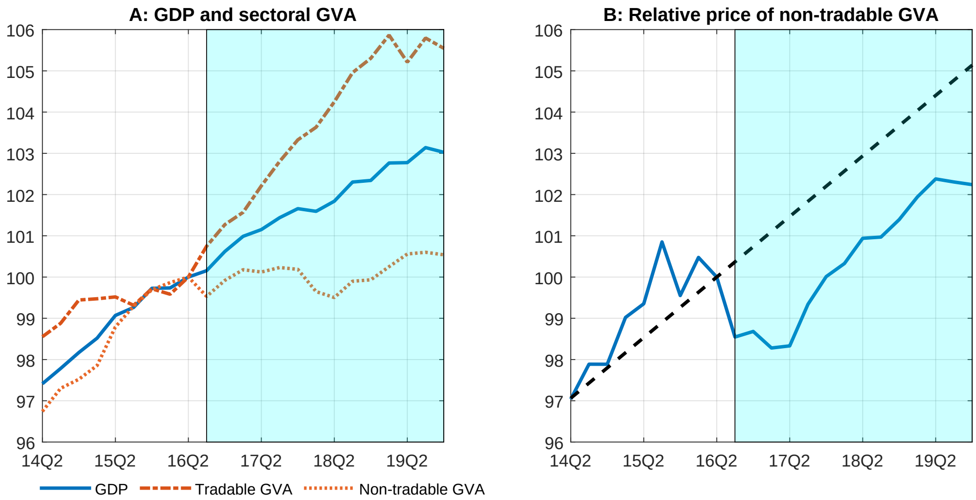

Figure 1: *Adjustments of the UK economy following the Brexit vote*

Notes. The unit in both panels is 100 $\times$ log index with 2016:Q2=100. Details on the construction of the underlying sectoral data are provided in Section 4.1.

Broadbent (2017*a*) offered a simple explanation for relative resilience of the tradable sector: "Brexit hasn't happened yet". The shift in activity from the non-tradable to the tradable sector is suggestive of a reallocative shock. Panel B of Figure 1 plots the relative price of non-tradables. As we discuss further below, this price trends up over time because productivity growth is slower in the non-tradable sector than in the tradable sector. The plot reveals an immediate and persistent fall in the relative price of non-tradables in the aftermath of the referendum. In particular, there is a distinct drop in the *level* of the relative price after 2016:Q2, while its growth rate returns to the pre-referendum growth rate within a few quarter thereafter. As an illustration, the black dashed line extrapolates the pre-referendum growth rate, making clear that the relative price of non-tradables shifts down to a broadly parallel growth path.

The hypothesis that we investigate in this paper is that the near-term macroeconomic adjustments reflect the UK economy's response to the *anticipation* of a structural change that reduces future tradable sector productivity, and

[10]In principle, aggregate real GVA is a better comparator to the series for tradable and non-tradable output. However, we plot GDP because the contemporary debate was couched in terms of this variable and because the dynamics of GDP and GVA are very similar.

ultimately future tradable output. The patterns in Figure 1 are consistent with this hypothesis. An immediate fall in the relative price of non-tradable output can be explained through an expected future decline in relative tradable sector productivity. Such a relative price movement creates an incentive to reallocate resources towards tradable sector production in the short term, before Brexit actually occurs and while tradable sector productivity growth has not actually declined. A short-run expansion of the tradable sector comes at the expense of slower growth in the non-tradable sector, consistent with the sectoral patterns in Figure 1, Panel A. Our model based on this interpretation will jointly explain these and additional facts about the UK economy's response to the Brexit vote.

2.2. Trade Frictions and Productivity: Theory and Evidence

While the patterns in Figure 1 are suggestive of our hypothesis, both theory and empirical evidence provide further support for the link between trade frictions and productivity, which we argue the referendum outcome contained news about. Theories of how the degree of trade barriers determines the rate of growth of an economy typically highlight distortions in the allocation of resources towards technical change as a central mechanism (Grossman and Helpman, 1989, 1991). For example, a larger market raises the rewards for research and innovation. Another mechanism might be that lower trade barriers foster import competition, which increases the incentive to innovate. More recent work on the link between trade and growth includes Sampson (2016) and Impullitti and Licandro (2018), who show that trade increases growth via firm selection. Bloom et al. (2015) find empirically that trade liberalization fosters technical change across and within firms, and increases productivity growth.

We extend existing work by exploring more explicitly the empirical link between changes in trade barriers and productivities across the tradable and non-tradable sector. While exits from free trade areas are rare, there are many observations of economies joining them. This provides an opportunity to examine the link between changes in trade barriers and sectoral productivities, which can shed light on the potential sectoral productivity implications of Brexit. That is because a plausible hypothesis is that the effects of raising trade barriers mirror the effects of lowering them. In other words, leaving the EU should broadly reverse the productivity consequences of entering it.[11]

We investigate this idea using data from the OECD Quarterly National Accounts and the Eurostat Quarterly National Accounts. Details and summary statistics are provided in Online Appendix A. We obtain quarterly productivity data for 31 countries and 10 sectors from 1997:Q1 to 2016:Q2 (around 25,000 country-sector-quarter observations). The countries in our sample include EU members, countries that join the EU, and countries outside the EU. To understand how growth differentials between countries' tradable and non-tradable sectors are impacted by joining the EU, consider the following regression across countries (c), sectors (s) and quarters (t):

$$\Delta z_{c,s,t} = \alpha \mathbb{1}_s^{TRD} \times \mathbb{1}_{c,[t,t+h]}^{EU} + \beta \mathbb{1}_s^{TRD} + \gamma \mathbb{1}_{c,[t,t+h]}^{EU} + \delta_{c,s} + \delta_{c,t} + \varepsilon_{c,s,t}, \tag{1}$$

where $\Delta z_{c,s,t}$ denotes productivity growth, $\mathbb{1}_s^{TRD}$ is a dummy variable that equals 1 if sector s is defined as tradable, and $\mathbb{1}_{c,[t,t+h]}^{EU}$ equals 1 if country c joins the EU in quarter t, and remains 1 for h quarters thereafter. The δ terms correspond to different fixed effects. α captures the differential impact of joining the EU on productivity growth in tradable relative to non-tradable sectors. $h > 0$ allows for this effect to be persistent, but not necessarily permanent.[12] Our preferred setting is $h = 20$, so that the coefficient captures a differential productivity growth effect during the 5-year period after joining the EU. We vary h in robustness checks.

We exploit the fact that some countries in our sample join the EU, and do so at different points in time: out of the 31 countries, for 15 countries $\mathbb{1}_{c,[t,t+h]}^{EU}$ is equal to 1 in some periods.[13] For each country, the data covers 10 sectors. We define agriculture, manufacturing and financial services as tradable, and the remaining sectors (construction and other services sectors) as non-tradable. For robustness, we explore different definitions.

We measure productivity growth as the quarter-on-quarter growth rate of

[11] Our empirical analysis focuses on actual EU accession. Given our mechanism of interest, it would also be desirable to directly test for the effects of *news* about EU future membership. However, joining the EU is a very gradual process over many years, which makes it difficult to identify the effects of such news. Indeed, this is one of the benefits of studying the Brexit referendum as a news event that can be timed quite precisely.

[12] The specification tests for the presence of a temporary and persistent effect on the growth rate of productivity, which implies a permanent effect on the level of productivity. The exogenous shock in our model simulations will have the same dynamic profile.

[13] The joiners are Czech Republic, Estonia, Cyprus, Latvia, Lithuania, Hungary, Poland, Slovakia, Slovenia (2004:Q2); Romania, Bulgaria (2007:Q1); Croatia (2013:Q1). Austria, Finland and Sweden join the EU in 1995:Q1, slightly before the sample start. As we set $h = 20$ quarters, they can also be included as EU joiners (though dropping them does not change our results).

real GVA divided by hours worked.[14] For a subset of countries, we use the number of employees instead of total hours because of data limitations. For robustness, we limit the analysis to only those countries with hours data. In the regressions, we winsorize GVA growth rates at the 5%-level to deal with outliers. In order to make GVA comparable across countries, we express all data in the same real consumption units, using Germany as a base country.[15] See Online Appendix A for details.

Figure 2 plots the mean difference in productivity growth between tradable and non-tradable sector separately for: all countries included in our analysis, and the group of countries that join the EU before and after joining, respectively. It is evident that the difference in productivity growth between tradable and non-tradable sectors widens after joining the EU. This simple look at the data anticipates the findings of our more formal regression analysis, in which we control for important confounders such as country-specific growth trends.

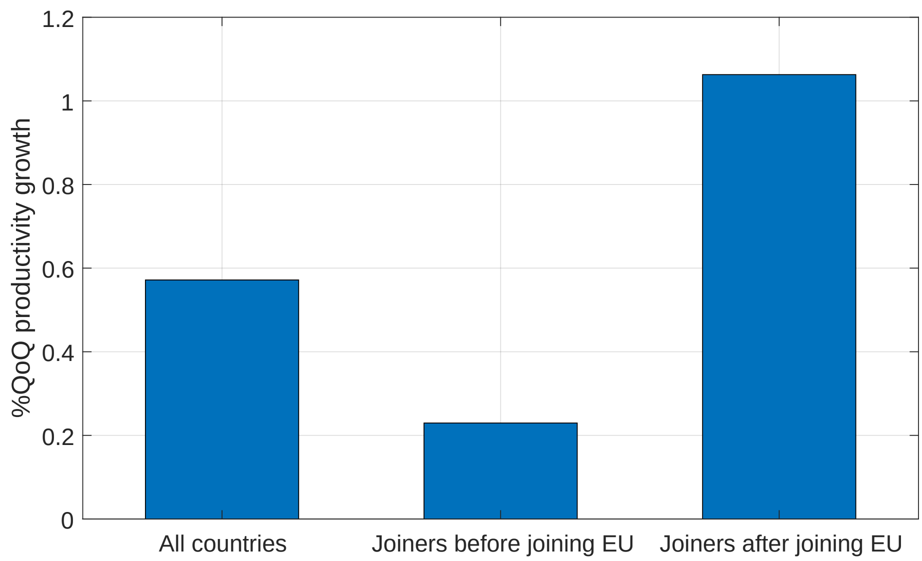

Figure 2: *Mean productivity growth difference between tradable and non-tradable sectors*

Notes. Equal-weighted means computed at the country-sector level. Calculations are based on OECD and Eurostat data between 1997:Q1 and 2016:Q2.

