

Demand or Supply? An empirical exploration of the effects of climate change on the macroeconomy

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Demand or Supply? An empirical exploration of the effects of climate change on the macroeconomy*

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Abstract

Using an original panel data set for 24 OECD countries over the sample 1990-2019 and a multivariate empirical macroeconomic framework for business cycle analysis, the paper tests the combined macroeconomic effects of climate change, environmental policies and green innovation. Overall, we find evidence of significant macroeconomic effects over the business cycle: physical risks act as negative demand shocks while transition risks as downward supply movements. The disruptive effects on the economy typical of a disorderly transition are exacerbated for low income, high emission countries with no history of environmental policy or with a high exposure to natural disasters. In general, one size does not fit all and results support the need for a (possibly country-specific) policy mix to counteract climate change with a balance between demand-pull and technology-push policies.

JEL Classification: C11, C33, E32, E58, Q5

Keywords: Environmental policy, Environment-related technologies, Physical risks, Business cycle, SVAR

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1 Introduction

The rise in human and economic activity since the industrial revolution – and the subsequent increase in carbon and other greenhouse gas (GHG) emissions, deforestation and air pollution – has already had a substantial and quantifiable impact on our planet’s climate. Scientists of the Intergovernmental Panel on Climate Change (IPCC) estimate that global temperatures have risen by around 1°C since 1850 and could exceed 4°C by the end of this century if no action to limit emissions is taken (IPCC (2018)). Under this business-as-usual scenario, climate change will adversely affect ecosystems, water resources, food production, human settlements and the frequency and magnitude of extreme natural events, resulting in great risks for our economy and financial system (IPCC (2022)).

The severity of climate change’s direct effects (such as rising sea levels and more frequent severe natural disasters) as well as the transition to a net-zero economy (through changes in government climate policy, technology and consumer preferences), will generate financial risks and economic consequences, involving unprecedented structural changes to our economies, countries and sectors. Therefore, when it comes to understanding the impact of climate change on economic activity it is important to distinguish between the impacts of what the literature identifies as physical and transition risks. Both types of risks (or shocks) affect the economy from both the supply and demand side through many channels.

As such, climate change is relevant to the central banks’ mission of maintaining monetary and financial stability. From a central bank perspective this implies that researchers need to investigate two fundamental aspects: first of all, we need to provide evidence that these effects materialize over a horizon that is relevant for monetary policy. Once this is supported, then modelling the interaction between climate change and the economy requires empirically validated assumptions (NGFS (2020b), McKibbin et al. (2021)).

This paper sheds light on these issues by answering three main questions: Are the economic effects of climate-related shocks significant enough over the business cycle (2 to 8 years horizon)? Do climate change and efforts to counteract those changes differ in their effects on the macroeconomy? And, if that is the case, can we determine if those effects resemble more demand- or more supply-type of shocks? Our main contribution is twofold: (i) we start filling the gap in the empirical macroeconomic literature about the effects of climate-related shocks over the short-to-medium term using an empirical framework that is otherwise standard for business cycle analysis; (ii) we provide important preliminary evidence on the interrelated effects of physical and transition risks which could turn useful to inform the assumptions of theoretical models. By carefully selecting the variables that proxy for adaptation, mitigation and damage, and interacting them with macroeconomic variables in a panel of 24 OECD countries over the period 1990-2019, the paper shows that climate change and policies to counteract them can have a significant and persistent effect on output and price levels. In particular, we find that the im-

impact on output and prices of physical risks is overall negative, whereas policies and technologies affect positively prices and negatively output. We interpret this result as supporting the view that on average for physical risks (downward) demand adjustments play a bigger role than for transition risks, for which supply-type adjustments are stronger. Results can differ significantly across countries according to institutional and economic characteristics. For instance, countries that have introduced a carbon tax tend to suffer less negative consequences in the transition to a low-carbon economy than countries without carbon tax or with a higher exposure to risks.

The paper is structured as follows: In Section 2 we selectively survey the literature on the macro impacts of climate-related events or policies and on the main transmission channels. In Section 3 we illustrate the data and the methodology, including the proposed identification strategy. In Section 4 we present the results and perform selected robustness checks. In Section 5 we discuss country heterogeneity. Section 6 provides a discussion on the implications of our findings for policy makers and economic modellers. Section 7 concludes.

2 Channels and literature

Several organizations and academic researchers have attempted to estimate the impact of climate change on the global economy. The focus of the literature is scattered across specific regions, characteristics and effects of climate change. Furthermore, these estimates are subject to considerable uncertainty, given the fact that the pace of climate change remains unclear to scientists and its impacts will most likely become more significant over the long horizon. There is an increasing number of reports and reviews that are key to understand the taxonomy and the transmission channels of climate change-related risks. In most of these reports, conclusions have been based on standard macroeconomic considerations (e.g., [Andersson et al. \(2020\)](#), [Batten et al. \(2020\)](#)), on model-based simulations (e.g. [NGFS \(2020a\)](#), [IMF \(2020\)](#)) or both ([Breckenfelder et al. \(2023\)](#)).

Our work relates closely to the growing empirical literature that aims at testing these channels and their macroeconomic consequences. However, given the uncertainty involved in the frequency and damages caused by these events and the difficulties in directly attributing such events to climate change, the available evidence on how the economy will be affected is still hazy. The impact of physical risks on prices and inflation is found to vary substantially by type, severity, location and sector of the economy (e.g., [Parker \(2018\)](#), [Kim et al. \(2021\)](#), [Heinen et al. \(2018\)](#), [Cavallo et al. \(2014\)](#), [Baldauf et al. \(2020\)](#), [Canova and Pappa \(2021\)](#)). With respect to the consequences of global warming, namely, the slow increase in average temperature, the literature agrees that an average temperature increase has adverse effects on the economy, even though this result is very sensitive to countries' differences ([Burke and Tanutama \(2019\)](#)). Extreme temperatures are found to reduce output ([Burke and Hsiang \(2015\)](#)), labour productivity ([Donadelli et al. \(2017\)](#)), agricultural production ([Winne and Peersman \(2019\)](#)) and food

security (Bandara and Cai (2014), Schaub and Finger (2020), Kamber et al. (2013)) and in general economic growth (see Mumtaz and Alessandri (2021), Kahn et al. (2019), Deryugina and Hsiang (2014)). Most of the evidence examines the effects on the supply side, while still scarce is the literature concerning the threats on the demand side. These are generated by disruption to income, consumption patterns, investments, exports, infrastructures and changes of consumers behavior, potentially related to migration and climate awareness. In fact, climate change is likely to exacerbate not only the frequency and intensity of natural disasters but also the gradual process of environmental degradation (i.e., air and water pollution, global warming, smog, acid rain, deforestation, wildfires), hence leading to premature deaths and injuries, forcing people to leave their homes and temporarily or permanently move to other places, and affecting well-being and welfare.

To mitigate and to adapt to climate change substantial changes to the economy are needed, implying significant policy intervention, investment and innovation (Gillingham and Stock (2018)). Unfortunately, while protecting our climate, environmental policies could alter economic activity substantially, having an impact on the demand and supply mix that affects output and prices. As well, the roll-out of new green technologies would encompass significant government expenditure, investment and innovation that could result in wide-ranging economic risks (see Andersson et al. (2020) for a review). Känzig (2021) identifies the specific effect of tightening of European carbon market. He finds that a higher pricing regime leads to a significant increase in energy prices, a persistent fall in emissions and an uptick in green innovation at the expense of a temporary fall in economic activity. Most of the empirical literature instead seems to point to the result that environmental policy and investments in climate mitigation can have positive effects on the economy (Metcalf and Stock (2020), Braennlund and Gren (1999), Batini et al. (2021), Sokolov-Mladenović and Mladenović (2016), Wong et al. (2013)). However, in order for these effects to be optimal, the blend between environmental policy and technological innovation has to be carefully planned, together with the potential risks connected with the wrong mix of the two. Generally, environmental policy intervention is necessary when facing two types of market failures: (1) environmental externalities (e.g., pollution is not priced by the market, firms and consumers have no incentive to reduce emissions without policy interventions) (2) knowledge failures concerning environmental R&D. The public good nature of innovations creates knowledge spillover and, as a result, firms do not have incentives to provide the socially optimal level of research activity. As a result, when the policy mix is characterised by a more balanced use of demand-pull and technology-push instruments facing these two types of externalities, its effects on environmental innovation tend to be greater, mitigating the occurrence of market failures

negatively affecting the economy (Costantini et al. (2017)).¹

To the best of our knowledge, we propose the first empirical exercise that includes the interrelated effects of both physical and transition risks on the economy. Our paper tries to fill this gap in the literature using standard macroeconomic tools such as Structural Vector Autoregressive (SVAR) models to test the combined effect of (1) exposure and vulnerability to climate change and, specifically, environmental degradation, (2) environmental policies and (3) environment-related technologies on the macroeconomy. Such a setup differs from the standard literature that applies (dynamic) panel methods to examine how weather and climate-related events influence economic outcomes in a single equation framework (e.g. Dell et al. (2014)). By using a multivariate setup, we also aim at providing some additional evidence that could be relevant for the structural modelling of climate and economics. An increasing number of papers that develop structural models often make use of too restrictive assumptions on the effects of climate change, e.g. modelling it as a supply shock (such as Economides and Xepapadeas (2018) or Keen and Pakko (2009)), or just simplifying on some relevant channels (Niu et al. (2018)). Furthermore, this paper takes a business cycle perspective and focuses on a medium-term gradual impact of climate-related risks instead of considering either the secular effects of climate change based on the temperature increase or the immediate impacts due to natural disasters possibly caused by it.

3 Data and Methodology

In order to cast the analysis into standard macroeconometric tools for business cycle analysis, the (available) data to proxy for both physical and transition risks requires a careful selection. In what follows, therefore, we first illustrate in detail the climate data set – that covers 30 years of annual observations (1990-2019) for 24 OECD countries² – and then we describe the econometric approach. To proxy for the macroeconomy we use standard concepts and variables that measure real activity – industrial production, investment, employment, business confidence – and prices – consumer price index (CPI) split in energy and food and core.

¹In the literature, policies addressing the first type of externalities are typically referred to as demand-pull policies. They foster technological change by stimulating their demand, increasing the market size for environmental innovation through regulation, carbon tax, financial incentives, standard-setting instruments or information campaigns (Popp (2019)). Policies that address knowledge market failures instead are called technology-push policies. This type of policies aim to foster socio-technical change by reducing the private cost of research and development from the supply side (Nemet (2009)). Typical technology-push policies are non-market based instruments such as public R&D funding or tax reductions for R&D investments.

²Australia, Austria, Belgium, Canada, Czech republic, Denmark, Finland, France, Germany, Greece, Hungary, Ireland, Italy, Japan, Korea, Netherlands, Norway, Portugal, Slovakia, Spain, Sweden, Switzerland, United Kingdom, and USA.

3.1 Measuring physical and transition risks

The database used for the analysis combines several variables coming from different sources. Climate related variables are downloaded from the OECD.stat Environment database.³ To measure environmental policy and technological development, we use two general proxies, namely: (1) the OECD Environmental Policy Stringency index (EPSI); and (2) the number of patents for each country for selected environment-related inventions and technologies. To proxy for climate change and environmental risks, we use two main variables: (1) The welfare costs of premature deaths due to exposures to climate-related events (that we call environmental degradation); and (2) Total greenhouse gases (GHG) emissions per unit of GDP (emission intensity). Data charts and additional details are in the (Online) Appendix A.

Environmental policy The EPSI is a newly developed OECD composite indicator of environmental policy stringency which records increasingly stringent environmental policies in all countries. It is a country-specific and internationally-comparable measure of the stringency of environmental policy, where stringency is defined as ‘the degree to which environmental policies put an explicit or implicit price on polluting or environmentally harmful behaviour’. The EPSI includes therefore the explicit and implicit, policy-induced cost of environmental externalities that polluters have to pay. The index ranges from 0 (not stringent) to 6 (highest degree of stringency) and is based on the degree of stringency of 14 environmental policy instruments divided in three equally-weighted subindices, which respectively group market-based (such as carbon taxes, or trading schemes), non-market-based (e.g. emission limit values), and technology support policies (mainly public R&D). See Figures A.1 - A.3 in the Online Appendix for more details on the composition of the index. The synthetic indicator, therefore, is inclusive of demand-pull and technology-push policies, primarily related to curbing greenhouse gas emissions and local air pollution, but not necessarily regulations across all sectors of the economy. In our analysis we use the overall index – as proxy for a combination of measures – and each of the sub-indices related to market-based, non-market-based, and technology support policies. For further details on the construction of the index and its properties see Botta and Kozluk (2014) and, more recently, Kruse et al. (2022).

Green Innovation The proxy for green innovation counts the number of patents related to developments in environmental related technologies. See Figure A.4 and Table 1 in the Online Appendix A for more details on the type of technologies included and the time series of patents over time. The statistics are constructed using data extracted from the Worldwide Patent Statistical Database (PATSTAT) of the European Patent Office (EPO) using algorithms developed by the OECD. We use an aggregate category labelled “selected mitigation technologies”. The number of inventions developed by country’s inventors are independent of the jurisdictions where

³See <https://www.oecd.org/environment/environment-at-a-glance>

patent protection is sought (i.e. all known patent families worldwide are considered). Cross-country comparability is ensured by the use of indicators based on patent family size which are flexible and can be adapted to various applications (see [Haščič et al. \(2015\)](#)). This variable provides therefore a good approximation of the innovation suitable for tracking developments in environment-related technologies for two reasons. First, patents themselves are a direct measure of countries' and firms' innovative performance that is eventually commercialized; Second, since patents applications are usually filled early in the research process they are also a reasonable indicator of the level of R&D activity itself.

Environmental degradation The main proxy for physical risks refers to the cost of premature deaths from exposure to environment-related risks and we use it as a damage function to measure environmental degradation (i.e. depletion of resources such as quality of air, water and soil; the destruction of habitat and ecosystems; and pollution).⁴ The measure is build by OECD using epidemiological data taken from Global Burden of Disease Study 2019 ([GBD \(2019\)](#)) while the welfare costs are calculated using a methodology adapted from [Roy and Braathen \(2017\)](#). The core idea of this indicator, conceptually very close to a damage function, is that environment-related risks, such as air pollution, carry a significant economic costs to society through the premature deaths and disabilities that they cause ([OECD \(2016\)](#)). The cost of premature deaths at the society level is measured through the so-called Value of Statistical Life (VSL). In essence, it represents the individuals' willingness to pay (WTP) to secure a marginal reduction in the risk of premature deaths. See subsection [A.3](#) and Figure [A.5](#) in the Online Appendix [A](#) for more details of the construction of the welfare cost and it evolution over time. We choose not to include in the baseline specification a variable that proxies for natural disasters for three main reasons. First, for all the countries in the analysis there is not a sufficient set of information about their nature and costs. This implies that we don't have data to build a long enough macroeconomic series to analyse their dynamic repercussions. Second, the concomitant happening of other events occurring either as triggers or as consequences of the disasters and the higher frequency of disasters in specific areas, would make it difficult to discern among the drivers of the effects on the macroeconomic variable when a disaster occurs. Finally, we adopt a business cycle perspective and do not focus on the immediate economic impact of natural disasters. However, we have performed some robustness check (see Figures [A.30](#) - [A.32](#)) by including temperature anomalies in the specification, and we use the available data on exposure to natural disasters in Section [5](#), where we test country heterogeneity in their responses to certain shocks.