Table 1 presents the estimation results for equation (1). The different columns correspond to alternative settings for the fixed effects that are included

[14]Real GVA per hour is of course an imperfect measure of productivity, as it could be affected for example by markups. In our model estimation, we account for measurement error in the mapping from labor productivity in the model to GVA per hour in the data.

[15]An alternative to using GVA per hour would be to construct a measure of total factor productivity across countries and sectors, which requires additional information, e.g. on factor shares. This is done by Berka et al. (2018) for nine Euro area countries. These authors emphasize the effect of *level* difference in productivity on real exchange rates, while we focus on changes in relative productivity *growth rates* across sectors.

in the specification. We cluster standard errors by country.[16] Our coefficient of interest, on the interaction between the tradable sector dummy and the dummy indicating the 5-year period after joining the EU, is statistically significant across all of the specifications. The estimates imply that on average, the period after joining the EU is associated with an increase in the difference between productivity growth rates in the tradable and the non-tradable sector by around 0.4 percentage points per quarter, more than 1.6 percentage points annually, an economically sizable effect.[17]

In Online Appendix A we document a variety of additional results, including a "Placebo test" in which we generate randomly drawn entry dates for the 15 EU joiners in our sample, and interact these entry dates with the tradable sector dummy. The resulting coefficients are very close to zero and statistically insignificant. Furthermore, we show that our results are robust to varying h, alternative definitions of tradable sectors, changes in the sample of countries, and to additionally including a Euro membership interaction.

These results are consistent with the theoretical mechanisms reviewed earlier. Productivity growth in tradable sectors is generally faster, indicating that technical change may be concentrated more heavily in these sectors. To the extent that both the absorption of limited factor inputs for innovative activity and the effect of import competition disproportionately affect activity in the production of tradables, a single market with lower trade barriers will foster stronger productivity growth in tradable relative to non-tradable production.[18]

We have demonstrated that our hypothesis about the economic news contained in the 2016 referendum result is consistent with both the empirical patterns in key UK variables after the Brexit vote and new cross-country evidence on the link between trade barriers and sectoral productivity growth. Our goal in the remainder of the paper is to investigate if the patterns in a broad range of post-referendum UK macro data are also consistent with an adjustment to news about future sectoral productivity differentials. We examine this through the lens of a structural model.

[16] This allows for the possibility of correlated errors across sectors within a country. The significance of the results remains unchanged when we cluster at the country-sector level.

[17] Note that at the country-sector level, productivity growth rates can range from negative to positive two-digit percentages, see the summary statistics presented in Online Appendix A.

[18] In Online Appendix B we provide some additional explanations for the relation between EU membership and productivity differentials based on capital flow (e.g. McGrattan and Waddle, 2020) and labor mobility (e.g. Portes and Forte, 2017) channels. Gourinchas and Hale (2017) characterize the common component of these different fundamental makes leaving the EU as a "deglobalization shock" that reduces specialization and efficiency.

Table 1: *The effects of joining the EU on productivity growth differentials between sectors*

	(1)	(2)	(3)	(4)	(5)	(6)	(7)
LHS variable	**growth in real output per hour ($\Delta z_{c,s,t}$)**						
tradable x joined EU	0.443***	0.442***	0.444***	0.441***	0.484***	0.438***	0.482***
	[0.117]	[0.117]	[0.117]	[0.118]	[0.134]	[0.117]	[0.134]
tradable	0.184***	0.184***		0.185***			
	[0.034]	[0.034]		[0.034]			
joined EU	0.396**	0.137	0.395**	0.453**	0.139		
	[0.168]	[0.118]	[0.168]	[0.194]	[0.126]		
Observations	25,006	25,006	25,006	25,006	25,006	25,006	25,006
Country FE	-	✓	-	-	-	-	-
Sector FE	-	-	✓	-	-	✓	-
Time FE	-	-	-	✓	✓	-	-
Country*sector FE	-	-	-	-	✓	-	✓
Country*time FE	-	-	-	-	-	✓	✓
R-squared	0.002	0.010	0.005	0.044	0.060	0.238	0.242

Notes. Estimation results of equation (1). The different columns correspond to different fixed effect specifications. Standard errors are shown in square brackets and are clustered at the country level. *** p<0.01, ** p<0.05, * p<0.1.

3. The Model

The setting is a real small open economy with a tradable (T) and a non-tradable (N) sector. As in Drechsel and Tenreyro (2018), sectors grow at their own rate, denoted by g_{Tt} and g_{Nt}. The presence of two different stochastic trends implies that the levels of variables may grow at different rates along a balanced growth path. To aid exposition, we use lower-case letters to denote stationary variables and upper-case letters to denote variables that contain a stochastic trend. The economy is small in the sense that the real interest rate is exogenous and the rest of the world absorbs any trade surplus or deficit fully elastically. Following Schmitt-Grohe and Uribe (2003), we close the model with a debt elastic premium on external borrowing. After presenting the agents' problems and market clearing conditions, we discuss key economic forces of the model.

3.1. The firms' problem

Firms in each sector $M = \{T, N\}$ produce a final good Y_{Mt} by combining capital K_{Mt} and labor n_{Mt} according to a Cobb-Douglas technology

$$Y_{Mt} = a_{Mt} K_{Mt}^{\alpha_M} (Z_{Mt} n_{Mt})^{1-\alpha_M}. \tag{2}$$

Capital used in both sectors is composed of tradables and non-tradables, which is explained further below. Labor is sector-specific.[19] a_{Mt} denotes a stationary total factor productivity (TFP) disturbance, which follows the process

$$\ln a_{Mt} = \varrho_M^a \ln a_{Mt-1} + \varepsilon_{Mt}^a, \quad \text{with} \quad \varepsilon_{Mt}^a \sim \mathbb{N}\left(0, \varsigma_M^a\right), \tag{3}$$

where ϱ_M^a is the persistence of stationary sectoral TFP and ς_M^a the dispersion of the shock. Z_{Mt} is the level of labor-augmenting productivity in sector M, which exhibits a stochastic trend. Its growth rate is given by

$$g_{Mt}^z = \frac{Z_{Mt}}{Z_{Mt-1}}, \tag{4}$$

and follows an autoregressive process of the form

$$\ln\left(g_{Mt}^z/\bar{g}_M^z\right) = \varrho_M^g \ln\left(g_{Mt-1}^z/\bar{g}_M^z\right) + \varepsilon_{Mt}^g, \quad \text{with} \quad \varepsilon_{Mt}^g \sim \mathbb{N}\left(0, \varsigma_M^g\right), \tag{5}$$

where ϱ_M^g captures the persistence of the process and ς_M^g the dispersion of the shock. Transitory shocks to g_{Mt}^z capture changes to the growth rate of labor-augmenting productivity in sector M, which permanently affect the level of productivity. $\bar{g}_M^z$ denotes the steady state value of the growth rate of labor productivity in sector M. We define each sector's total level of productivity as X_{Mt}. Given the production technology,

$$X_{Mt} = \left(X_{Tt}\right)^{\alpha_M} \left(Z_{Mt}\right)^{1-\alpha_M},$$

with the corresponding growth rate denoted by

$$g_{Mt} = \frac{X_{Mt}}{X_{Mt-1}}. \tag{6}$$

This means that for the tradable sector $g_{Tt} = g_{Tt}^z$, while for the non-tradable sector $g_{Nt} = (g_{Tt})^{\alpha_N}(g_{Nt}^z)^{1-\alpha_N}$. These sectoral productivity processes allow for a balanced growth path along which investment in both sectors is a composite of tradables and non-tradables, as specified further below.

Firms rent capital and labor in competitive factor markets at the real rental rate r_{Mt}^k and real wage w_{Mt}, respectively. Profits, expressed in tradable units, are given by

$$Y_{Tt} - W_{Tt} n_{Tt} - r_{Tt}^k K_{Tt} \tag{7}$$

[19] Given that we focus on short-run adjustments, assuming that labor is freely mobile would likely generate implausibly rapid inter-sectoral reallocation.

in the tradable sector and

$$P_t Y_{Nt} - W_{Nt} n_{Nt} - r^k_{Nt} K_{Nt} \tag{8}$$

in the non-tradable sector. Under the assumption of perfect competition, firms make zero profits in equilibrium. The variable P_t denotes the relative price of the non-tradable vis-à-vis tradable goods. This price can be interpreted as an 'internal' measure of the real exchange rate. This interpretation goes back to the work of Balassa (1964) and Samuelson (1964), who have studied international productivity differences and their implications for relative prices across countries.[20] The model implies that the relative price P_t exhibits a stochastic trend as a consequence of different growth rates across sectors.

3.2. The household's problem

From the perspective of the representative household, tradable and non-tradable consumption are gross complements. The consumption of home tradable goods and their foreign counterpart can be perfectly substituted (the law of one price for tradable goods holds). Following Drechsel and Tenreyro (2018), we specify the period utility function as in Greenwood et al. (1988). We scale the disutility of labor by the level of tradable productivity to ensure that both consumption and labor elements of the utility function grow at the same rate. Formally,

$$\mathcal{U}\left(C_t, X_{Tt-1}, X_{Nt-1}, n_{Tt}, n_{Nt}\right) = \frac{\left[C_t - X_{Tt-1}\epsilon_t\left(\frac{\theta_T}{\omega_T} n_{Tt}^{\omega_T} + \frac{\theta_N}{\omega_N} n_{Nt}^{\omega_N}\right)\right]^{1-\gamma}}{1-\gamma}, \tag{9}$$

where θ_M denotes the disutility of labor and ω_M the elasticity of labor supply in sector M. ϵ_t is a labor supply shock, which follows

$$\ln \epsilon_t = \varrho_\epsilon \ln \epsilon_{t-1} + \varepsilon_{\epsilon t} \quad \text{with} \quad \varepsilon_{\epsilon t} \sim \mathbb{N}\left(0, \varsigma_\epsilon\right). \tag{10}$$

[20]The *Harrod-Balassa-Samuelson effect* is the empirically observed tendency for countries with stronger productivity in tradable goods relative to non-tradable goods to have higher price levels overall. The mechanics of this effect feature in our model, where weaker productivity growth in the tradable sector puts downward pressure on the domestic price level. We discuss this and additional key economic forces in our model at the end of this section.