⁴Environmental degradation is one of the ten threats officially cautioned by the high-level Panel on Threats, Challenges and Change of the United Nations.

GHG emission intensities The data on emissions refers to man-made emissions of major greenhouse gases and emissions by gas.⁵ We use the intensities (i.e. GHG per unit of GDP) which are calculated on gross direct emissions excluding emissions or removals from land-use, land-use change and forestry (LULUCF). The GDP used to calculate intensities is expressed in USD at 2015 prices and purchasing power parities (PPPs). The main reason to use intensities as opposed to GHG total emissions is that emissions intensities, at least with respect to energy and industrial emissions, are influenced primarily by shifts in energy intensity, economic structure, and fuel mix. It follows that emission intensities are not directly correlated with changes in activity levels (such as Industrial Production or GDP). Even in the event of major GDP changes, changes in intensity levels may be modest. Absolute emission levels, on the other hand, are strongly procyclical and influenced by GDP shifts (Doda (2014) and Herzog et al. (2005)). Overall, GHG emissions intensities have been reducing for all countries in the sample at an average rate of 1%. The data also show a sort of beta-convergence across countries, namely, countries with a higher initial level of GHG are also those with a higher emission reduction rate (not shown). However this convergence process is far from over and countries generally maintain their initial position with respect to the average.

3.2 The econometric model

We investigate the dynamic relationship between measurements of physical and transition risks, and macroeconomic variables in a SVAR model estimated with panel data. For each country, the model can be written as:

$$A_{i0}Y_{it_i} = \mu_i + A_i(L)Y_{it_i-1} + \nu_{it_i} \quad (1)$$

where the A s are coefficient matrices, μ_i is a vector of country-specific constants, and ν_{it_i} is a zero-mean vector of orthogonal structural shocks with diagonal variance-covariance matrix D_i ; and the notation X_{t_i} indicates that the panel is potentially unbalanced and that the number of time series observations is country-specific. The vector Y_{it_i} consists of two sets of variables, the climate-related variables and the macroeconomic ones. The climate block contains the four variables illustrated in the previous section: the Environmental Policy Stringency index, mitigation technologies, the welfare cost of premature deaths due to exposure to environmental risks and GHG emission intensity. The macroeconomic set of variables of interest include: industrial production, energy prices, food prices and core prices (i.e. total prices excluding energy and food). To account for and check the role of possible channels through which a shock to a climate-related variable reaches productions and prices, the VAR includes also variables that

⁵It includes total emissions of CO2 (emissions from energy use and industrial processes, e.g. cement production), CH4 (methane emissions from solid waste, livestock, mining of hard coal and lignite, rice paddies, agriculture and leaks from natural gas pipelines), nitrous oxide (N2O), hydrofluorocarbons (HFCs), perfluorocarbons (PFCs), sulphur hexafluoride (SF6) and nitrogen trifluoride (NF3). Data exclude indirect CO2.

proxy for some of the main transmission variables: the Business Confidence Index, Investments (governments, households and corporate), and Employment. More details on these variable are in subsection A.4 in the Appendix. In the empirical analysis, all variables are in log levels multiplied by 100. The estimation period spans from 1990 to 2019 and the panel is homogeneous but unbalanced, as for some countries data are not always available over the full sample.⁶

We make the following general assumptions for the reduced-form estimation of the model:

1. The data generating process features dynamic and static homogeneity, namely that $A_i(L) = A(L)$, and that $D_i = I$ and $A_{i0} = A_0$. The latter implies that the variance-covariance matrix of the reduced form shocks, $A_{i0}^{-1} A_{i0}^{-1'} = \Sigma_i$, is also common across countries ($\Sigma_i = \Sigma$).
2. The reduced-form shocks (ϵ_{it}) are assumed to be serially and cross-sectionally uncorrelated.
3. A linear trend is used in the estimation to deal with part of the non-stationarity of most variables, complemented with a general Minnesota prior and a sum of coefficients prior.

Under these assumptions, pooled estimation with fixed effects – potentially capturing idiosyncratic but constant heterogeneity across variables and countries – is the standard approach to estimate the parameters of the model (Canova and Ciccarelli (2013)). We now discuss these assumptions in turn.

The homogeneity assumption is probably the strongest one because if the slope parameters differ across countries, a (frequentist) fixed effect-type estimator is biased and inconsistent (Pesaran and Smith (1995)) even when N (the cross section dimension) and T (the time series dimension) are large enough, which is anyway not the case in our analysis. We therefore only use this assumption as a first approximation because we are constrained by the available data which covers too short of a time span to fully account for country heterogeneity (even for a mean group estimation). This assumption will however be partially relaxed in Section 5 when we discuss the heterogeneous responses of different groups of countries to climate-related shocks. In that case, we split the countries in various groups according to country-specific characteristics (such as their level of GHG emissions, their adoption and use of a carbon tax, or their degree of exposure to natural disasters or other risks) and pool the data for estimation separately by groups.

Assuming absence of serial and sectional correlation is standard when estimating a panel of dynamic simultaneous equation models (see e.g. Rebucci (2010)). However, while the serial uncorrelation is a standard practice in VAR models, the sectional uncorrelation can be stronger than usually discussed with panel data, especially in a macroeconomic setup where international spillovers are the norm rather than the exception. Therefore, we also add a global variable to the

⁶In particular, the Business Confidence Indicator is not available for Canada and Hungary over 1990-1997, and for Czech Republic, Finland, Slovakia, and Sweden over 1990-1992, with a total NaN = 29. Investments are missing over 1990-1995 for all countries but US, Sweden, Norway, Korea, Finland, France, Australia with NaN=79. Employment is missing for all countries in 1990, with NaN= 24.

single country specifications – the global commodity price index – with the aim of capturing a factor that is common among macro and climate measurements and can account for correlations and possible spillovers across country. This is similar in spirit to the usual Global VAR approach (e.g. Chudik and Pesaran (2016))

Finally, the linear trend is an empirically convenient way to account for part of non-stationary data, to partially compensate for the low lag order of the VAR, and to condition the estimation on initial values of the endogenous variables which are in levels. A standard Minnesota prior augmented with a prior on the sum-of-coefficient is also used to complement this assumption. Under this specification, the model is a priori assumed to be difference-stationary for all variables with some residual (possibly linear) non-stationarity captured by a deterministic trend.

3.2.1 Reduced-form estimation

The reduced-form of model (1) is

$$Y_{it_i} = C_i + B(L) Y_{it_i-1} + \epsilon_{it_i} \quad (2)$$

where $C_i = A_0^{-1} \mu_i$, $B(L) = A_0^{-1} A(L)$, and $\epsilon_{it_i} = A_0^{-1} \nu_{it_i}$. We estimate this model using Bayesian techniques, which require specifying a prior information for the unknown, in terms of a functional form for the distribution of the error term and for the parameters. We re-write the model in matrix format stacking first by t for each country and then by i as:

$$\mathbf{Y} = \mathbf{X}\mathbf{B} + \mathbf{E} \quad (3)$$

where \mathbf{Y} is a matrix of $NT \times m$, $NT = \sum_{i=1}^N T_i$, m is the number of variables in the VAR for each country, \mathbf{X} is the re-arranged matrix of lagged \mathbf{Y} and of dummy variables for the country “fixed-effects” and \mathbf{B} is the matrix of the coefficients which contains the common $B(L)$ ’s and the loadings of the country specific constants. We assume that the errors are normally distributed and we use a conjugate Normal-Inverse Wishart prior distribution for the parameters, such that:

$$p(\mathbf{B}, \Sigma) = p(\mathbf{B} | \Sigma) p(\Sigma) \quad (4)$$

with

$$p(\Sigma) = iW(S, \nu) \quad (5)$$

and

$$p(\mathbf{B} | \Sigma) = N(\mathbf{B}_0, \Sigma \otimes \Omega_0) \quad (6)$$

Under this prior, the posterior distribution has the same functional form and is easy to simulate from. To elicit the prior hyperparameters we use a standard Minnesota prior for the prior hyperparameters \mathbf{B}_0 and $\bar{\Omega}$, with the mean for the own lag equal to 1, the general tightness

(λ) equal to 0.3 and the tightness for the constant is diffuse. As for the covariance matrix of the residuals it is assumed to be diagonal and its elements are estimated from univariate AR(p) model. Finally, we use a sum-of-coefficient prior with shrinkage parameter $\tau = 3$. We implement the priors adding dummy observations. The posterior distribution is simulated 10000 times and the VAR is estimated with one lag.

3.3 Empirical strategy

The purpose of our paper is to analyse to what extent shocks to climate-related variables have meaningful effects on the macroeconomy over a business cycle horizon.⁷ Impulse response functions to shocks to climate variables are obtained using a block triangular (Choleski) factorization of the variance-covariance matrix of the reduced form errors, with the climate block ordered before the macro block. This assumption – in line with similar empirical studies, such as [Mumtaz and Alessandri \(2021\)](#) and [Kim et al. \(2021\)](#) – implies assuming that the shocks hitting the macroeconomic variables will not impact the climate variables contemporaneously, and therefore the possible consequences on climate or climate policy of macro shocks can be appreciated only after one year. On the other hand, shocks hitting climate-related variables are more likely to have effect on the macroeconomy during the same year. This assumption may seem somewhat unconventional for, in the loop between the climate and the economic systems, emissions are usually a consequence of economic activity while the economy gets hit by the damage that generates after emissions affect the climate system. However, we include in the model emission intensities which, because their main drivers are energy intensity and the fuel mix, are not directly correlated with changes in economic activity ([Herzog et al. \(2005\)](#)).

In line with the same argument, even with low frequency data, it makes sense to assume that environmental policy-making or the patenting of a new green technology in a given year are likely to affect the economy in the same year, whereas macroeconomic shocks take relatively longer to reach the climate block. Environmental policy is the most exogenous variable in the system, being the result of public interventions due to political shifts and social and environmental pressures. Furthermore, while absolute technological development can respond quickly to economic activity ([Dechezleprêtre et al. \(2021\)](#)), specific environmental technologies aimed at mitigating, and adapting to, climate change, have very high costs, represent a small portion of the market, and are currently mostly driven by technology push policies and R&D expenditure or incentives. For this reason, even in times of economic crisis, it is reasonable to think that the effect on environmental specific patenting activity will unfold relatively slowly.

In the climate block we identify three shocks: an environmental policy shock (to the strin-

⁷We are less interested in the effects of the typical macroeconomic shocks (say demand and supply) on climate variables, although their (relatively more standard) identification can allow us both to understand if physical and transition shocks can be classified as demand or supply, and to help us gauge the size and persistence of the effects of climate related shocks in a comparative manner (see the robustness Subsection of the Working paper version [Ciccarelli and Marotta \(2021\)](#)).

gency index), a green innovation shock (to mitigation technologies) and an environmental degradation shock (to the welfare cost of premature deaths). We test the robustness of this identification strategy with multiple checks (see subsection 4.3). When assessing the effect of environmental policies, the composition and structure of the stringency index as described in section 3 allow for a granular analysis of the effects of environmental policies and can be used either in its general version – as a combination of all policies – or for all individual measures that have different policy targets. In fact, the market- and non-market based components target primarily the negative externalities of emissions, whereas the technology support component targets positive externalities from R&D that – absent public policy – may lead to sub-optimally low investment. Therefore, we can check the consequences of unexpected shocks to (i) a combination of all policies, (ii) market-based policies; (iii) non-market-based policies; and (iv) technology support.

When assessing the physical risks we compute an unexpected shock to the welfare costs of environmental degradation while using the GHG intensities only as a control to proxy for future climate damages. We don't show the consequences of a shock to this variable, which could be more problematic to identify given that emissions may respond more rapidly to the state of the economy than other slow moving climate variables, such as environmental degradation or temperatures. The latter is also used for robustness check in our analysis, and provides the same qualitative results as the proxy for environmental degradation.

The variable ordering in the VAR is such that an environmental policy shock (including technology support) increases the stringency index at time 0 while a technology shock increases the number of mitigation technologies without affecting at time 0 the policy index, which can react to it only after one year, and affects contemporaneously the emissions' intensities and the environmental degradation proxy but do not react contemporaneously to their movements. The assumption therefore is that, as a consequence of a shock to physical risks, governments are slow to put in place the policies and technologies needed for mitigating climate change consequences. On the other hand, the transition shocks, if suddenly implemented in the form of new policy or in support of technology, can have visible effects on emissions and welfare costs in the same year. Finally, the macroeconomic block is left unidentified in the baseline specification.⁸ It is important to notice that the results we report in what follows based on the Choleski orthogonalisation are qualitatively and quantitatively similar to those obtained using Generalised Impulse Response functions (Pesaran and Shin (1998)), which do not require orthogonalization of shocks and are invariant to the ordering of the variables in the VAR.⁹

⁸In further robustness checks contained in the Working Paper version (Ciccarelli and Marotta (2021)) we also experiment by identifying standard demand, supply and monetary policy shocks with the typical assumptions that the former have positive signs on both output, prices and interest rates, whereas the second is a negative technological shock or a type of cost-push shock that reduces output and increases prices and interest rates. The monetary policy shock instead is identified with the assumption of a negative effect on both output and prices.

⁹The results of this robustness check are reported in Ciccarelli and Marotta (2021).

3.3.1 Policy scenarios and selected channels

Following a similar approach as in [Mountford and Uhlig \(2009\)](#), we complement the impulse response analysis and investigate also the effects of the physical and transition risks shocks under scenarios which can be used to gauge the effectiveness of the policy or the technology support, as well as the importance of selected channels. More specifically, we conduct counterfactual experiments whereby, for instance, we leave unresponsive the policy support after a shock to technology, or we check the effects of a physical shock when leaving unchanged the policy and the technology support. Similarly, we check how important the expectation or the investment channels are in transmitting transition or physical shocks.¹⁰ Finally, when discussing the effects of a shock to environmental degradation, we also compare the baseline results with the ones obtained in a case where we restrict policy and innovation to react positively to such a shock (instead of being unresponsive either contemporaneously or over the whole horizon).