C_t is a CES consumption aggregator, expressed in tradable units, that combines tradable and non-tradable consumption C_{Tt} and C_{Nt}, so that

$$C_t = \left[\zeta^{1+\sigma} C_{Tt}^{-\sigma} + (1-\zeta)^{1+\sigma} \left(\frac{X_{Tt-1}}{X_{Nt-1}} C_{Nt} \right)^{-\sigma} \right]^{\frac{1}{-\sigma}}. \tag{11}$$

$\gamma > 1$ is the inverse inter-temporal elasticity of substitution (IES) and $\eta = 1/(1+\sigma)$ the elasticity of substitution between tradable and non-tradable consumption.[21] Similarly, there is an investment aggregator that transforms the amounts of tradables and non-tradables I_{Tt} and I_{Nt} into aggregate investment

$$I_t = \left[\zeta^{1+\sigma} I_{Tt}^{-\sigma} + (1-\zeta)^{1+\sigma} \left(\frac{X_{Tt-1}}{X_{Nt-1}} I_{Nt} \right)^{-\sigma} \right]^{\frac{1}{-\sigma}}. \tag{12}$$

Given the aggregators (11) and (12), the price of the aggregate bundles of both consumption and investment in tradable units is

$$P_t^c = \left[\zeta + (1-\zeta) \left(\frac{X_{Nt-1}}{X_{Tt-1}} P_t \right)^{\frac{\sigma}{1+\sigma}} \right]^{\frac{1+\sigma}{\sigma}}. \tag{13}$$

Note that the relative price of non-tradable output P_t features a stochastic trend, while P_t^c is stationary. The representative household seeks to maximize

$$\mathbb{E}_0 \sum_{t=0}^{\infty} \nu_t \beta^t \frac{\left[C_t - X_{Tt-1} \epsilon_t \left(\frac{\theta_T}{\omega_T} n_{Tt}^{\omega_T} + \frac{\theta_N}{\omega_N} n_{Nt}^{\omega_N} \right) \right]^{1-\gamma}}{1-\gamma}, \tag{14}$$

subject to the budget constraint (expressed in tradable units)

$$\begin{aligned} P_t^c C_t + P_t^c I_t + B_t^* + P_t^c B_t + P_t Y_{Nt} \frac{s}{y_N} s_t + \sum_{M=\{N,T\}} P_t^c \frac{\phi_M}{2} \left(\frac{K_{Mt+1}}{K_{Mt}} - g_T \right)^2 K_{Mt} \\ = r_{Tt}^k K_{Tt} + r_{Nt}^k K_{Nt} + W_{Tt} n_{Tt} + W_{Nt} n_{Nt} + \frac{B_{t+1}^*}{(1+r_t^*)} + P_t^c \frac{B_{t+1}}{1+r_t}. \end{aligned} \tag{15}$$

$\beta \in (0,1)$ denotes the subjective discount factor, ϕ_M captures how costly is to adjust capital in sector M, s/y_N denotes the steady state share of government

[21] Note that X_{Tt-1} and X_{Nt-1} enter the utility function to ensure a balanced growth path in which utility is bounded. See Acemoglu and Guerrieri (2008) for a model of "unbalanced growth" in the context of differences in factor proportions across sectors. The parameters θ_T and θ_N will allow us to match the relative quantities of labor used in the two sectors.

consumption in non-tradable output, and ν_t is a preference shock given by:

$$\ln \nu_t = \varrho_\nu \ln \nu_{t-1} + \varepsilon_{\nu t} \quad \text{with} \quad \varepsilon_{\nu t} \sim \mathbb{N}\left(0, \varsigma_\nu\right). \tag{16}$$

Sectoral physical capital depreciates at the rate δ_M. The law of motion for aggregate investment is:

$$I_t = K_{Tt+1} - (1-\delta_T) K_{Tt} + K_{Nt+1} - (1-\delta_N) K_{Nt}. \tag{17}$$

There are two different risk-free bonds, B^*_t and B_t, with corresponding interest rates r^*_t and r_t. These pay one unit of tradable goods and one unit of the consumption bundle in the following period, respectively. They can be thought of as bonds that are indexed to different types of inflation rates in practice. While a bond that pays tradable units – a standard ingredient of SOE models – allows the economy to achieve a trade balance that is different from zero, the bond that pays units of the consumption bundle remains in zero net supply. Introducing it allows us to determine its interest rate r_t, which will move differently from r^*_t, shedding light on how 'domestic' relative to world interest rates can diverge in response to the Brexit news. The interest rate on the bonds denominated in tradable goods is given by

$$r^*_t = \bar{r}^* + \psi\left(e^{B^*_{t+1}/X_{Tt} - \bar{b}^*} - 1\right) + (e^{\mu_t - 1} - 1), \tag{18}$$

where $\bar{r}^*$ is the steady state world interest rate, and the term multiplied by ψ captures a country risk premium, which is increasing in the amount of external debt. The latter assumption follows Schmitt-Grohe and Uribe (2003) and ensures a stationary solution of the model after detrending.[22] Finally, the term $(e^{\mu_t - 1} - 1)$ captures an interest rate shock, which follows

$$\ln \mu_t = \varrho_\mu \ln \mu_{t-1} + \varepsilon_{\mu t} \quad \text{with} \quad \varepsilon_{\mu t} \sim \mathbb{N}_t\left(0, \varsigma_\mu\right). \tag{19}$$

The variable s_t is a government expenditure shock, which can be thought of as a broader domestic demand shifter, and which follows

$$\ln s_t = \varrho_s \ln s_{t-1} + \varepsilon_{st} \quad \text{with} \quad \varepsilon_{st} \sim \mathbb{N}\left(0, \varsigma_s\right). \tag{20}$$

[22]The conclusions we draw in this paper are robust to alternatives to this assumption. We explored this in an earlier version of the paper and related appendices (Broadbent et al., 2019).

3.3. Market clearing and equilibrium

The resource constraints in the two sectors are

$$Y_{Tt} = C_{Tt} + I_{Tt} + TB_t + P_t^c \frac{\phi_T}{2} \left(\frac{K_{Tt+1}}{K_{Tt}} - g_T \right)^2 K_{Tt}, \tag{21}$$

and

$$Y_{Nt} = C_{Nt} + I_{Nt} + Y_{Nt} \frac{s}{y_N} s_t + \frac{P_t^c}{P_t} \frac{\phi_N}{2} \left(\frac{K_{Nt+1}}{K_{Nt}} - g_T \right)^2 K_{Nt}. \tag{22}$$

We define the trade balance as

$$TB_t = B_t^* - \frac{B_{t+1}^*}{1 + r_t^*}. \tag{23}$$

The model exhibits two stochastic trends and is detrended to characterize a stationary equilibrium. Following Aguiar and Gopinath (2007) and Drechsel and Tenreyro (2018), we normalize the sectoral variables by their corresponding level of technology. We then calculate the deterministic steady state of the normalized model. Details are provided in Online Appendix C.

3.4. The model's main economic forces

Using the model, we will show that empirical facts about the UK economy after the referendum can be understood as adjustments to news about a lower future productivity growth rate in the tradable sector g_T. Before we turn to the estimation and simulation steps, we highlight some key economic relationships in the model. This guides intuition, and also gives grounds for our choice of a real model, which abstracts from nominal rigidities, and generates the main effects purely through relative price and intertemporal substitution effects.

The most central force behind the mechanism is that the relative price of output across sectors varies inversely with relative productivities. This is a key feature of multi-sector production economies: lower efficiency in making a good implies that it is more expensive relative to other goods. Therefore, a fall in productivity growth in the production of tradables moves the price of non-tradable output down. At its core, this is an intratemporal force that would also be present in a static two-sector model.[23]

[23] Indeed, classic papers that highlight the relation between relative productivities and relative prices across countries use static models (Balassa, 1964; Samuelson, 1964). It is also worth noting that in these studies wages equate across sectors, whereas our model features different labor types, allowing for additional margins of adjustment. In our simulation, wages in the two sectors move in the same direction in response to the tradable productivity news shock.

In addition to the effect through productivity differentials, the fall in g_T makes the economy less productive overall and thus lowers permanent income. This in turn reduces total consumption demand. When tradable and non-tradable goods are complements, and given that productivity in the non-tradable sector is unchanged, the fall in demand in both sectors generates further downward pressure on the relative price of non-tradables.[24]

Importantly, in a dynamic model with forward-looking agents, both of these channels kick in on impact when news about future productivity developments are received. Forward-looking behavior implies that today's consumption-saving decisions depend on the full path of future productivity. As a result, news about lower productivity growth in the tradable sector leads to a reduction in the full path of the relative price of non-tradable goods, as well as a fall in consumption that is spread out over time. Since productivity initially remains unchanged, these forces both generate relatively favorable conditions for the tradable sector until the news actually materialize.[25]

4. New UK Data Set and Estimation Strategy

Our strategy of bringing the model to the data and carrying out the Brexit simulation consists of two steps. First, we estimate the model up to the quarter of the EU referendum (2016:Q2), using our new UK macro data set. By exploiting variation in this data at business cycle frequency, this pins down the structural parameters and balanced growth path of the model, which determines the starting point for the Brexit simulation. The estimation using pre-referendum data is based on variation driven by typical business cycle disturbances. Second, we simulate the impact of Brexit from 2016:Q3 onwards, by feeding a news shock into the model. Since we interpret Brexit as a unique and unprecedented event, this news shock is not included in the estimation of the model's parameters. This section describes the first step. We present the construction of the data, how we select observables for estimation, as well as the estimation algorithm and settings. The second step is explained and carried out in Section 5, which forms the core of the analysis.

[24]See Dornbusch (1983) for a simple model that generates similar effects.

[25]The reasoning provided here also applies to level shocks to relative productivities. Only a growth rate shock, however, generates the effects on interest rates observed empirically after Brexit. We examine this when we study alternative types of news shocks for robustness.

4.1. Data and sectoral classification

We construct a new UK macroeconomic data set from 1987:Q3 to 2016:Q2, the period during which the UK was a full member of the EU. A key contribution of this paper is that we put together time series data for tradable and non-tradable GVA, hours, labor productivity, and relative prices. These sectoral time series complement standard macroeconomic variables, such as aggregate GDP, consumption and investment. To the best of our knowledge, we are the first to apply such a classification on industry-level data from the UK and the first to generate sectoral time series aggregates that are used to estimate a structural model. Specifically, we use detailed industry-level GVA data from the UK Office of National Statistics (ONS) and treat a given 2-digit SIC industry as tradable if more than 10% of its final demand is traded, a standard cutoff suggested in the literature, for example in Lombardo and Ravenna (2012). We chain-link the data using the standard national accounts methodology employed by the ONS and also compute series for sectoral total hours by adding up hours data using the same industry classification. The time-series for sectoral labor productivities are then constructed by taking the ratio between sectoral GVA and total hours. Having aggregated detailed GVA data, we calculate the relative price of non-tradable goods by dividing the resulting implicit price deflators.

Table 2: *Industries shares in the non-tradable and tradable sector (%)*

	Non-tradable	**Tradable**
Agriculture	0.05	1.41
Mining and Quarrying	0.00	2.60
Manufacturing	1.31	21.56
Electricity, Gas, Steam Air Conditioning	2.49	0.00
Water Supply, Sewage, Waste Mgmt	1.53	0.93
Construction	11.34	0.00
Services	83.26	73.50

Notes. Nominal output shares of each SIC industry broken down by the classification into tradable and non-tradable sectors. This is shown as a snapshot for the year 2018. The supply and use tables are used to calculate the tradability index; nominal GVA data at factor prices are taken from low level aggregates published by the ONS.

Our classification into tradable and non-tradable sectors leads to a roughly 45-55 split of total UK hours worked on average over the sample (our model will be calibrated accordingly). The same is approximately the case for sectoral output using nominal GVA shares. Table 2 shows that in 2018, 22% of tradable GVA was produced by manufacturing sectors, 74% by services. The corresponding numbers for the non-tradable sector are 1% and 83%. The most important tradable manufacturing industries are motor vehicles, wearing apparel and alcoholic beverages and tobacco products, with food and beverage services, insurance services and financial services, representing key tradable services. For robustness, we also exclude government-related sectors from the non-tradable sector. The resulting dynamics in non-tradable GVA are very similar, with a correlation of 0.93 between non-tradable GVA and non-tradable GVA excluding government. More details, including a list of all 2-digit industries and their classifications, are provided in Online Appendix D.

4.2. Mapping the model to observable variables

As observable variables for the estimation of the model, we use the ratios of nominal consumption and investment to GDP, demeaned total hours (all available from 1987:Q3), the quarterly growth rates of sectoral labor productivity (available from 1994:Q1), the growth rate of the relative price of non-tradable goods both at quarterly frequency (available from 1997:Q1) and annual frequency (available from 1990), as well as two measures of the real foreign interest rate.[26] Table 3 presents our full list of observables. We make use of the Kalman filter to handle missing observations in the time series of sectoral labor productivities and the relative price of non-tradable goods. In the estimation step, we allow for measurement errors in sectoral labor productivity, the annual growth rate of the relative price and the real interest rates.

Table 3: *Observables used for model estimation*

Time series	Transformation	Time period
Consumption / GDP	Nominal ratio	1987:Q3 - 2016:Q2
Investment / GDP	Nominal ratio	1987:Q3 - 2016:Q2
Total hours (scaled by population)	Dev. from mean	1987:Q3 - 2016:Q2
Labor productivity in T	% QoQ	1994:Q1 - 2016:Q2
Labor productivity in N	% QoQ	1994:Q1 - 2016:Q2
Relative price of non-tradable goods	% QoQ	1997:Q1 - 2016:Q2
Relative price of non-tradable goods	% Annual	1990 - 2016
Real US Interest Rate (based on SPF infl. exp.)	Percent	1987:Q3 - 2016:Q2
Real US Interest Rate (based on 5-year inf. MA)	Percent	1987:Q3 - 2016:Q2

Notes. List of time series used to estimate the model. We use the Kalman filter to address the fact that observables become available at different starting dates. The estimation period ends in 2016:Q2, the quarter of the referendum.

Our way of constructing observables to estimate our model addresses a key

[26]We proxy r_t^* by the real US short-term interest rate. To compute the real rate we subtract inflation expectations from the FED Funds rate. We use two alternative measures of inflation expectations: the three-month inflation expectations from the Survey of Professional Forecasters (SPF) and a five-year inflation moving average.

challenge entailed by the use of implicit price deflators to derive real quantities. Model consistent consumption and investment could in principle be computed by deflating nominal consumption and investment by the tradable GVA implicit price deflator. However, since the resulting quarterly GVA deflators are only available from 1997:Q1, using them to calculate model consistent aggregates would imply discarding useful information. To circumvent this issue, we use the ratios of nominal aggregates, rather than the growth rate of real quantities, following Christiano et al. (2015). To estimate the structural parameters more precisely, our procedure requires that the values of the steady state ratios implied by the model match the averages in the data.

4.3. Estimation procedure, calibration and priors

The model is estimated with Bayesian techniques using the observables shown in Table 3. The variation in UK macroeconomic time series from 1987 to 2016 is assumed to be driven by the collection of structural shocks present in the model in Section 3. The structural parameters and initial balanced growth path, that is, the starting point for our Brexit experiments, are estimated based on the information coming from this variation prior to the Brexit vote.

Table 4: *Calibrated parameter values*

	Description	Source	Period	Value or target
θ_T	disutility of labor (T)	ONS/own calc.	1994 – 2016	$n_T/n = 0.45$
θ_N	disutility of labor (N)	ONS/own calc.	1994 – 2016	$n_N/n = 0.55$
δ_M	depreciation in M	ONS	1987 – 2016	$\frac{i}{y} = 0.192$
$\frac{c}{y}$	consumption/GDP	own calculations	1987 – 2016	0.644
$\bar{g}_T$	trend growth rate of productivity (T)	ONS/own calc.	1994 – 2016	1.6% ann.
$\bar{g}_N$	trend growth rate of productivity (N)	ONS/own calc.	1994 – 2016	1.2% ann.
β	discount factor			$r^* = 0.01$
ψ	debt-elasticity of premium			5×10^{-6}

The model has a relatively small number of parameters due to its parsimonious structure. We calibrate some parameters based on empirical targets, and estimate the remaining ones, including those governing the dynamics of the shock processes. We first comment on the calibrated parameters, summarized in Table 4, and then turn to the estimated ones. We choose θ_N and θ_T to target the empirically observed distribution of hours worked across sectors in our data on tradable and non-tradable sectors. We calculate the investment and consumption to output ratios ($\frac{i}{y}$ and $\frac{c}{y}$) to be 0.192 and 0.644, respectively. The depreciation rates are assumed to be equal across sectors and are set to 0.006 to match $\frac{i}{y} = 0.192$, while being consistent with the sample averages of the capital shares. In line with the SOE literature, we assume that trade is balanced over the long-run ($\frac{tb}{y} = 0$), and then recover the ratio of government expenditure as a residual.[27] We compute $\bar{g}_T$ and $\bar{g}_N$ directly from the data. The growth rate of hours differs across sectors in the data. Therefore we re-scale the growth rates of sectoral productivity, in order to match the growth rates of sectoral output between data and model. The discount factor β is set to match a quarterly foreign real interest rate of 1%. Finally, the elasticity of the foreign interest rate with respect to debt ψ is set to a very small number (5×10^{-6}). We do so to exclude the debt-elastic premium as part of the core mechanism, that is, Brexit does not make the UK more default prone in our model.

Table 5 shows the specification of priors for the parameters that we estimate. Using the ONS supply-and-use tables for the period 1997-2016, we compute the annual shares of tradables into aggregate consumption and then set the prior mean of ζ to the sample average of 0.59. We calculate the sample means of the sectoral capital shares to be $\alpha_T = 0.316$ and $\alpha_N = 0.245$. In principle, we could calibrate these parameters, but given that the calculated values come out to be somewhat smaller than in existing studies, we introduce some estimation uncertainty. We do so by estimating the share of tradables in aggregate consumption and investment, as well as the ratio of the capital shares. We center the prior means relatively tightly around the sample averages and then compute their posterior distributions.

Our posterior estimates are also presented in Table 5. The elasticities of labor supply ω_N and ω_T are estimated to be 2.65 and 2.55. These values are higher than in the literature on emerging countries, likely because total hours worked in UK exhibit a great deal of persistence which the model captures through greater values for ω_M. The posterior mean of the tradable share ζ is 0.62. The mean estimates of the investment adjustment costs in the non-tradable sector (12.28) and tradable sectors (14.13) are higher than in related studies, but plausible given the volatility of aggregate investment and the relatively low depreciation rates at the sectoral level. The posterior mean of the elasticity of substitution between tradable and non-tradable goods σ is 0.68. This corresponds to an elasticity of substitution equal to $\eta = \frac{1}{1+\sigma} = 0.6$, which is within the range of estimates in the literature. This value gives rise to a gross complementarity across tradable and non-tradable consumption aggregates,

[27] Varying the values of the ratio between government expenditure and output and between trade balance and output to match long-term averages changes the results very little.