4 Baseline Results

In this section we report the results in the form of impulse response functions, to check if and how macro variables move after a one-standard deviation shock in two transition risks – policy and technology – and one physical risk – environmental degradation or welfare costs. The evidence will be subsequently complemented in Section 4.3 with some robustness checks, and in Section 5 with the analysis by country groups to test how sensitive results are to characteristics that are related to country economic features – such as income – climate traits – such as their exposure to risks of natural disasters – or institutional elements – such as the adoption and use of a carbon tax. Because the variables are transformed in log multiplied by 100, the unit scale of the IRFs is directly expressed in percentages.

4.1 Transition Risks

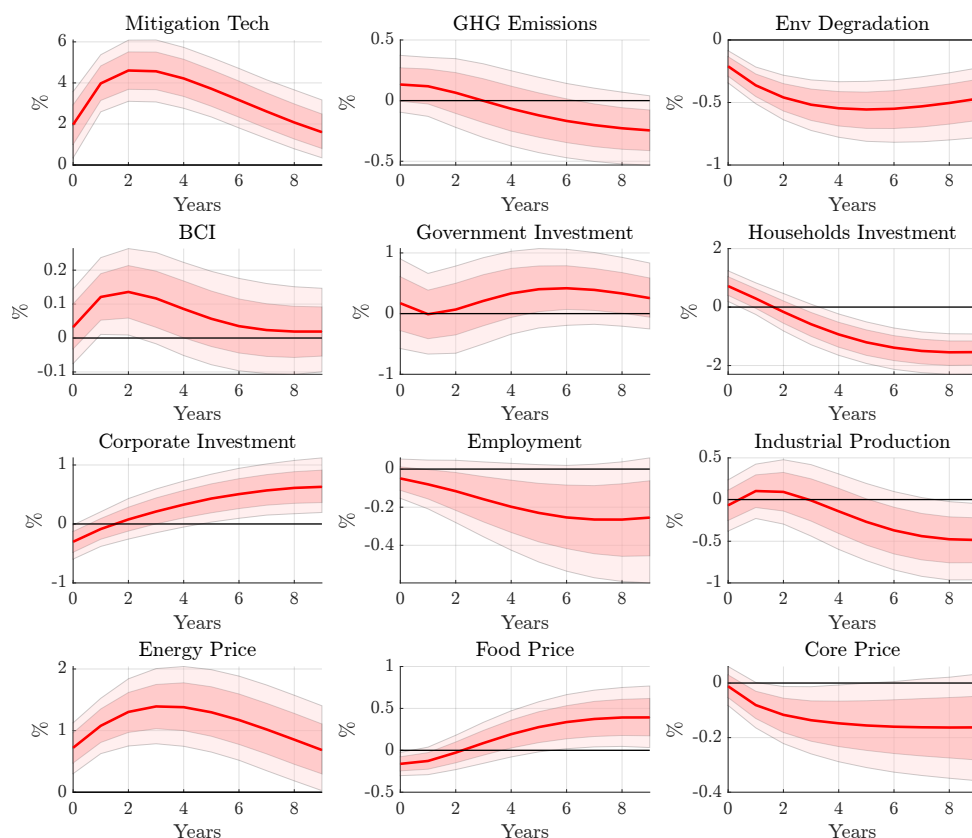
4.1.1 The effects of environmental policies

Figure 1 reports the effects of an unexpected shock to the aggregate measure of environmental policies as measured by the total stringency index. The red line represents the median responses and the shaded areas are the 68 percent (dark) and 95 percent (light) Bayesian posterior probability intervals or credible sets. We will describe results as “significant” if at least the darker shaded area does not contains the zero line.

The shock to the aggregate environmental policy variable generates some expected dynamics in the “climate block”, as it stimulates the number of patents in environmental technology destined to mitigation, and is in turn followed by visible mitigation effects as represented by

¹⁰The technical details to engineer these scenarios in our framework are similar to what explained e.g. in [Wong \(2015\)](#).

Figure 1: Impulse response functions of a shock to Environmental Policy



Sources: Authors' calculation; Sample: 1990-2019.

a significant reduction in environmental degradation and a medium term reduction in GHG emission intensity (after a small and insignificant initial increase). The increase in mitigation technology is presumably linked to the mix of demand-pull and technology-push policies included in the total EPSI, and to the rise of investments in environmental research and development (R&D). This intuition is compatible with the positive response of government and corporate investments. The latter after being immediately crowded out pick up in a positive and sustained manner over the whole horizon.

This finding is consistent with the idea that environmental policies (and policy-induced innovation) create externalities that may require further policy action to provide sufficient incentives for private R&D directed at exploring new technologies as well as for the adoption of greener production methods (Popp (2019)). Therefore, while the goal of public direct investment (or incentives and tax policies) might not be enough to build the clean energy economy of the future, it can certainly create the conditions for the private sector to closing the adaptation gap. This seems to be confirmed by our results. Notice, however, that the tighter climate policy paired with higher private and government investment in green technologies crowds out entirely

households investments, a typical demand-type shock induced by climate policies that promote investment in low-carbon technologies (Batten et al. (2020)).

Regarding the other effects on the macroeconomic block, a striking general result is that climate-related shocks can have a significant impact on macroeconomic variables over an horizon comprised between 2 and 8 years, i.e. the “typical” range for a business cycle periodicity. Moreover, the impact is quite strong on energy prices and can translate into significant variation in business (and consumers) sentiments or investments. In turn, this could affect overall spending in the macroeconomy and these shocks could eventually impact the business cycle fluctuations becoming of first order importance also for central banks.

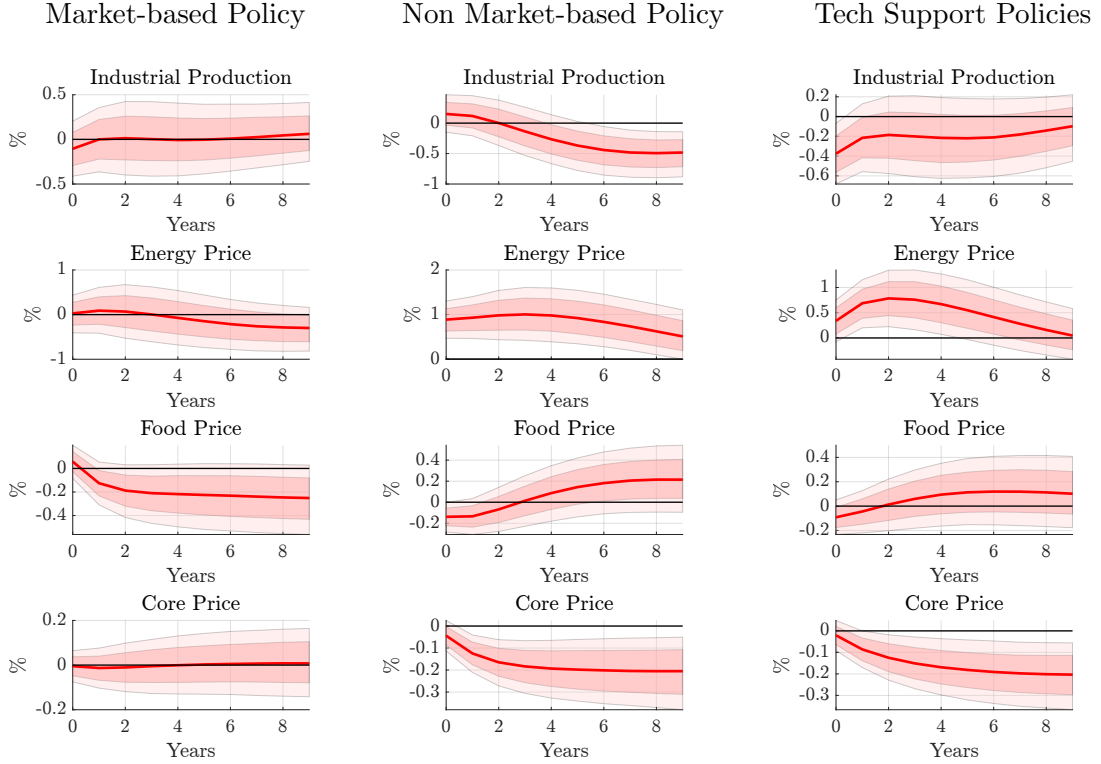
More in detail, Figure 1 shows that an initial muted effect on industrial production is followed by a more negative and persistent response over the medium term. Energy prices increase as expected in a significant and sustained manner together with food prices – possibly contributing positively to some pressure on headline inflation – while core prices decrease somewhat persistently. In other words, an unexpected shock to a combination of environmental policies generates a relative price adjustments with an overall reduction of the output and therefore a dominance of supply-type effects, driven by the energy sector, similar to a typical cost-push shock (in line with e.g., Känzig (2021)).

We also observe a negative effect on employment. This result seems to indicate that the net effect between the job creation driven in a number of economic sectors with low emission intensities by a transition to low-carbon, environmentally sustainable economy can be more than compensated by a significant job destruction in traditional emission-intensive sectors which likely causes a final negative effect on total employment. Notice, though, that the effects on employment and output as measured by industrial production, seem to point to an immediate increase in overall productivity, a result that is consistent with the work of Brunel (2019) and Franco and Marin (2015).

To better understand the strength of the transmission channels after an environmental policy shock, we perform two additional exercises. In the first exercise, we produce a scenario where a shock to environmental policies is not followed by a response to the government investments and by mitigation technologies that can guarantee a transition to an effective low-carbon economy. We engineer this experiment by creating a sequence of shocks to environmental policy such that it shuts down the responses of mitigation technologies and public investments over the whole horizon. The results of the first exercise are reported in Figure A.7 in the Online Appendix. By shutting down the technology channel we find that the reductions of environmental degradation is less intense, and there is a more muted reduction of employment as well as a lower inflationary pressure coming from energy prices.

In the second exercise, we investigate the results of a shock to each individual components of the EPSI (which we use one by one in the VAR in place of the aggregate measure), and we try to assess if the different types of policies, namely market-based, non market-based, and

Figure 2: Impulse response functions of a shock to Components of EPSI



Sources: Authors' calculation; Sample: 1990-2019.

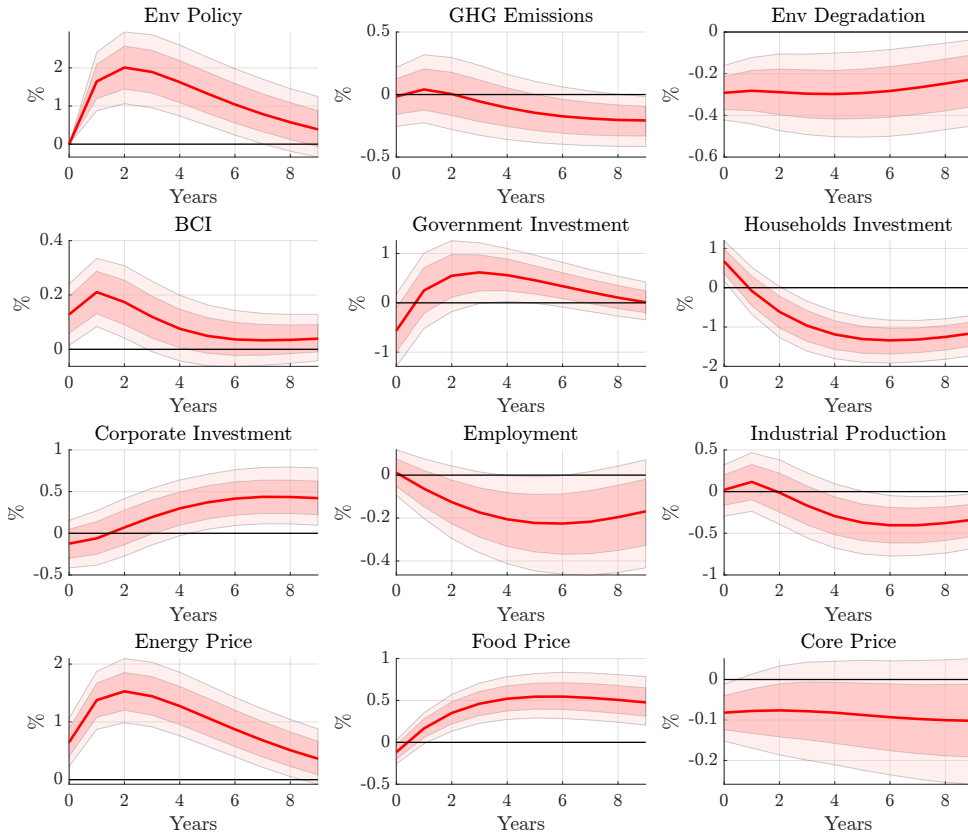
technological support, have different effects both on the climate and on the macro block. See Figure A.3 for more details on the different components of EPSI.

The results of the second exercise are reported in Figure 2, while the full set of results is in the appendix (Figures A.12 - A.14). Several considerations are in order. First, a shock to market-based instruments, although more effective than other instruments to curb emissions, does not appear to have a significant effect on output and prices, contrary to some of the recent empirical evidence. This might be due to the little adoption of carbon taxes across countries in the panel and in the definition of market-based instruments which does not focus on one specific measure. This result is nevertheless not necessarily controversial, as also found e.g. by Konradt and Weder-Di Mauro (2021) for carbon taxes only. Secondly, non market-based instruments which include mostly emission limits seem to have a positive effect on energy prices but their effect on output is negative only in the long term. Finally, it seems that the strong negative supply type of effect that we have seen in the baseline result can be attributed to technology support policies. Those include, R&D subsidies and support for renewable energy, more specifically wind and solar. In conclusion, overall for some environmental policy instruments (notably carbon prices more than technology support measures) we don't find substantial disruptive effects on the

real economy, with an almost perfect offsetting between (negative) demand-side and supply-side effects. Results are instead more clear-cut for shocks to policy instruments that induce a change in environmental technology. In the next subsection we explore in more detail the implications of a shock to green innovation.

4.1.2 The effects of green innovation

Figure 3: Impulse response functions of a shock to Mitigation Technology



Sources: Authors' calculation; Sample: 1990-2019.

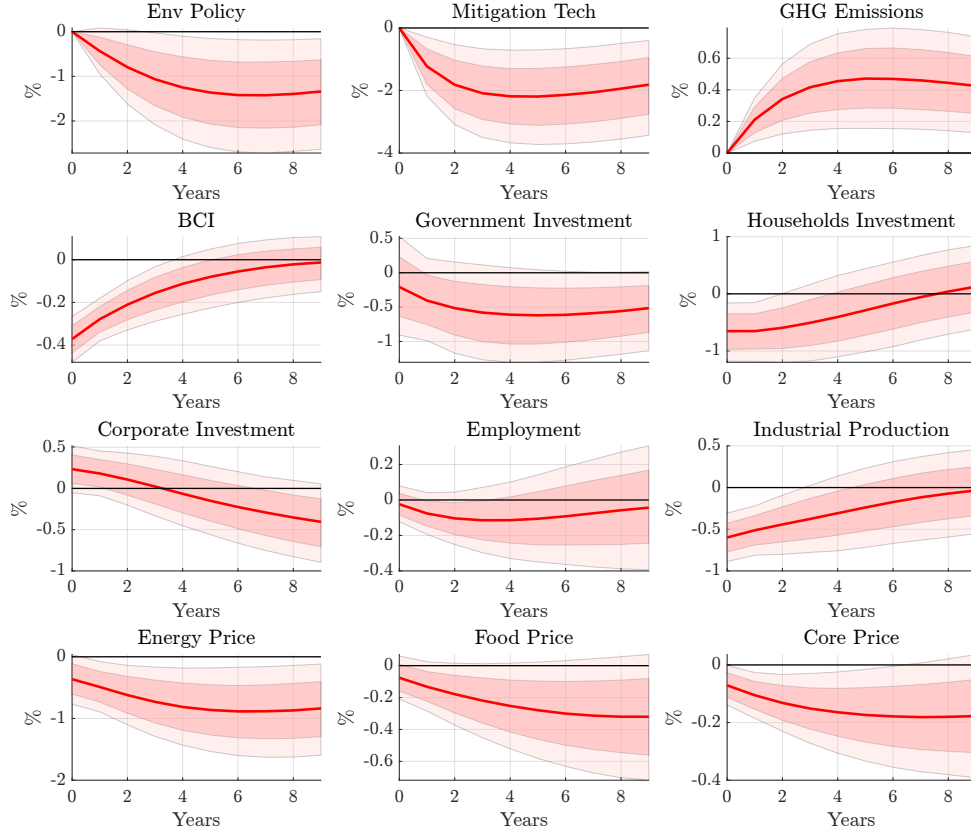
The results of a shock that exogenously increases climate change mitigation technologies is reported in Figure 3. The impulse responses are very much consistent with the effects of a shock to the stringency index, in particular with those stemming from its non-market-based and technology-compatible policies, i.e. those types of policy instruments that stimulate green investment – either directly or indirectly via emission limits – more than putting a price on carbon emissions. Although by the identification scheme this shock is interpreted as an exogenous increase in environmental technology that is not induced (or supported) by a contemporaneous increase in environmental policies or public green investments, the chart confirms that green in-

novation and environmental policy can reinforce each other – as indicated by a positive response of the policy index already one year after the shock.

In a counterfactual exercise, we created the shock to environment-related technologies such that they would have no effect on the IRF of EPSI. The effect on the macro block does not change drastically, suggesting that the effect of technology on output and prices does not pass through the increase of policy or government investments. The result of this counterfactual exercise is shown in Figure A.8 in the Online Appendix. Moreover, a change in green innovation induces a reduction both in the level of emissions and in the cost of environmental degradation over the business cycle. This combination of results from the climate system, although stimulating the business confidence, has a negative effect on employment and on output between 2 and 10 years (after an initial insignificant impact) and a significant effect on all price levels with different signs and dynamics: the price of energy increases faster and more forcefully with a peak between one and two years; food prices peak positively after three to four years and react in a more persistent manner over the whole horizon; core prices react somewhat negatively and persistently over the whole horizon. All together these effects suggest that the technological transition to low-carbon emission can come at the cost of diverting resources from current productive activities to mitigation investments, mostly impulsed by government and corporations. New investment opportunities are initially pushed by the government (perhaps as a consequence of the endogenous increase in policy mitigation), and only after about four years they are also taken up by the private sector, following a positive reaction of business confidence that takes some time to dissipate the possible uncertainty about the rate of innovation and the adoption of clean energy technologies that follows the increase of the newly patented inventions (Batten et al. (2020)). Households' investments continue to be crowded out after an initial positive reaction, perhaps because the more stable prospects of green innovations turn obsolete several available durable goods.

Overall the results of this section provide preliminary evidence that a shock to environmental policy, even though it acts as a supply shock (especially on the energy sector) increasing prices and reducing output, does mitigate the effect of climate change and, at least for non-market-based policy instruments, has the potential to boost economic activity. On the other hand, however, the results of a shock to green innovation (or to policies that support and induce green technologies) suggest that, if innovation is not supported from the supply- and demand-side by the right policy mix, the weight of the transition to a low-carbon economy would be carried by businesses and private investments, resulting in market failures that have the potential to slow down the economy over the medium run.

Figure 4: Impulse response functions of a shock to Environmental Degradation



Sources: Authors' calculation; Sample: 1990-2019.

4.2 Physical Risks

We now turn to the results of a one-standard-deviation shock to our proxy for physical risks (Figure 4), identified as a shocks to the welfare cost of premature deaths due to environmental degradation (our damage function), in absence of a contemporaneous reaction of environmental policy, green innovation, and GHG emission intensity. The charts show that, in the climate block, such a shock generates a positive impact on emissions and a negative impact on policy and green innovation in the years after the initial shock. In a sense, the responses of the other climate-related variables go in the direction of reinforcing a (slow-moving) deterioration of climate conditions and physical risks in an environment that is not only not protected by green policy or innovation efforts, but that is also worsening because of the additional intensity of GHG emissions. This increase in emission intensities is of particular interest. The reinforcing link between emissions and welfare costs is not surprising on a long time span but is perfectly plausible also in the short-to-medium run. Among other things, GHG emissions contribute strongly not only to global warming through the accumulation of CO₂ particles in the atmosphere, but also

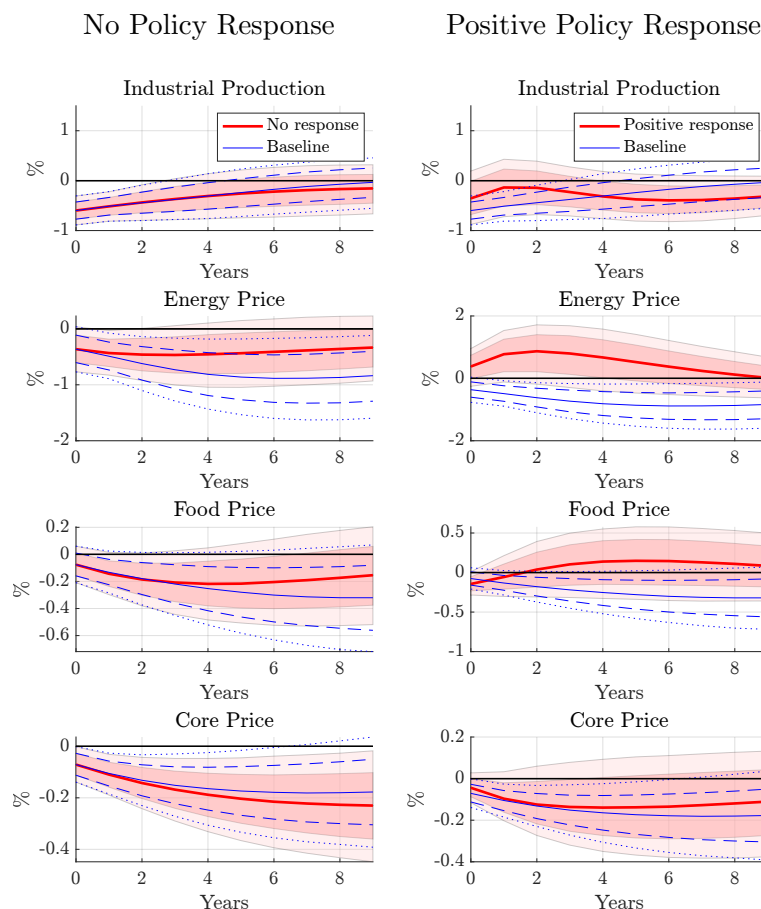
to local air pollution levels, which in turns have a direct effect on peoples' health, implying a non negligible economic cost (OECD (2016)). Therefore, the proxy for environmental degradation, being by construction a measure of the economic harm in a given year due to environmental degradation (including air pollution) is strongly linked to GHG emissions.

The shock to physical risks and the described effects on the climate block induce on the macroeconomic block a reaction that is equivalent to a strong negative demand shock: (1) It depresses expectations as embedded in business confidence; (2) It increases temporary corporate investment while crowding out government and household investments; (3) It has a negative and significant impact on employment, output and prices. While the effect on production is fast – with a negative sign at impact – and relatively “short-lived”, the responses of all prices typically peak between 5 and 10 years and are much more persistent. Notice also that the fact that this shock has a negative effect on production and prices ensures that it cannot be confused with a technology shock or with any other (positive) shock to economic activity that causes emissions to increase and environment to deteriorate.

To further qualify the above results, we conduct two policy scenarios. In the first exercise we build a shock to environmental degradation such that the responses of environmental policy and green innovation are shut down over the entire horizon. In the second exercise we identify with sign restrictions a physical risk shock that increases environmental degradation and impose a positive reaction onto the responses of environmental policy and green innovation. Figure 5 reports the results. In the first scenario we want to simulate a world where there is no response at all from the policy side to the deterioration of environmental conditions, on the other side we want to see how the effects on the macroeconomy differ when mitigation efforts are in place. The first scenario (left panel of Figure 5) confirms the baseline results with a negative demand-type effect on output and prices. More interestingly, the second scenario (right panel) shows that the negative effect on the macroeconomy due to the environmental degradation can be mitigated by policy interventions at least on relative prices, and that, if policy and innovation react to counteract a physical shock, energy and food prices increase similar to a standard supply-type of shock.

Moreover, in order to gauge how strong the expectation channel can be, we performed an additional counterfactual exercise where we create a shock to environmental degradation such that it does not have a (negative) effect on business confidence, i.e. shutting down the response of the variable BCI over the whole horizon. Unsurprisingly, the effect of shutting down this channel confirms the idea that if firms become more pessimistic about the future due to the impact of climate change they would reduce investments (which would be taken up by government), leading to a more disruptive effect onto output and employment. Figure A.9 in Appendix shows the responses of such a shock.

Figure 5: Impulse response functions of a shock to Env Degradation: 2 policy scenarios



Sources: Authors' calculation; Sample: 1990-2019.

4.3 Robustness analysis

To check the robustness of our results, we perform five additional exercises about the model specification and the identification assumptions. Specifically, we estimate the model by (1) removing the linear trend; (2) using two lags instead of one; (3) splitting the sample to check the presence of possible structural breaks; (4) changing the variable ordering in the identification scheme and identifying shocks with sign restrictions; and (5) experimenting with different proxies for real activity and for physical risks. All figures describing the robustness checks are reported in the Online Appendix A.

With respect to (1)-(2) the results turn out to be very robust to alternative choices (see Figures A.15 - A.20). Regarding (3), to check for the possibility of changing parameters over time we performed a simple exercise which compared the results of the model estimated over the full sample (1990-2019) with those of the same model estimated only over the sample (2008 - 2019), i.e. after the great recession and the financial crisis. Over this period, as we know,

the data show some visible changes that could be key to understanding our findings. Results (see Appendix, Figures A.21 - A.23) do show some interesting changes in that, after the great recession, a shock to policy stringency can reduce emissions more and earlier than before but at the mere cost of crowding out government investment and green innovation and at expenses of business confidence. After 2008, however, a shock to green policies tends to stimulate private investment earlier than before which, in turn, affects positively industrial production in the very short run, and has a less persistent positive impact on energy prices. Very similar results are found for a shock to Mitigation Technology, while a shock to environmental degradation overall behaves more like a negative supply shock and increase energy and food prices. Some of these changes with respect to the baseline, such as the reduction in green innovation and negative effect on confidence are consistent with the view that right after the great recession public's concern about climate change have generally declined, and that the "crisis of confidence" in climate change can rebound only after business cycle conditions, and the labor market in particular, improve (see e.g., [Scruggs and Benegal \(2012\)](#)).

With respect to the robustness check (4) on the identification assumption and the variable ordering, Table 4 in the Appendix reports the correlation matrix of the reduced-form residuals of the model. The table allows to identify for which variables the Choleski ordering still leaves some significant correlations. For instance environmental degradation appears to still have some correlations with the climate block variables. For this reason we perform the first order check using environmental degradation as the first variable in the model. The second check is to place the macro block before the climate block, in line with the circular scheme that typically starts with economic activity having an impact on emissions and therefore on climate. Results are again very robust to all possible ordering checks, as shown in Figures A.24 - A.29 in the Online Appendix. The sign-restriction identification – also reported in the Online Appendix (A.6) – delivers very consistent results with the baseline. The ones for a shock to physical risks has been discussed above (Figure 5). The ones for a shock to transition risks (which is identified as increasing policy and innovation and decreasing emission intensities and environmental degradation) are also in line with the baseline, with a less negative impact on production.

Finally, baseline results are also robust if we use the GDP level as an alternative measure of output, and temperature anomalies as an alternative measure of Physical Risks. Results are reported in Figures A.30 - A.35 of the Online Appendix. When using temperature anomalies the only notable difference with the baseline results after a physical shock is the immediate increase of household investments (with other results remaining qualitatively similar), which is consistent with the fact that households respond to an increase in temperature by an increase in electricity usage in response to temperature shocks ([Ciccarelli et al. \(2023\)](#)).

4.4 Summary of the findings and interpretation

To conclude this section, we can summarise and interpret our findings through the lens of the discussion on the channels we have entertained in Section 2.

First of all, to answer the very first question that we ask, our results robustly show that climate related shocks have a significant effect on the business cycle. Nevertheless, the forecast error variance decomposition (FEVD) (see Table 3 in the Online Appendix) shows that their magnitude is not so sizeable to imply that they are to be regarded as strong direct sources of business cycle movements. Even though the effect on the business cycle is small, the importance of the climate shocks can become more substantial over a longer cycle in line with the idea that climate change’s economic implications are bound to become more and more significant in the long run if no mitigation and adaptation actions are taken.

Secondly, it is important to recall that in our simple set up we do not have extreme weather events or natural disaster associated with climate change. In fact, the proxies that we use for physical risks are more associated with medium-to-long term effects of global warming or with the exposure and vulnerability of society and natural systems to climate events (in short, environmental degradation). Though different in timing and immediate severity, both risks are dynamically evolving over time and interacting with each other in a complex and non-linear fashion, a feature that our linear model of course cannot capture. But the sign and persistence of the responses we obtain are quite telling of the kind of shocks that they subsume.