Table 5: *Priors and posteriors for estimated parameters*

	Description	Prior			Posterior		
		Prior Distr.	Mean	Std	Mean	90% HPDI	
	Structural parameters						
γ	inter-termporal elast. of subs.	Gamma	2	0.1	2.00	1.83	2.16
α_T/α_N	ratio of capital shares (T over N)	Gaussian	1.3	0.05	1.3	1.22	1.38
ω_T	elast. of labor supply (T)	Gamma	2	0.2	2.55	2.24	2.86
ω_N	elast. of labor supply (N)	Gamma	2	0.2	2.65	2.35	2.95
ζ	tradable share	Beta	0.59	0.01	0.62	0.61	0.63
ϕ_T	capital adjustment cost in T	Gamma	5	4	14.13	8.02	20.12
ϕ_N	capital adjustment cost in N	Gamma	5	4	12.28	6.13	18.39
σ	elast. of subs. between T and N	Gamma	1	0.2	0.68	0.44	0.90
	Shocks						
ς_N^g	st.dev. of prod. growth shock in N	Inv. Gamma	0.1	2	0.01	0.013	0.015
ς_T^g	st.dev. of prod. growth shock in T	Inv. Gamma	0.1	2	0.012	0.011	0.014
ς_s	st.dev. of expenditure shock	Inv. Gamma	0.1	2	0.02	0.017	0.023
ς_μ	st.dev. of foreign interest rate shock	Inv. Gamma	0.1	2	0.008	0.007	0.009
ς_ν	st.dev. of preference shock	Inv. Gamma	0.1	2	0.027	0.022	0.032
ς_T^a	st.dev. of TFP level shock in T	Inv. Gamma	0.1	2	0.012	0.011	0.014
ς_N^a	st.dev. of TFP level shock in N	Inv. Gamma	0.1	2	0.012	0.011	0.014
ς_ϵ	st.dev. of labor supply shock	Inv. Gamma	0.1	2	0.017	0.015	0.019
ϱ_N^g	persistence of prod. growth shock in N	Beta	0.5	0.15	0.37	0.18	0.56
ϱ_T^g	persistence of prod. growth shock in T	Beta	0.5	0.15	0.23	0.12	0.35
ϱ_s	persistence of expenditure shock	Beta	0.5	0.15	0.58	0.35	0.82
ϱ_μ	persistence of foreign interest rate shock	Beta	0.5	0.15	0.56	0.46	0.65
ϱ_ν	persistence of preference shock	Beta	0.5	0.15	0.92	0.88	0.98
ϱ_N^a	persistence of TFP level shock in N	Beta	0.5	0.15	0.91	0.82	0.98
ϱ_T^a	persistence of TFP level shock in T	Beta	0.5	0.15	0.90	0.85	0.97
ϱ_ϵ	persistence of labor supply shock	Beta	0.5	0.15	0.95	0.91	0.99
	Measurement errors						
ι_P	relative price (annual)	Inv. Gamma	0.01	0.0001	0.01	0.01	0.01
ι_N	labor productivity in N	Inv. Gamma	0.01	0.005	0.005	0.004	0.007
ι_T	labor productivity in T	Inv. Gamma	0.01	0.005	0.006	0.005	0.008
ι_{R_1}	real foreign interest rate (1)	Inv. Gamma	0.01	0.01	0.002	0.002	0.002
ι_{R_2}	real foreign interest rate (2)	Inv. Gamma	0.01	0.01	0.002	0.002	0.002

and likely generates unconditional output co-movement across sectors. Several of the stochastic disturbances are estimated to be quite persistent. In line with existing models with stochastic trends in labor-augmenting productivity, the estimated persistence of the growth processes are relatively low ($\rho_N^g = 0.38$ and $\rho_T^g = 0.23$). The foreign interest rate shock reflects some persistence in real rates internationally. The posterior standard deviation of measurement errors for sectoral labor productivities, the relative price of non-tradable goods and the foreign rate are small but statistically different from zero.

5. The Brexit Simulation

This section presents our main Brexit experiment. It shows that the model produces responses to news about a future reduction in tradable sector productivity growth that are consistent with the observed macroeconomic adjustment of the UK economy to the Brexit vote. First, we describe the assumptions underlying our simulation. Second, we present the simulated paths of key macroeconomic variables, alongside a discussion of the economic mechanism that gives rise to them. Third, we compare the simulation with the actual realization of UK post-referendum data. This includes the empirical patterns around sectoral activity and relative prices that motivate the paper, as well as a variety of additional outcome variables. Finally, we discuss robustness checks and simulations based on other macroeconomic shocks.

5.1. Brexit simulation specification

We model Brexit as news about a future reduction in tradable sector productivity growth (g_{Tt}). This reduction is persistent but ultimately temporary. As a result, there is a permanent effect on the *level* of future tradable sector productivity, but the growth rate eventually fully recovers.[28] In our estimation of the model, the process for $g_{Tt} = g^z_{Tt}$, given by equation (5), captures regular business cycle shocks to productivity during the period of EU membership. However, the Brexit vote was a rare and unexpected arrival of information about the future, observed at a well-identified point in time, resembling a quasi-natural experiment. For these reasons, we assume that the effects of Brexit on g_{Tt} are captured by a distinct process that embodies salient features of the future productivity adjustment that UK households and firms receive news about.

Specifically, we assume that the Brexit shock ε^B_t affects a separate component of tradable sector productivity growth, which is not present in the estimation of the model with information prior to the referendum, but which we feed into the model to generate our Brexit simulation. We denote this $\widetilde{g}_{Tt}$, and it follows

$$\ln\left(\widetilde{g}_{T,t}\right) = \widetilde{\vartheta}\ln\left(\widetilde{g}_{Tt-1}\right) + \left(1-\widetilde{\vartheta}\right)\ln\left(\bar{g}_T\right) + \varepsilon^B_t,$$

so that the $\widetilde{g}_{T,t}$ eventually converges on the steady-state tradable sector productivity growth rate, $\bar{g}_T$. To capture slow convergence, we set $\vartheta = 0.95$. Furthermore, we assume

$$\ln\left(g_{Tt}\right) = \varpi\ln\left(g_{Tt-1}\right) + \left(1-\varpi\right)\ln\left(\widetilde{g}_{Tt}\right),$$

where we set $\varpi = 0.8$, so that the dynamics of g_{Tt} are predominantly driven by the slower-moving component a few quarters after the shock arrives. Impor-

[28] In the short-run, a fully permanent reduction in the growth rate delivers similar results. We study an alternative news shock about the future *level* of productivity below.

tantly, we then study a simulation where we generate a negative shock to ε_t^B in the future. The economy is assumed to be on its initial balanced growth path in quarter 0 and agents assume that the probability of a Brexit shock at any period in the future is zero. In quarter 1, it is revealed that Brexit will happen in quarter 15 and agents perfectly foresee the future Brexit shock $\varepsilon_{15}^B < 0$.[29]

Given the informational assumptions in quarters 0 and 1 and the fact that the Brexit shock occurs in quarter 15, the experiment might alternatively be labeled as an "MIT news shock". We emphasize that our implementation is intended to capture key elements of the shock induced by the referendum result, which resembles a quasi-natural experiment, and thereby differs from the usual interpretation and modeling of business cycle news shocks, referred to in the literature review in the introduction.

We calibrate the scale of the shock to match the trough of the reduction in the relative price of non-tradable goods P_t, which occurs after around one year and implies a 2.5% lower relative price. We choose this target variable as it is one of the key empirical observations in Section 2 that motivates our approach to modeling the Brexit news shock.

Our simulation abstracts from *uncertainty* about the news shock and its timing. While the outcome of the Brexit vote is likely to have affected both first and second moments, our results show that first moment effects alone can rationalize many of the adjustments of the UK economy in response to the shock.[30] We present various robustness checks of our simulation with respect to the profile and the timing of the Brexit news shock.

5.2. Main results of the Brexit simulation

Figures 3 and 4 present the simulated paths of macroeconomic variables, including those examined empirically in Section 2. In each panel, the shaded area marks the phase after the news about the shock have been revealed, but before it materializes. The black dashed lines represent the counterfactual balanced growth path along which the Brexit news shock does not occur.

[29] This anticipation horizon broadly mimics the planned timeline for EU exit following the referendum. The referendum was held on 23 June 2016. The UK government triggered Article 50 of the Lisbon treaty on 30 March 2017, with the United Kingdom's membership of the European Union to end within two years of that date. The end date of the UK's EU membership was subsequently postponed as the negotiation process developed. The UK ultimately left the EU on 31 January 2020.

[30] We refer to the work of Bloom et al. (2019) for a firm-level analysis that focuses explicitly on uncertainty. Using a structural model, Steinberg (2017) finds that uncertainty plays a relatively small role in the context of Brexit. Caldara et al. (2020) provide a model for the US economy that features both news and uncertainty about trade.

Studying the simulation of the model's variables, shown in solid blue, allows us to explain the impact of the Brexit news shock, and the underlying economic mechanism. Section 5.3 compares our simulation with empirical patterns.

Panel A of Figure 3 shows the trajectory of tradable sector productivity growth that we feed into the model. In quarter 15, productivity growth falls for several quarters before starting to recover gradually. During the anticipation phase, agents know about the future change, but actual tradable sector productivity growth is unchanged from the original balanced growth path. The revelation of this future productivity growth trajectory leads to an immediate fall in the relative price of *non-tradable* output, which will become relatively more efficient to produce in the future. This relative price effect is one of the core economic forces of the model discussed in Section 3.4. Indeed, Panel E shows that the price of non-tradable output falls immediately, well before productivity growth has changed. During the anticipation phase, tradable goods are relatively attractive to produce because productivity growth has not yet begun to fall: the "sweet spot" effect. As shown in Panel C, this effect encourages production of tradable goods and activity in the tradable sector increases. Once tradable sector productivity falls, however, the incentives to produce tradable goods decline in the longer term.

The response of non-tradable output is shown in Panel D. On impact, it is the mirror image of tradable output. When the relative price changes in anticipation of future productivity differentials, producing non-tradable output becomes relatively unattractive and output declines. Even after the shock materializes and tradable sector productivity falls, the production of non-tradables does not return to its pre-Brexit growth path. This long-lasting decline in non-tradable activity, despite unchanged productivity in this sector, is explained by the fact that the non-tradable sector partly uses tradables as capital, which are produced with lower productivity over the longer term.