It has been fairly common to assume that physical risks associated with climate change act as (negative) supply-side shocks or as a combination of both negative supply and demand shocks through a number of different channels. Therefore the effect of these shocks on production or output is certainly negative at least in the near term. Our results are consistent with this simple fact. By contrast, the overall impact on prices (and inflation) is in principle ambiguous, since it depends on the overall balance of supply and demand shocks, which may differ between individual events. Moreover, that balance may itself differ between sectors, such that the overall impact on the economy in general and on prices in particular may depend on its sectoral make-up. Looking at the responses of prices it seems that the effects on prices are significantly negative and persistent in our sample, and indeed show a marked difference between sectors, with the effects on energy prices being much more pronounced than those on food and core prices. In other words, looking at both production and prices these results would be consistent with a predominance of demand (relative to supply) type of adjustments.

Let’s turn to what the literature identifies as transition risks, namely the risks associated with the introduction of more stringent policies or the sponsorship of more climate-friendly technologies. The macroeconomic impacts from transition risks arise from fundamental shifts in energy and land use which can cause output loss. For these risks it is also reasonable to expect a mix of demand and supply downward adjustments (Batten (2018)), although the downward

impact on supply could be more pronounced than the one on demand, leading to increasing prices and depressing production. The upward pressures on prices come from the transition to a low-carbon economy through the pricing of the externalities associated with carbon emissions. These upward pressures could partially be offset by technological changes that improve productivity or to the adjustment of consumers' preferences towards carbon-neutral goods and services. Our results are consistent with the view that the combination of green policy and investment shocks reflect downward supply pressures more than demand movements, especially for a shock to technology or to technology-inducing policies which give rise to a significant downward impact on production and significant positive impacts on sectoral prices. The effects of market-based policies instead seems to be much more ambiguous and certainly less negative on production than a shock to green technology over the business cycle.

Notice that this evidence is very much supported by and consistent with the expectations of large European firms. In a recent ECB survey, more than 80% of responses indicate that the overall impact of the green transition in terms of climate change and related policies will be to increase investment, costs and prices, especially during the transition phase (Kuik et al. (2022)). We will discuss the implications for policy makers and modellers in Section 6.

5 Country-specific Characteristics

So far we have documented that, in general, shocks to transition risks put an upward pressure on prices while shocks to physical risks put a downward pressure on prices and output. The aim of this section is to examine whether countries with different characteristics in terms of adaptation, mitigation, vulnerability, and exposure to both transition and physical risks are on average affected differently from a specific climate shock. The results of this section can help provide stylized facts relevant for policy makers that could potentially improve our understanding of climate shocks transmission to the global economy. In order to do so, the baseline VAR model is estimated by groups of countries homogeneously chosen based on a priori common specific features. The composition of the groups depends on a selection of country characteristics over the entire sample 1990-2019 related to climate, institutional, and geographical key features. Table 2 illustrates the different groups. The model is estimated by pooling the data for each selected subset of countries and the responses are normalized such that each IRF is divided by the standard deviation of the variable that we shock, for the sake of comparability across groups. A selection of results is discussed in the next subsections.

5.1 Carbon Pricing

Carbon taxes are widely considered as a potential cost-effective approach to reducing GHG emissions and an economically efficient policy instrument for de-carbonizing the energy supply and limit global warming. Its limited adoption (see Table 2) is explained by the several concerns

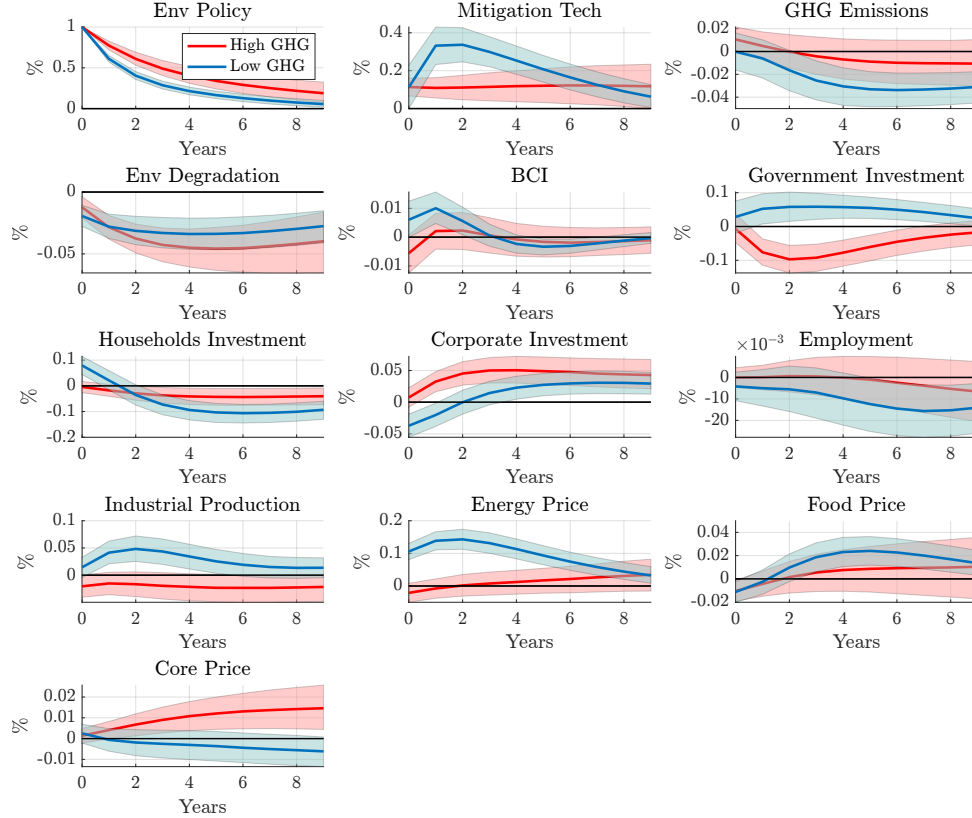
over its negative effects on the economy (growth, income distribution, competitiveness) unless an efficient revenue recycling is adopted ([Braennlund and Gren \(1999\)](#)). As argued in Section 3 and illustrated in Figure A.1, the 24 countries in the analysis had a different evolution of climate policies during the 30 years of our sample, with some countries preferring technological innovation to putting a tax on carbon emissions. The question we ask, therefore, is: how does the adoption of a carbon tax change the macroeconomic effects of environmental policy-related shocks?

Before answering the question, notice that, conditional to acknowledging that the countries included in this analysis are overall the largest emitters in the world, countries that have introduced a carbon tax are also the same who are categorised as low emitters in the sample. This is an important remark: when considering transition risks such as sudden adoption of environmental policy or diffusion of a specific new green technology, we must also look at which countries are more at risk. The literature and the general debate consider that countries with the highest GHG emissions are the ones whose economies are most likely to be more exposed to a faster and disorderly transition in order to reach their climate targets.

Figure 6 shows the macroeconomic responses to an environmental policy shock when we run the VAR for two sets of countries, according to whether they have implemented a carbon tax (low emitters, blue line) or did not adopt a carbon tax in the time span of our analysis (high emitters, red line). Five sets of differences seem to emerge. First of all, when countries have a carbon tax in place, the same sudden policy shock does not need to be as persistent as for the high emission countries with no carbon tax. However, this additional policy is enough to stimulate green innovation in virtuous countries much more than in countries with no carbon tax, and to induce a much stronger and persistent decrease in emission intensities. Second, countries with low emissions and a carbon tax have a significantly higher confidence in near future business performance than countries without a carbon tax and high emissions. Third, when a carbon tax is in place, the possible recycling of its revenues would initially encourage households' investment, which will only later be crowded out by government and private investment. Instead, for high emitting countries with no history of carbon tax, an unforeseen shock in environmental policies implies only a response of corporate investments, with a quite negative effect on government investments, signaling the lack of historical government intervention for those countries. Fourth, consistently with e.g. [Metcalf and Stock \(2020\)](#) and [Braennlund and Gren \(1999\)](#), in countries with a carbon tax and low level of emissions, the real effects on the economy are much less negative, and although with a more visible net job destruction, productivity increases due to a positive reaction of industrial production whereas in high emission countries production declines persistently. Finally, the price of energy increases more significantly for countries with a history of carbon tax whose firms have to face an even tighter price on polluting. However, this does not translate in a higher impact on core prices. In fact, core prices increase quite substantially and persistently in countries with no carbon tax and higher emissions. This evidence, together

with a negative response of real activity, reinforces the view that a disorderly transition can act as strong negative supply shock for high emitters.

Figure 6: Impulse response functions of a shock to Environmental Policy: Carbon Tax/Low Emissions vs No-Carbon-Tax/High Emissions

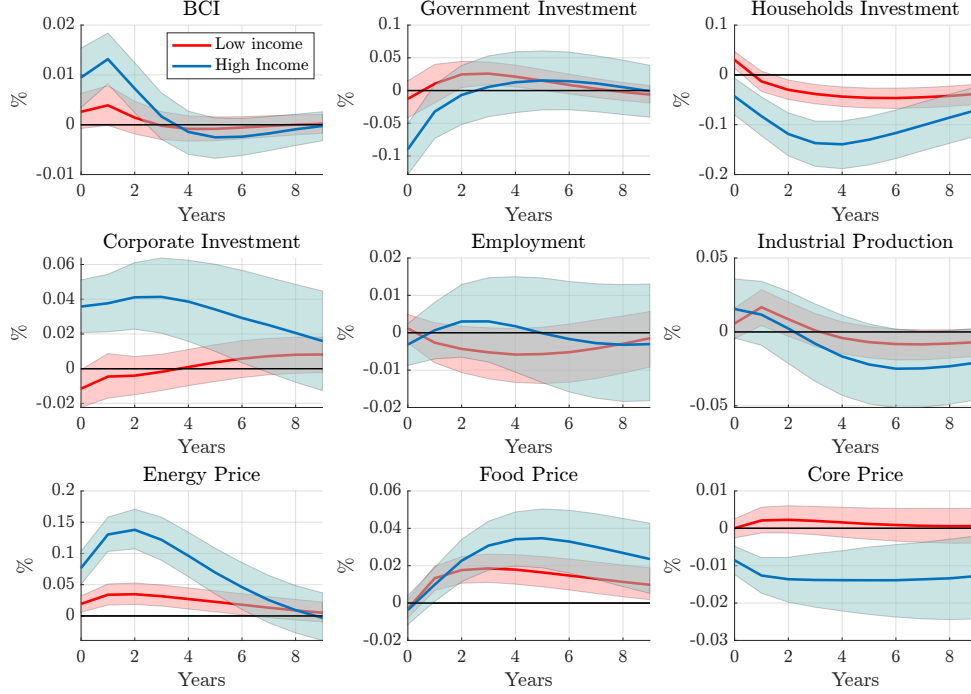


Sources: Authors' calculation; Sample: 1990-2019.

5.2 Gross National Income

Climate change and level of income are certainly intertwined because climate change can affect low-income communities and developing countries more than advanced economies due not only to the increased exposure and vulnerability of the former but also to the better preparedness of the latter in terms of either mitigation policies or existing innovative solutions (Jay et al. (2018)). Given that in our sample we only have OECD countries and that the difference between low and high income countries is not huge, grouping the results according to income will give us an accurate idea on the different macroeconomic impacts of climate-related shocks between countries that have already in place good structures to mitigate climate or adapt their technology and countries that are not yet prepared. For instance, Figure 7 reports the impulse responses to a shock to mitigation technologies for low (red) and high (blue) income countries. Several

Figure 7: Impulse response functions of a shock to Mitigation Technology: High Income vs. Low Income



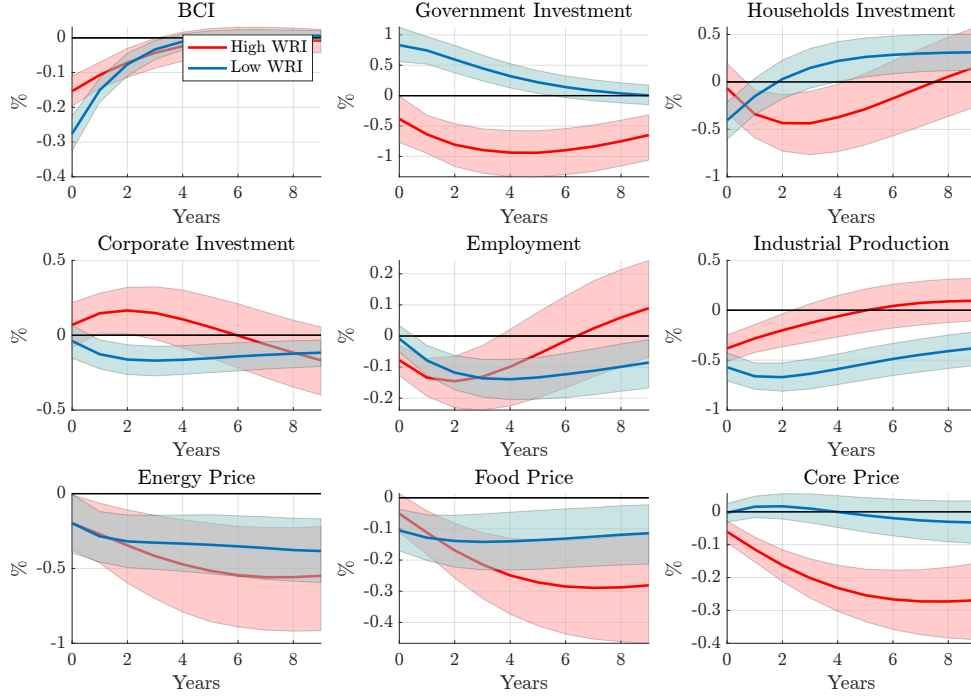
Sources: Authors' calculation; Sample: 1990-2019.

differences are noticeable. For higher income countries an increase in green innovation improves the business confidence more than in low-income countries. This in turn is associated with higher corporate investments in high-income countries which crowd-out households investment much more than in low-income countries, possibly due to substitution effects and a sensible reduction of durable goods based on soon-to-be obsolete technology. Third, labor market adjustment to new green technologies seem to have a more negative effect on employment in the low-income group, although not in a statistically significant manner. Industrial production is also more or less unchanged over the medium-term. Finally, while in high income countries a shock to green innovation translates into a relative price effect, for low income countries total prices increase, confirming a strong supply-side effect of the green transition in countries that are supposedly less prepared to receive it.