The net effect of the opposing forces on the tradable and non-tradable sectors gives rise to a negative but relatively muted initial response of GDP, as shown in Panel B.[31] Aggregate activity starts decelerating relative to the path that agents would have expected in the absence of the Brexit news shock. The negative effect on GDP builds over time and the level of GDP 8 years after the shock is about 1.5% lower than the no-Brexit balanced growth path. We compare the long-run impact on the level of GDP to the range of estimates in

[31] The chain-linked GDP growth rate is computed as $g_t^{GDP} = \omega_{T,t} \frac{y_{Tt}}{y_{Tt-1}} g_{Tt-1} + (1-\omega_{T,t}) \frac{y_{Nt}}{y_{Nt-1}} g_{Nt-1}$, where $\omega_{T,t}$ is calculated as a one-year rolling average of the expenditure share on tradable goods, $\frac{y_{Tt}}{y_{Tt}+p_t y_{Nt}}$. This approximates a national accounts treatment.

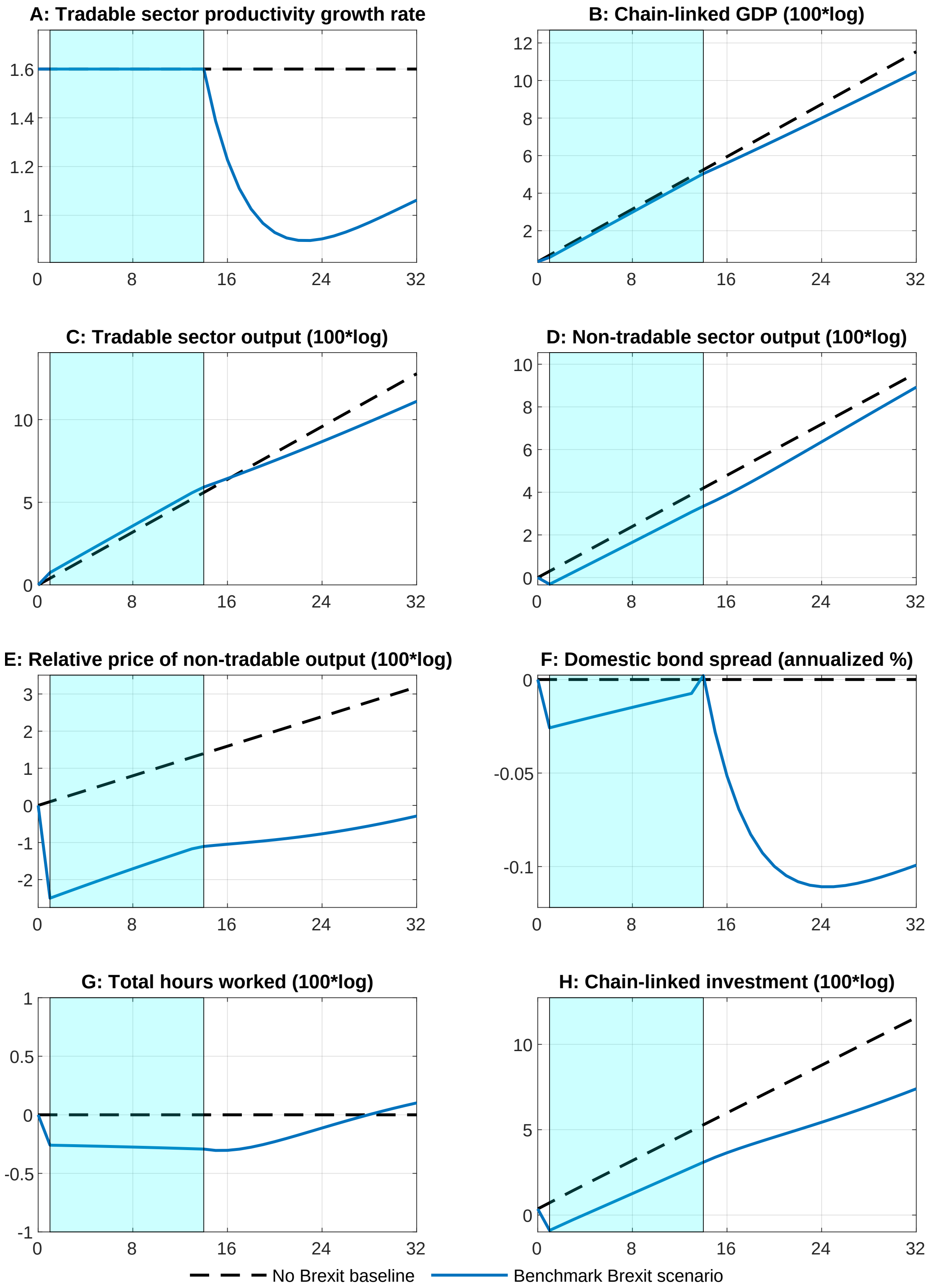

Figure 3: *Main model responses in benchmark Brexit scenario*

the literature further below.

Panel F examines the effect on UK interest rates, by plotting the return on bonds denominated in consumption as a spread over the return on bonds paying tradable goods (expressed in tradable units). This is the notion of domestic interest rates in our model. The plot shows that the domestic UK interest rate falls immediately, before gradually recovering during the anticipation phase, and ultimately declining more strongly after the shock has materialized.[32] As we discuss further below, only a shock to the future growth rate (rather than the level) of tradable sector productivity generates a negative interest rate response in the anticipation phase, as was evident in the data following the Brexit vote.

Panels G and H of Figure 3 turn to factors of production. A slowdown in investment begins after the Brexit news arrives and accelerates when the shock materializes. Aggregate hours, however, remain relatively stable. The former response is related to the fact that future economy-wide productivity is permanently lower, so that agents reduce the extent to which they move resources to the future. The latter response reflects the "sweet spot" effect: since activity today is still relatively strong – driven by robust output and employment in the tradable sector – aggregate labor input falls, but not substantially. We confirm this logic by examining the dynamics of sectoral hours further below.

Figure 4 presents the simulation paths of additional model variables to further unpack the adjustment mechanisms. Panel A shows the trade balance scaled by output, which rises significantly upon announcement of the Brexit news. This is a direct reflection of the dynamics of relative prices and higher activity in the tradable sector, with the UK temporarily exporting more goods and services. Note that our model does not distinguish between gross and net exports, as we discuss further below.

Panel B reveals that consumption falls in response to the Brexit news. This decline is a manifestation of the permanent income force resulting from the future productivity reduction, as explained in Section 3.4. While in our narrative for the Brexit news, we mainly emphasize the effect of productivity differentials on relative prices, this permanent income effect puts additional downward pressure on the relative price of non-tradable output. Panels C and D show that the fall in consumption is visible for both tradable and non-tradable goods, consistent with the permanent income effect.

Panels E and F examine the sectoral hours responses. Again, the inter-sectoral reallocation is consistent with the main mechanism underpinning our

[32]The bond rate denominated in tradable goods only changes minimally since ψ in equation (18) is calibrated to be small.