5.3 Exposure and vulnerability to climate change

Natural disasters (also those related to climate change) have a directly observable negative impact on the macroeconomy, especially in the short-run. As discussed in Section 3.1, we have decided not to use a direct measure of climate-related natural disasters or extreme weather events in the VAR and rather preferred a more medium-run orientation in the choice of the

Figure 8: Impulse response functions of a shock to Environmental Degradation: High risk vs Low risk countries based on the World Risk Index



Sources: Authors' calculation; Sample: 1990-2019.

variables. However, the relative exposure of countries and their vulnerability to natural disasters and extreme weather events is an important dimension of country heterogeneity to account for. Therefore in this section we check if certain shocks have different impacts on countries with different degree of vulnerability. To define which countries are most exposed and vulnerable, we rely on a measure called World Risk Index. The variable developed by UNU-EHS describes the disaster risk for various countries and regions and is part of a bigger publication, the World Risk Report (Day et al. (2019)).¹¹ The report focuses on the threats from and the exposure to key natural hazards and the rise in sea level caused by climate change, as well as social vulnerability in the form of the population's and societies' susceptibility and their capacity for coping and adapting to climate change.¹² Results to a shock to environmental degradation are reported in Figure 8 where we plot the impulse responses of high-risk (red) and low-risk (blue) countries.

¹¹Sources: United Nations University's Institute for Environment and Human Security (UNU-EHS), Institute for International Law of Peace and Armed Conflict (IFHV) of Ruhr-University Bochum.

¹²The WorldRiskIndex shows the level of risk of disaster due to extreme natural events for 181 of the world's countries. It is calculated on a country-by-country basis through the product of exposure and vulnerability. Exposure covers threats of the population due to natural disasters. Vulnerability entails the societal sphere and is comprised of three components: susceptibility, coping and adaptation, see Figure A.6 in Appendix. The composition of the index is described in greater details in the methodological notes available at www.WorldRiskReport.org/#data.

One notable result is that the responses of prices in high-risk countries are all more persistent than in low-risk countries. Moreover, the demand-side effect of the shock (with a strong negative effect on all prices, especially core prices) is strongest for countries with a high exposure to natural disasters and a higher vulnerability to them. By definition of the WRI, countries are considered to have a high exposure to natural disasters based on their historical exposure in the last 30 years as well as in terms of their vulnerability, susceptibility, and adaptive capacity. Hence, these results suggest that for countries at high risk (which, interestingly enough, are also for the majority low-income countries), an additional positive shock to the cost that society has to pay due to environmental degradation has a more disruptive effect on the macroeconomy than for countries with lower risks, reinforcing the negative demand-type shock showed in the baseline results. Similar negative results for output and employment are found by [Kim et al. \(2021\)](#) when analysing the macroeconomic effects of extreme weather shocks. Furthermore, these results are also consistent with recent work by [Canova and Pappa \(2021\)](#) who find that lower-income US states may be more severely hit by the catastrophic events. A possible explanation could be that in lower income states (or, in our case, countries) physical risks affect a bigger portion of their economic activity or, alternatively, because they lack the needed infrastructures or suitable private and public insurance schemes.

6 Discussion and policy implications

We have motivated our paper claiming the relevance of this type of research for policy makers and modellers. From a central banking perspective, for instance, the question is related to the extent to which climate change and policies can not only modify the monetary policy strategy but also imply additional trade-offs to be managed, over the short and the medium run. For economists and modellers, evidence on the interaction between climate change and the economy establishes empirically validated assumptions for the models.

The results presented above seem consistent with facts about the relationship between climate and the macroeconomy which can indeed have important implications for modellers and policy makers. The first robust finding is that climate change and policies to counteract them have a significant albeit not sizeable effect on the macroeconomy over a business cycle horizon (i.e., between 2 and 8 years). This implies that climate change not only is a concern for government and fiscal authorities, but it can also imply the need for monetary authorities to modify their reaction functions accordingly. More concretely, the data of this analysis supports the view that physical risks are consistent with developments that push prices and activity in the same direction, whereas the final impact of policies and technology is positive on prices and negative on output. Therefore, while physical risks are more associated with demand-type shocks, transition policies and technological improvement might be more consistent with supply adjustments. In other words, the green transition can create an additional trade-off to central banks,

as conventional (and unconventional) monetary instruments are designed to act on output and prices in the same direction. Depending on the persistence or entrenchment of the consequences of these shocks on inflation, the monetary authority may flexibly decide to intervene or to look through the shocks, and allow inflation to deviate from the target in the short term.

Our results also go a bit further. One of the findings of our analysis is that, overall, a combination of climate policies has strong positive effects on energy and food and a moderate or even negative effects on core prices. In other words, ultimately a combination of these policies seems to affect relative prices only. To the extent that these shocks are not dissimilar from the usual relative price shocks of the past, the monetary authorities will let the economy adjust without intervening. However, as also stressed by a recent report of the Bank of England, the relative price shocks associated with the transition to net zero may be different from the types of shocks that the central banks have faced in the past. Concretely, “the price of carbon (whether set via a tax, emissions trading scheme, or other means) rises steadily over time. Therefore, it is possible that the impact on inflation may become generalized and persistent” ([Angeli et al. \(2022\)](#)).

When it comes to the green transition, an important qualification that we make in the paper has to do with the types of different policies. When economists talk about climate policies one of the immediate associations is with carbon prices: If the emitted CO₂ is costly, we typically produce less of it. Therefore, carbon pricing is one of the most effective ways to reduce emissions because it eliminates a market failure directly at the source by pricing the emission costs. However, carbon prices are only a limited fraction of the whole set of policies: The OECD policy stringency index that we have used in the analysis – conveniently split according to the various sources of policy measures used by countries – shows very precisely that market-based policies are more than doubled by non-market based and technological support policies. Our results show that different climate policies affect prices and quantities very differently, with technology support being the only ‘pure’ supply shocks, while non-market-based policies can generate positive response of output and energy prices and can have a negative effect on core prices.

Another fundamental caveat – for both economists and policy makers – is that results differ according to country-specific (institutional and economic) characteristics as well as to their different degrees of exposure to risks and vulnerabilities. In countries with little or no history of environmental policy and where the level of emission intensities is relatively higher, a shock to aggregate climate policies (including a mix of market, non-market, and technology) behaves like a pure supply shock with a persistent increase of all prices. Moreover, in countries that have adopted a carbon tax and recycle its revenues, as well as in countries that have been adapting their institutions or are less vulnerable to climate or general risks, the disruptive effects of climate change and of the introduction of new policies or technologies to mitigate them are more contained. These findings reinforce the view that a disorderly transition can certainly

have negative effects over the medium term.

These results give several important messages to both modellers and policy makers. Available models give somewhat plausible but ambiguous responses depending on key modelling assumptions about, e.g., expectations or policy rules (see e.g. [Ferrari and Landi \(2022\)](#) for deflationary effects of the green transition). They have other limitations: (i) they only focus on one policy measure, namely carbon taxes; (ii) their conclusions are very uncertain and depend on different (but all plausible) assumptions on the relative importance of various channels that can generate either inflationary or deflationary dynamics; anyway (iii) their calibration is based on a history with little or no climate transition and very low carbon taxes. Our results also suggest that we need more sophisticated and complete models which include various form of heterogeneity (across countries and sectors) as well as more realistic designs of the scenarios. Models should notably consider other features of the green transition that do not only include carbon tax but also other types of policies, green technology, and climate shocks. Moreover, they also need empirically validated facts based on all ingredients and general equilibrium considerations as well as non-linearities in their response to physical and transition risks.

Our results definitely confirm that climate change and policies have macro implications that are relevant for central banks, the conduct of monetary policy, and financial stability. Climate risks may complicate the correct identification of shocks relevant for the medium-term inflation outlook, making it more difficult to assess the monetary policy stance. Therefore the strategy of some central banks (notably the ECB) includes now climate change considerations: climate change and policies imply additional constraints in the usual trade-offs for central banks and may affect the transmission mechanism of monetary policy by changing the demand side (e.g. consumption and investment decisions) via several channels (e.g. business confidence and the uncertainty around the nature and timing of the structural transformation implied by the green transition can reduce the sensitivity of demand to conventional policies). The optimal Central Bank response to climate risks at a given time will clearly depend on the projections of the state of the economy at medium term given initial conditions (e.g., the inflation rate at the time), using all available information ([Breckenfelder et al. \(2023\)](#)).

From a more general policy perspective, our results support the idea that one size does not fit all, and suggest instead the need for a policy mix to counteract climate change with a balance between demand-pull and technology-push policies that help limit the disruptive effects on the economy in the short-to-medium run. Overall, green technological development that is not supported by the right policy mix may result in market failures that have different sizes for different countries with heterogeneous consequences on the phases and duration of their respective cycles. A coordinated approach on climate policies would therefore be essential for instance in a monetary union with common monetary and financial objectives, but with some heterogeneity due to GHG emissions, carbon tax recycling, or other institutional and economic factors.

Finally, the whole analysis and discussion relies on the available data and concepts. Our society is changing very rapidly and concepts that have been useful to measure wealth and welfare of nations are bound to change. Our results are certainly not robust to the incorporation of new concepts (such as resilience, biodiversity, degradation) that will be included in the measurement of our main reference variables. Some of these, like “Economic Resilience”, are key concepts for the future. Only with reliable measures of these concepts can we know if our economies are able to adapt to change and deliver environmental and social goals, whilst also overcoming traditional and new shocks. The introduction of new data concepts is firmly advocated by several think tanks who argue that GDP per capita is already an unreliable indicator of economies’ capacity to recover from crisis. Using a newly developed economic resilience index, for instance, the ZOE Institute confirms some of our results. In particular, not only do they show that there are big differences in how well EU economies can absorb, recover from, and adapt to shocks depending on their resilience, but also they argue that “countries already hit hardest by crises are generally least prepared for future challenges.”¹³

7 Concluding remarks

This paper provides an empirical exploration of the macroeconomic effects of climate-related events and climate policies. Its main contribution is twofold: First, we take a business cycle perspective and focus on the “gradual” impact of climate-related risks (both physical and transition), as opposed to considering either the very long run effects of climate change or the immediate impacts of natural disasters possibly caused by it. Second, to the best of our knowledge this is the first empirical attempt to include the interrelated effects of both physical and transition risks, and test their economic consequences within a standard framework that combines exposure and vulnerability to climate change and environmental degradation, climate mitigation policies and adaptation technologies. In so doing, we select carefully the variables that proxy for adaptation, mitigation and damage using a panel of 24 OECD countries over the period 1990-2019.

The paper shows that climate change and policies to counteract them have a significant albeit not sizeable effect on the macroeconomy over a horizon between 2 and 8 years. In particular, the data of this analysis robustly support the view that the impact on output and prices of physical risks is overall negative whereas the final impact of policies and technology is positive on prices and negative on output. Therefore, physical risks are associated with demand-type shocks while transition policies and technological improvement are more consistent with supply adjustments. Results also differ according to country specific institutional and economic characteristics as well as their different degrees of exposure to risks and vulnerabilities. Notably, in countries that have adopted a carbon tax and recycle its revenues, as well as in countries that have been

¹³<https://zoe-institut.de/en/publication/defining-resilience-in-economic-policymaking/>

adapting their institutions or are less vulnerable to climate or general risks, the disruptive effects of climate change and of the introduction of new policies or technologies to mitigate them are more contained.

These results support the idea that one size cannot fit all and would therefore suggest the need for a (possibly country-specific) policy mix to counteract climate change with a balance between demand-pull and technology-push policies that help limit the disruptive effects on the economy in the short-to-medium run. Overall, green technological development that is not supported by the right policy mix may result in market failures that have different sizes for different countries with heterogeneous consequences on the phases and duration of their respective cycles. A coordinated approach on climate policies would therefore also be essential for instance in a monetary union with common monetary and financial objectives. Climate change and the transition towards a more sustainable economy can affect price and financial stability through their impact on macroeconomic indicators, becoming a “threat” to business cycle synchronization among union members and, therefore, an additional constraint for the central bank’s monetary policy strategy, as also recently acknowledged by e.g. the [European Central Bank](#) (2021).

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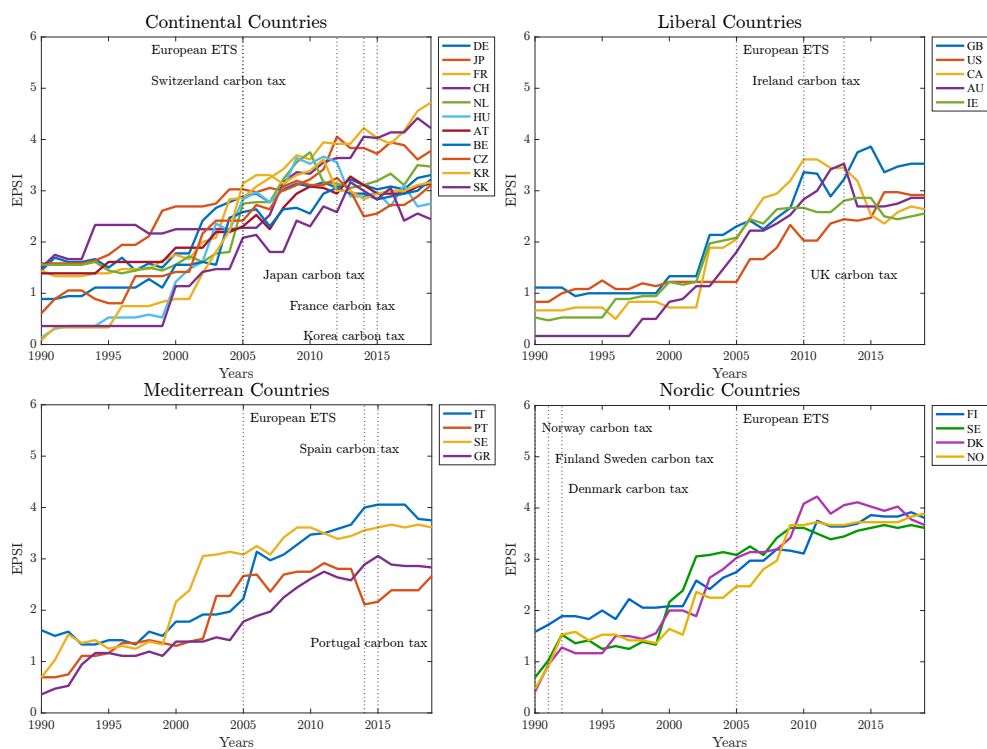
A Online Appendix

In this Online Appendix we report:

- Additional details and charts on the climate and macroeconomic data used in the analysis (A.1 to A4);
- Some counterfactual scenarios used in the main text to interpret results further (A.5);
- Results based on of a sign-restriction identification (A.6);
- Impulse response functions to a shock to the various components of the Environmental Policy Stringeny Index of the OECD (A.7);
- Further robustness results as described in section [4.3](#) (A.8).