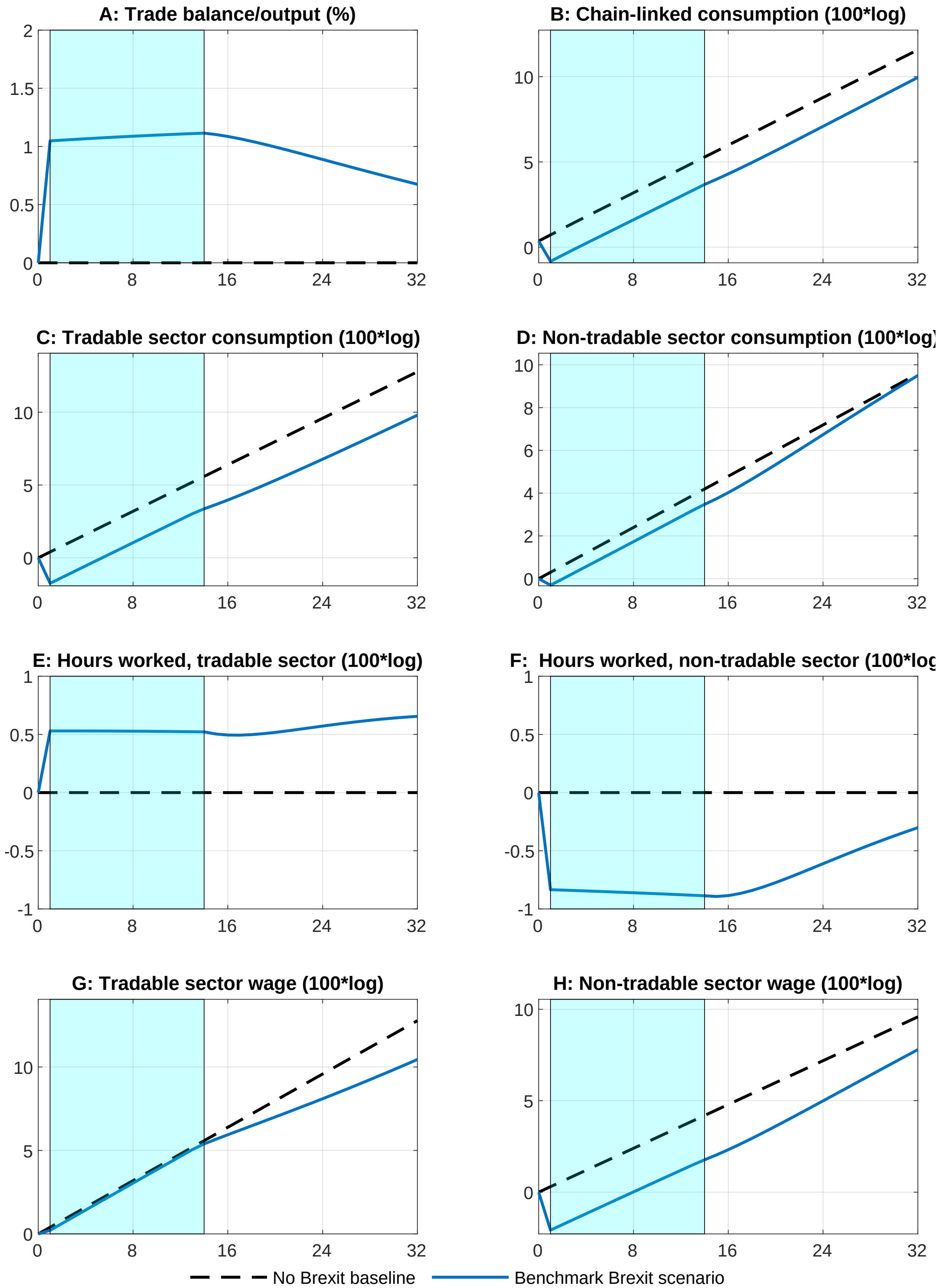

Figure 4: *Additional model responses in benchmark Brexit scenario*

results: during the anticipation phase, the tradable sector becomes relatively attractive, but this effect is reversed once tradable sector productivity actually falls. Labor input falls in the non-tradable sector and rises in the tradable sector during the anticipation period, to support increased production of tradable goods. Overall, total employment is reduced mildly during the anticipation phase. The decline in hours in the non-tradable sector starts to reverse once productivity growth in the tradable sector actually falls. As shown in Panels G and H, wages fall in both sectors. While the reduction is immediate in the non-tradable sector, the bulk of the wage slowdown in the tradable sector begins after lower productivity growth materializes. In the longer run, slower productivity growth in the tradable sector drives down wages across the economy.

5.3. Comparing the simulation to empirical patterns

We now study the extent to which our simulation is consistent with the UK data following the referendum outcome. This includes the responses of sectoral activity and relative prices that motivate our analysis, but also a number of the other outcome variables shown in Figures 3 and 4. While this comparison is primarily qualitative, we also compare the magnitudes of responses in the data to our simulation. This provides an assessment of the degree to which the mechanism that we study, based on a single news shock, explains patterns in post-referendum data. Since other mechanisms were also at play, we do not expect the simulation to entirely explain the observed movements in the data. Moreover, the period following the Brexit vote was shaped by additional, arguably unforeseen macroeconomic developments, such as US-China trade frictions, which likely contributed to the empirical patters in the data, over and above the single shock that we study.

Table 6 shows that our simulation lines up with post-referendum UK data along several dimensions. The table presents model variables and their data counterparts 1.5 and 3 years after the Brexit vote. In both data and simulation, we normalize variables to zero in the quarter prior to the referendum and compare their magnitudes in terms of log deviations from their pre-referendum trend, multiplied by 100.[33] A positive ratio implies that simulation and data display the same sign, and a ratio greater (smaller) than 1 implies that the response in the simulation (data) is relatively stronger in absolute magnitudes.

[33] In the data, we compute deviations from a linear trend from 2000:Q1 to 2016:Q2. As the trend of several variables experiences a level shift in 2008-2010, we control for a post 2010-dummy. We provide a sensitivity analysis with respect to the detrending in Online Appendix E.

Table 6: *Comparison of Brexit simulation with UK data*

	6 quarter horizon			12 quarter horizon		
Sectoral variables	**Simulation**	**Data**	**Ratio**	**Simulation**	**Data**	**Ratio**
Tradable output	0.4	1.0	0.4	0.4	0.5	0.7
Non-tradable output	-0.7	-1.3	0.6	-0.8	-2.3	0.3
Tradable sector hours	0.5	1.1	0.5	0.5	5.4	0.1
Non-tradable sector hours	-0.9	-0.4	2.0	-0.9	-0.6	1.6
Tradable consumption	-2.2	-0.5	4.1	-2.2	-2.2	1.0
Non-tradable consumption	-0.6	-1.8	0.4	-0.7	-1.1	0.6
	6 quarter horizon			**12 quarter horizon**		
Aggregate variables	**Simulation**	**Data**	**Ratio**	**Simulation**	**Data**	**Ratio**
GDP	-0.2	-0.1	1.9	-0.2	-0.7	0.3
Total consumption	-1.4	-1.2	1.2	-1.4	-1.7	0.8
Total investment	-1.7	-0.5	3.1	-1.9	-4.2	0.5
Tradable net export ratio	1.1	0.5	2.2	1.1	-0.1	-18.1
Average real wage	-1.2	-2.5	0.5	-1.2	-2.8	0.4

Recall that the simulation is configured to exactly match the decline in the relative price of non-tradable output.

We discuss both sectoral and aggregate variables in turn. The increase in tradable sector output and decrease in non-tradable sector output observed in the simulation are both clearly in line with the patterns in UK data presented in Section 2.1. Table 6 shows that similar picture emerges for sectoral hours: consistent with our simulation, the tradable sector experiences an expansion, while the non-tradable sector falls below the pre-referendum trend. The data also exhibit a slowdown in consumption growth in both sectors, also as observed in the simulation. Taken together, with one exception the ratios between simulation and data for sectoral variables are positive at both horizons, which demonstrates the broad consistency between our simulation and the data.

In terms of magnitudes, the sectoral reallocation in the data is even stronger than those that our simulation implies. At the 12-quarter horizon, the simulation can account for 70% of the tradable sector expansion in the data, while the non-tradable sector contraction in the simulation is 30% as strong as in the data. In the case of hours, the simulation implies a stronger reduction in the non-tradable sector, and a weaker increase in the tradable sector. The simulation is in line with the consumption response for tradables at the 12-quarter horizon, and is roughly consistent with the response of consumption of non-tradables, where the fall is 60% as large as observed in the data. While the sectoral consumption adjustment is relatively fast in the simulation, it follows different profiles in UK data, with a more delayed reduction in the tradable sector and a more front-loaded response in the non-tradable sector.

Turning to aggregates, Table 6 reveals that GDP falls in both the simulation and the data. After three years, the simulation implies a moderate 0.2% reduction in the level of UK GDP relative to the pre-referendum trend, compared to a more marked decline of 0.7% in the data.

Over longer horizons, our simulation implies a more substantial reduction in GDP as the gradual adjustment of sectoral productivities progresses. Indeed, according to our simulation the level of GDP falls by around 3.6% in the long run.[34] To put this number into context, Table 7 provides a summary of estimated long-run effects of Brexit in the literature. The GDP reduction implied by our simulation falls into the lower end of the range of these estimates. This is perhaps unsurprising given that a reversion to WTO rules represented the largest change in trading arrangements factored into expectations and that our simulation captures a single mechanism through which Brexit may have affected the UK economy.[35] Nevertheless, our calibration to match the fall in the relative price of non-tradables in the short run, implies a long-run GDP outcome that is within the range of estimates explicitly constructed to gauge the long-term effects of Brexit.[36]

Table 7: *Estimates of long-run effects of Brexit on UK GDP*

Study	Estimated reduction in GDP (%)
Ebell and Warren (2016)	2.7–3.7
IMF (2018)	5.2–7.8
Kierzenkowski et al. (2016)	2.7–7.5
UK Government (2018)	6.3–10.7
Our simulation	3.6

The aggregate consumption response in the simulation is broadly similar to its empirical counterpart, capturing around 80% of the reduction observed in the data. This reflects that the simulation captures sectoral consumption dynamics fairly well. Aggregate investment also falls in both the simulation and the data, but declines by substantially more in the data after 12 quarters. Moreover, this decline occurs with a delay relative to our simulation. The gradual decline in UK investment after the Brexit vote is discussed by Bloom et al. (2019),

[34]The adjustment process is slow, with a half life of around 15 years.

[35]The estimates in Table 7 focus on the move to trading arrangements governed by World Trade Organization (WTO) rules. The long-run scenarios studied in the literature often contrasted some form of membership of the European Economic Area (EEA) with a "hard Brexit" in which the UK and EEA revert to WTO rules. Of the available estimates, the WTO variant therefore comes closest to the eventual implementation of Brexit in 2020.

[36]Note, however, that comparisons with actual outcomes over long horizons is clouded by other important shocks to the UK and global economy, most notably the COVID-19 pandemic.

who link the gradual pattern directly to firm-level uncertainty. This suggests that the omission of the effects of uncertainty in our simulation could be a particular shortcoming in explaining the dynamic profile of investment. Aside from aggregate investment, however, the first-moment news in our simulation captures the timing of the responses of other variables relatively well.

For trade, we consider a model-consistent trade balance measure in the data, the *tradable net export ratio*, which is computed by subtracting tradable consumption and investment from tradable output and dividing by aggregate output.[37] The table shows that the simulation matches the directional change of this measure over the 6-quarter horizon, but predicts a larger adjustment than in the data. After 12 quarters, the response in the data is mildly negative, different from the simulation. As it is very close to zero, the ratio between the simulated response in the data becomes quite large at that horizon.[38] We discuss the trade balance results further below.

While data limitations prevent us from computing wages separately for the tradable and non-tradable sector, the simulation predicts that wages decline in both sectors and therefore on average across the economy. This is also evident in the data, where the decline of average wages is actually about twice as large as in the simulation.[39]

Our overall conclusion is that the Brexit simulation broadly matches the UK's macroeconomic adjustment to the referendum result. While our model is relatively simple, and our simulation is generated based on a single news shock, the dynamic responses of almost all variables at both horizons presented in Table 6 are directionally consistent with post-referendum UK data. The simulation also generates magnitudes that can account for a significant share of the responses of important economic variables in the data. This indicates that the quantitative contribution of our mechanism to post-referendum UK data, which were of course also affected by other aspects of Brexit, is significant. We discuss the most important limitations of our model in the next section.

[37] Omitting adjustment costs, the tradable sector resource constraint (21) shows that the response of TB_t is equal to $Y_{Tt} - C_{Tt} - I_{Tt}$. Our measure $\frac{tbnx}{y} = \frac{y_T - c_T - i_T}{y_T + py_N}$ reflects this equality.