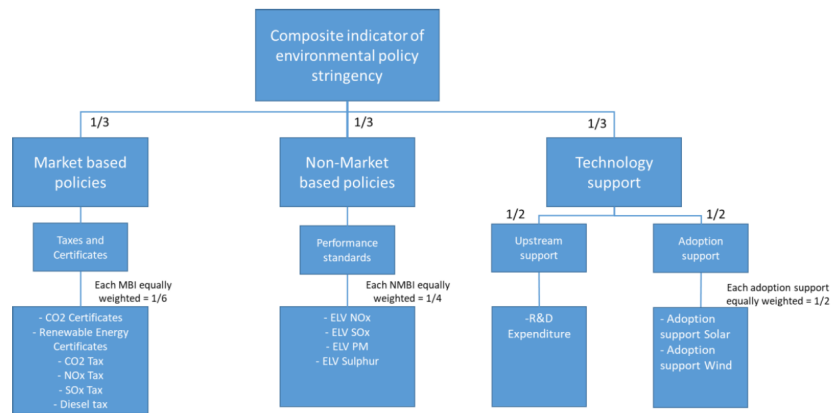
A.1 Environmental Policy Stringency Index

Figure A.1: Evolution of Environmental Policy Stringency Index



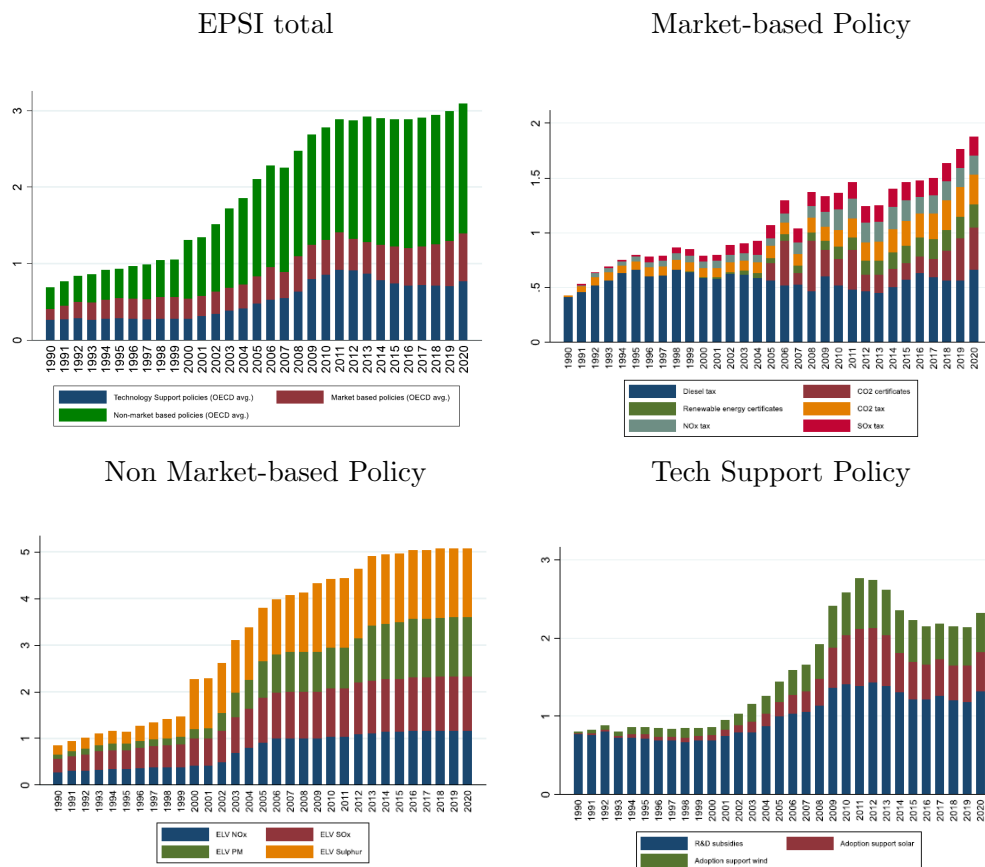
Sources: OECD; Sample: 1990-2019.

Figure A.2: Composition of Environmental Policy Stringency Index (1)



Sources: OECD; Sample: 1990-2019.

Figure A.3: Composition of Environmental Policy Stringency Index (2)



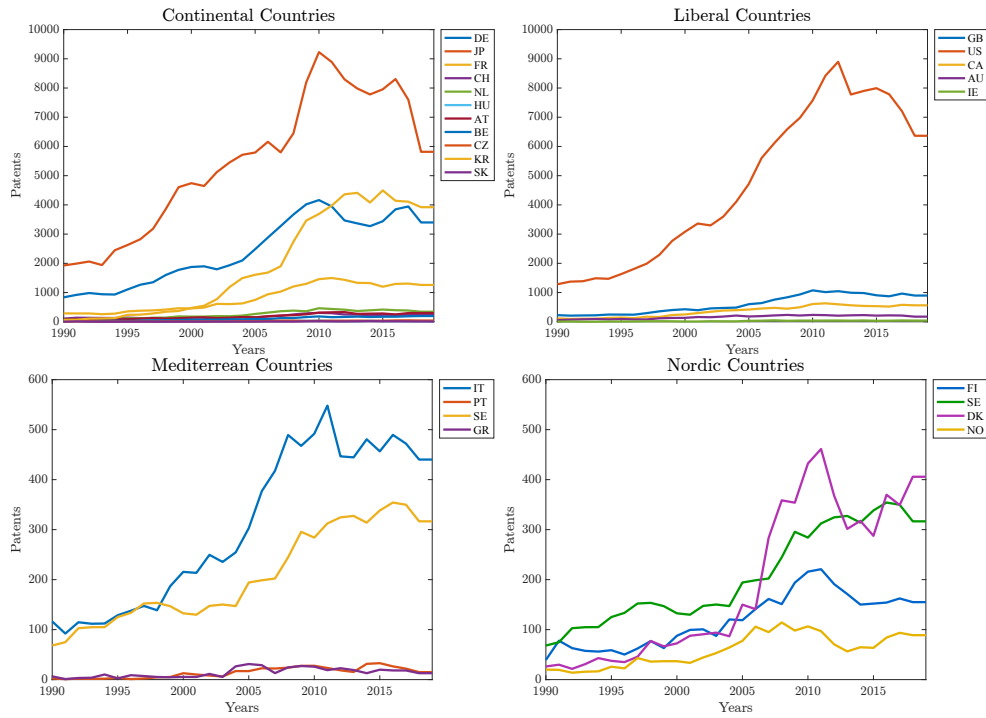
Sources: OECD; Sample: 1990-2019.

A.2 Patents in Environmental Related Technologies

Table 1: Patents in Environmental Related Technologies

Environmental Management
Air and water pollution abatement, waste management
Climate Change Mitigation
Energy generation, transmission and distribution (renewable and from non fossil fuels energy generation, combustion tech for output and input efficiency, efficient electrical power generation, energy storage, energy conversion to reduce CO2), waste management, info and communication technologies, capture storage, sequestration and disposal of GHG, transport, buildings, production and processing of goods.
Climate Change Adaptation
To sea level rising, water resources management and availability, infrastructures, agriculture, forestry, livestock and agro-alimentary production, human health protection

Figure A.4: Patents for mitigation technologies



Sources: OECD; Sample: 1990-2019.

A.3 Welfare Cost of Premature Deaths due to Environmental Related Risks

The calculation of the VSL, as described in great detail in [Roy and Braathen \(2017\)](#) can be summarised as follows. Suppose that each individual has an expected utility function, EU , relating the utility of consumption over a period $U(y)$ and the risk of dying in that period r :

$$EU(y, r) = (1 - r)U(y) \quad (7)$$

then, the individual's WTP to maintain the same expected utility in the case of a reduction of risk from r to r_1 is the solution to

$$EU(Y - WTP, r_1) = EU(y, r). \quad (8)$$

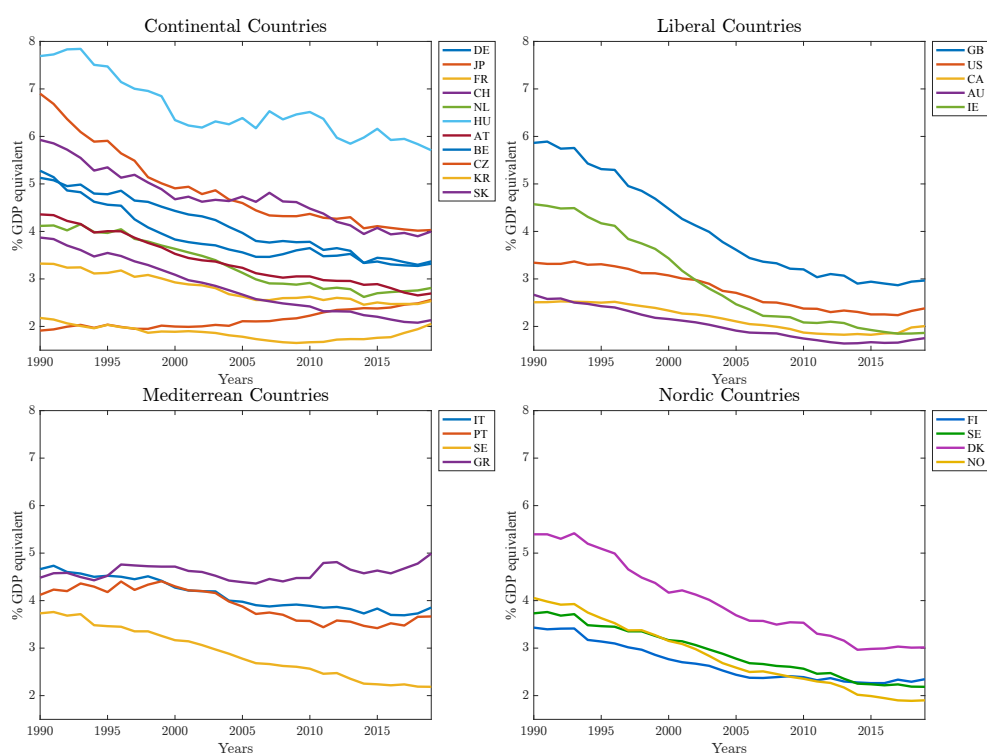
Thus the VSL is the marginal rate of substitution between the value of consumption and the reduction of risk of dying, such that:

$$VSL = \frac{\delta WTP}{\delta r}. \quad (9)$$

The WTP, which is derived from surveys (OECD (2012)) is eventually multiplied by the total number of premature deaths, becoming a measure of the economic cost of the impact of environment-related risks. In the model we use three measures of costs due in particular to (i) air pollution (ambient particulate matter, ambient ozone), (ii) environment-related occupational risks (occupational carcinogens), and (iii) environment-related behavioural risks (diet high in processed meat). Figure A.5 illustrates the welfare cost of premature deaths from exposure to the selected risks (expressed in % of GDP equivalent).¹⁴ The figure reports in blue averages in the first part of our sample (1990-2004) and in orange the averages in the second 15 years (2005-2019). We believe that the welfare costs of deaths related to exposures to environmental risks are a reasonable and tangible measure of the damages caused by physical risks related to climate change. By construction, the variable does not capture the consequences of extreme weather events but is a good proxy for the medium-to-long term effects that gradual climate change and environmental degradation have on our everyday life. In the empirical analysis we take a simple average over the three welfare costs. This measure shows a decreasing trend not only of the mean – which has been reducing at an approximate rate of 0.8% between 1990 and 2017 across countries – but also of cross-country dispersion – the standard deviation has gone from 0.7 in 1990 to 0.5 in 2017.

¹⁴The dataset includes the following types of risks: Air pollution; Climate risks; Unsafe water, sanitation and handwashing; Environment-related occupational risks; Environment-related behavioral risks. We selected the risks with the higher cost, but results with all the risks included do not differ in sign and magnitudes.

Figure A.5: Evolution of Welfare Cost of Premature Deaths due to Environmental Related Technologies

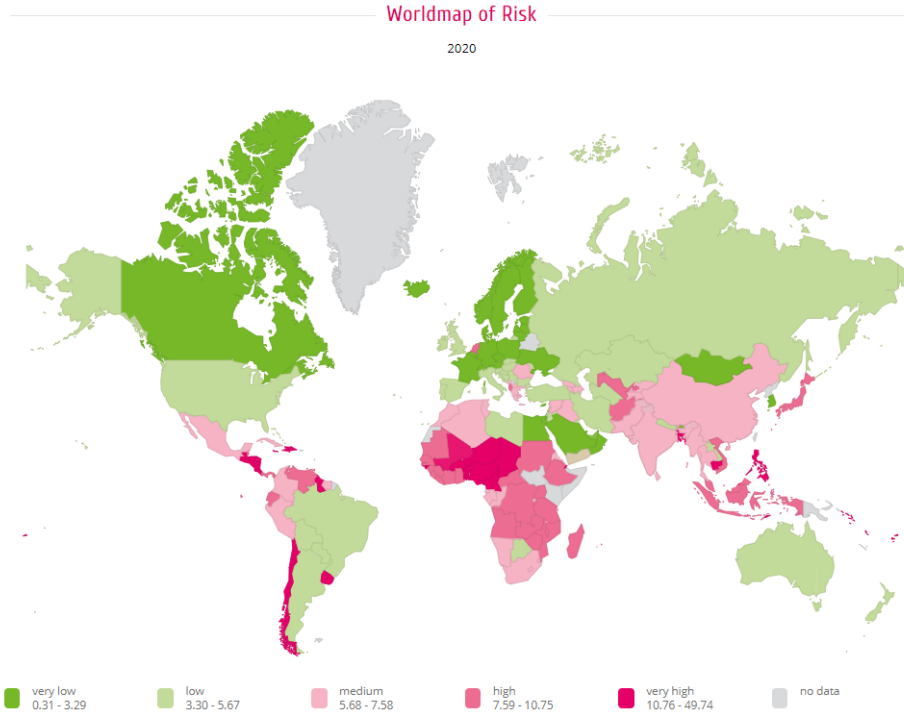


Sources: OECD; Sample: 1990-2019.