[38] One could argue that for the ratio of the trade balance to output, it might be more appropriate to take the difference between simulation and data rather than dividing one by the other. In this case the discrepancy would appear smaller.

[39] We compute wages as real average weekly earnings divided by weekly hours worked.

5.4. Model simplifications and empirical limitations

Our two-sector SOE model embodies several simplifications and we focus our discussion on three variables that are most affected by these simplifications. First, the model is silent about differences between gross and net exports. This makes it challenging to compare the simulated trade balance to the official headline data.[40] In Table 6, we consider the tradable net export ratio as a model-consistent counterpart in the data. Directionally, the simulation does match the data over the short horizon. 1.5 years after the referendum the tradable net export ratio had increased by only 0.5% in the data compared with 1.1% in the simulation.[41] 3 years after the referendum, the response in the data has reverted back close to zero (and even mildly negative) unlike in our simulation.

In the data, the weak trade balance response contrasts with the strong expansion in activity in the UK tradable sector and increasing gross exports. Indeed, there is a swift and pronounced pickup in UK gross exports in the data: the export to GDP ratio rose by almost 3 percentage points 1.5 years after the Brexit vote.[42] Mechanically, a trade balance increase that is smaller than that of gross exports must be explained by an increase in gross imports. Moreover, in the absence of a material decline in import quantities through expenditure switching effects, the value of imports would increase because of the higher relative price of tradables.[43] One specific reason why import quantities did not fall after the referendum is that UK firms built stockpiles of imported durable materials in the anticipation of the higher future cost of importing associated with Brexit (De Lyon and Dhingra, 2021).[44] Our model does not capture such effects. Therefore our "sweet spot" interpretation is most applicable to the expansion in overall activity in the tradable sector, as well as to the dynamics in *gross* exports. As the model abstracts from differences between gross imports and gross exports, it is less well suited to explain the dynamic response of the trade balance to the referendum result.

[40]In addition, UK trade data is generally quite volatile and has measurement issues, which further complicates the comparison between model and data.

[41]A similar inconsistency between simulation and data arises when the trade balance is calculated simply as exports net of imports. Here the data shows no clear movement in either direction for two years, and then a very delayed increase.

[42]Three years after the referendum, gross exports relative to GDP were still around 1 percentage point higher that before the referendum.

[43]Indeed, Blaum (2019) shows that during exchange rate devaluations the aggregate share of imported inputs increases. Export-intensive firms tend to be also import-intensive, so importing activity is stimulated when exports increase due to relative price effects.

[44]According to the UK Decision Maker Panel (2019), a comprehensive firm survey, 30% of all firms reported that by 2019 they had built up stocks of some form due to Brexit.

Second, interest rates in our model simulation do not incorporate risk premia or changes in monetary policy. The model thus allows us to interpret interest rate changes in the data only in terms of the part of their variation that is driven by expectations of future productivity. UK 10-year real yields display an economically significant and persistent decrease after the referendum, and were 0.5 and 0.8 percentage points lower than the pre-referendum trend after 1.5 and 3 years respectively.[45] Our simulation implies a decline in UK real interest rates, as shown in Figure 3, Panel F.[46] Hence, while a quantitative comparison is limited by the simplicity of our framework, the effects of news about productivity growth in the tradable sector is qualitatively consistent with the empirical behavior of real interest rates. The fact that the simulated interest rate reduction is quite persistent allows to distinguish our interpretation of the referendum result from other candidate shocks, as discussed further below.

Third, our framework is not well suited to analyze measures of the exchange rate based on consumer prices indices (CPI). As discussed in Section 3, the relative price of non-tradable output can be interpreted as an 'internal' measure of the real exchange rate. What is key for the main economic mechanism in our model is the reduction in P, triggered by the change in the path of relative productivity across sectors in the future. Indeed, our comparison between model and data in Table 6 is based on directly targeting the decline in the relative price on non-tradable output in the data. The CPI-based real exchange rate is linked to changes in P, but additionally driven by differences in the prices of tradable goods across countries, which are absent from our model. A simple comparison between the relative price of non-tradable output and the UK's real effective exchange rate (REER) reveals that both measures drop sharply and persistently around the time of the Brexit vote, confirming the notion that they are related concepts. Quantitatively, the drop in REER is more pronounced, amounting to a maximum reduction of around 15%, compared to a 2.5% fall in the relative price on UK non-tradable output.[47]

[45]See also the discussion in Broadbent (2017*a*).

[46]For comparison, converting the path of the short-term real interest rate differential plotted in Figure 3 into a ten-year rate using the expectations theory of the term structure suggests a fall in ten-year rates of around 10 basis points during the anticipation horizon of our simulation.

[47]Engel (1993) and Chari et al. (2002) argue that the CPI-based real exchange rate is mostly driven by the real exchange rate between traded goods across countries. These studies, as well as the relative magnitudes between the fall in the REER and P in 2016 make clear that a richer model would be needed to properly investigate the dynamics of the UK's CPI-based exchange rate in response to the referendum news.

5.5. Robustness

Online Appendix E presents three experiments to explore the robustness of our main simulation results. First, the results are qualitatively similar for plausible variation in the timing of the decline in tradable sector productivity growth. Online Appendix E.1 reports results for cases in which the shock is anticipated to occur earlier or further in the future, alongside the main assumption of 15 quarters. The timing of reversals in inter-sectoral allocation changes, but the dominant force underpinning the scenario is the long-run decline in the level of tradable sector productivity. Since the long-run decline is independent of the timing of the productivity growth reduction, the results from the variants considered are very similar. This suggests that uncertainty over the precise timing of the UK's actual withdrawal from the EU is unlikely to have affected the broad pattern of immediate macroeconomic adjustments to the referendum result that are the focus of our study. Second, the responses are robust to the assumption that productivity falls more sharply than in our main simulation. Again, this reflects the fact that the dominant force is the effect on the long-run *level* of tradable sector productivity. Holding the scale of this effect constant, a faster decline in tradable sector productivity has relatively little effect on the dynamic responses, even in the near term. Online Appendix E.2 provides the details. Third, Online Appendix E.3 presents a sensitivity analysis for the comparison of our simulation with empirical counterparts computed using alternative detrending methods.

5.6. Comparison with alternative shocks

In this section we show that simulations using other shocks are inconsistent with the dynamics observed in UK data. Specifically, we repeat our simulation for two different news shocks. The first is news about a future reduction in the *level* (rather than the growth rate) of productivity in the tradable sector. The second generates news about an *acceleration* in the growth rate of productivity in the *non-tradable* sector (rather than a deceleration in the tradable sector). In principle, we can repeat our simulation for any of the other shocks in our model. We focus on these two because they enter as a very similar wedge in the equations of the model as the shock we study in our main simulation. As such, they are likely "competitors" to our preferred interpretation of the Brexit vote in terms of generating comparable model dynamics.

The first alternative shock is a future reduction in a_{Tt}. We calibrate the shock to generate the same reduction in the relative price of non-tradables as in our main simulation. This experiment is a relevant comparison, as it works through the same economic margin but reduces the level rather than the growth of productivity in the production of tradable output. The simulation results, provided in Online Appendix F, show that this shock indeed generates dynamics in activity across sectors that are qualitatively similar. We observe a rise in tradable production and a fall in non-tradable production, accompanied by a fall in the relative price. However, an important difference is the response of relative returns. The a_{Tt} shock generates a short-lived and large increase in the interest rate differential in the quarter when a_{Tt} actually falls. This is inconsistent with the persistent drop of UK relative to world interest rates in the data after the referendum, discussed in the previous section. The model structure implies that variation in the technology *growth rate* is required to generate *persistent* changes in returns. This tells us that the adjustment of the UK economy is more plausibly related to expectations about growth rates than about levels.

The motivation for studying the second alternative, a future acceleration in the growth rate of non-tradable productivity, is to verify whether our mechanism is symmetric in the sense that it only requires a variation in the ratio g_{Tt}/g_{Nt} but does depend on whether numerator or denominator are changed. The corresponding results in Online Appendix F show that a positive shock to g_{Nt} of equal magnitude to our main shock to g_{Tt} has virtually no effect on the economy during the anticipation phase, in stark contrast to our main simulation. This reflects the centrality of tradable sector productivity growth in the Euler equations of the model, which follows from the structure of the consumption and investment aggregators used to deliver a balanced growth path. Moreover, the longer run projection of this simulation is also vastly different from our main simulation. The acceleration in future g_{Nt} implies a long-run expansion in GDP. While the unobserved longer run outcomes cannot be used to reject the explanation with certainty, we are not aware of any theoretical argument which would link Brexit with a productivity growth improvement in the non-tradable sector. On the contrary, a number of mechanisms link Brexit to a reduction in tradable sector productivity growth, as discussed in Section 2.2.

6. Conclusion

While Brexit encompasses a variety of economic forces, this paper demonstrates that a single news shock is consistent with many of the macroeconomic impacts of its announcement. This result is of both academic and policy relevance. On the academic front, our analysis contributes to the news shock literature by studying a large quasi-natural policy experiment, the unexpected outcome of the Brexit referendum. Negative news to productivity growth in the tradable sector – our characterization of a key element of Brexit – results in a downward adjustment in the relative price of non-tradable output. Almost paradoxically, in the short run, this benefits the tradable sector, creating a "sweet spot" for exporters. This pattern is temporary and we predict will eventually reverse. Our mechanism is in line with patterns observed in UK data following the Brexit vote, and helps to rationalize even some of the apparently surprising survey evidence, in which exporters report no (first-order) effects from Brexit (Hassan et al., 2020). On the policy front, the paper contributes to our understanding of the impact and propagation of a shock that has governed the macroeconomic and political dynamics of the UK for several years, which might find parallels for other nations that decide to increase trade barriers in the future. As such, the mechanism we identify can contribute as a key input into more complex macroeconomic models used for forecasting and policy analysis.

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7. Data Availability Statement

The data underlying this article are available on Zenodo at https://doi.org/10.5281/zenodo.8190229