Table 2: Groups

Variable	Groups	Countries
Carbon pricing <i>The World Bank - Carbon Pricing Dashboard</i>	no carbon tax implemented or ETS	Australia, Austria, Belgium, Czech Republic, Germany, Greece, Hungary, Italy, Republic of Korea, Netherlands, Slovakia, United States
	carbon tax implemented	Canada (2019), Denmark (1992), Finland (1990), France (2014), Ireland (2010), Japan (2012), Norway (1991), Portugal (2015), Spain (2014), Switzerland (2008), United Kingdom (2013)
	revenue recycling	Denmark, Finland, Ireland, Norway, Sweden, Switzerland
World Risk Index	high: ≥ 3.30	Netherlands, Greece, Hungary, Italy, Ireland, Portugal, Spain, Japan, United Kingdom, Slovakia, United States, Australia
<i>UNU-EHS, IFHV Ruhr-University Bochum</i>	low: < 3.30	Austria, Czech Republic, Denmark, Belgium, Germany, Norway, France, Sweden, Switzerland, Finland, Korea, Canada
GHG Emissions, <i>OECD.stat</i>	high	Australia, Austria, Belgium, Czech Republic, Germany, Greece, Hungary, Italy, Korea, Netherlands, Slovakia, United States
	low	Canada, Denmark, Finland, France, Ireland, Japan, Norway, Portugal, Spain, Sweden, Switzerland, UK
Gross National Income, US dollars/capita, 2019	high: $> 57K$	Norway, Switzerland, Ireland, United States, Denmark, Netherlands, Austria, Germany
	medium	Sweden, Belgium, Australia, Finland, Canada, France, United Kingdom
<i>OECD.stat</i>	low: $< 47K$	Italy, Japan, Korea, Spain, Czech Republic, Portugal, Slovakia, Greece, Hungary
Political Economy	nordic	Finland, Sweden, Denmark, Norway
	continental	Austria, Belgium, Germany, Czech Republic, France, Netherlands, Slovakia, Switzerland, Hungary, Korea, Japan
	mediterranean	Spain, Portugal, Greece, Italy
	liberal	United States, United Kingdom, Canada, Australia, Ireland

Figure A.6: World Risk Index

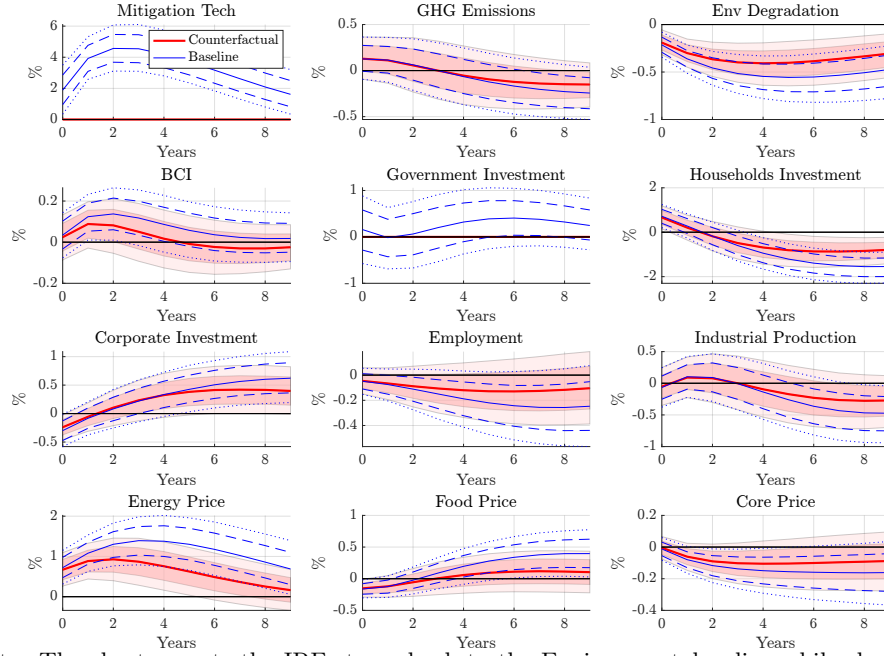


A.4 Additional macroeconomic variables

All additional variables (BCI, Investments, and Employment) are downloaded from the OEDC.stat database. The business confidence indicator provides information on future developments, based upon opinion surveys on developments in production, orders and stock of finished goods in the industry sector. Numbers above 100 suggest an increased confidence in near future business performance, and numbers below 100 indicate pessimism towards future performance. To proxy for investments we use the gross fixed capital formation (GFCF). Investment by sector (measured as % of total GFCF) includes household, corporate and general government. For government this typically means investment in R&D, military weapons systems, transport infrastructure and public buildings such as schools and hospitals. Employment rates are defined as a measure of the extent to which available labour resources (people available to work) are being used. They are calculated as the ratio of the employed to the working age population.

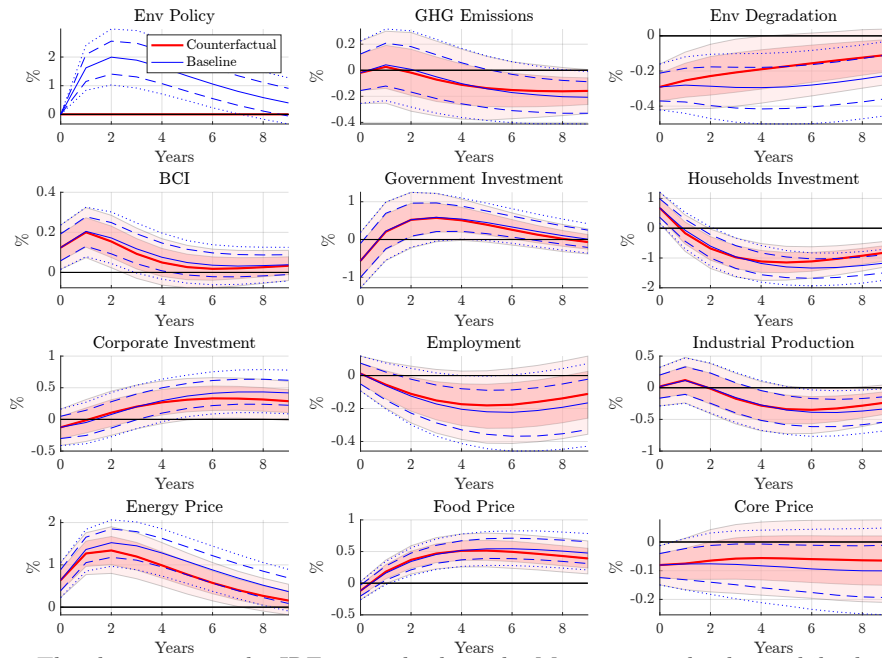
A.5 Counterfactuals

Figure A.7: A shock to Environmental Policy



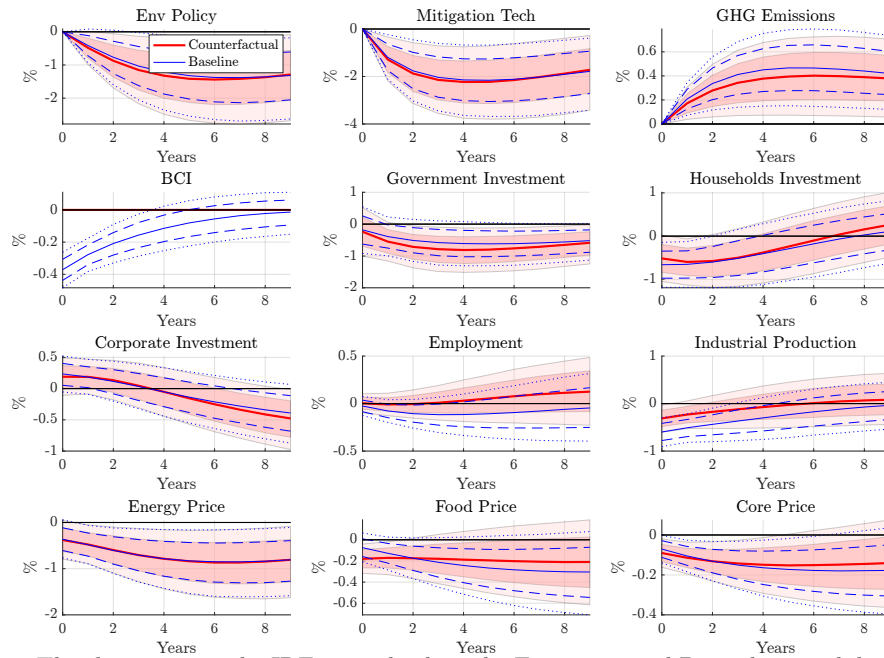
Note: The chart reports the IRFs to a shock to the Environmental policy while shutting down the responses of Mitigation technology and Government Investment. The counterfactual scenarios are generated following the approach used e.g. by [Wong \(2015\)](#).

Figure A.8: A shock to Mitigation Technologies



Note: The chart reports the IRFs to a shock to the Mitigation technology while shutting down the response of the Stringency Index. The counterfactual scenarios are generated following the approach used e.g. by [Wong \(2015\)](#).

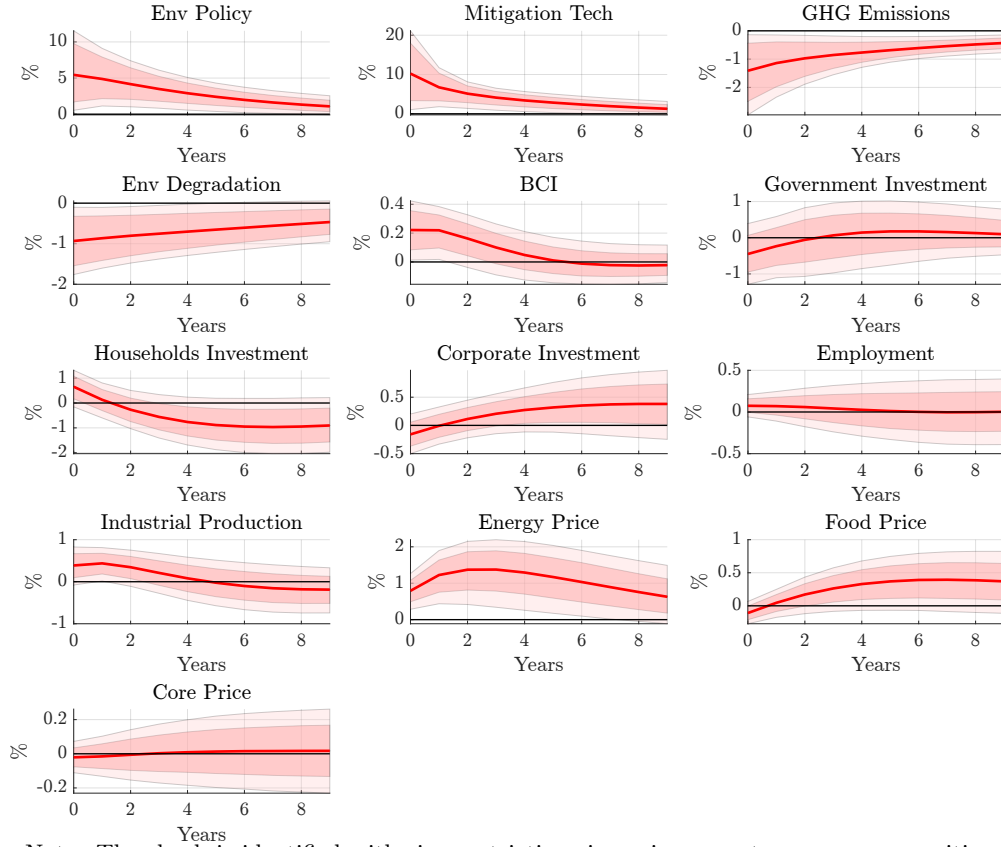
Figure A.9: A shock to Environmental Degradation



Note: The chart reports the IRFs to a shock to the Environmental Degradation while shutting down the response of the Business confidence indicator. The counterfactual scenarios are generated following the approach used e.g. by [Wong \(2015\)](#).

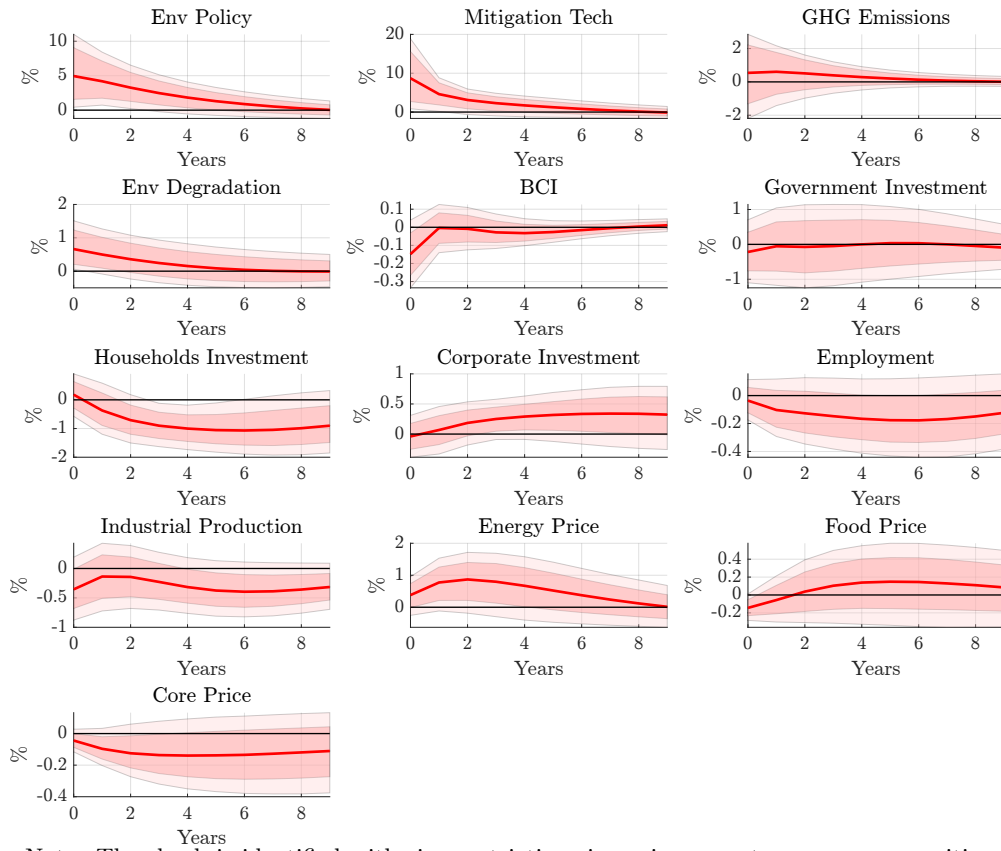
A.6 Identification with sign restrictions

Figure A.10: A shock to Environmental Policy



Note: The shock is identified with sign restrictions imposing a contemporaneous positive response of Environmental Policy and Mitigation Technologies and a negative response of GHG emissions and Environmental Degradation

Figure A.11: A shock to Environmental Degradation



Note: The shock is identified with sign restrictions imposing a contemporaneous positive response of Environmental Policy and Mitigation Technologies and a positive response of Environmental Degradation

A.7 Impulse response functions of a shock to components of EPSI

Figure A.12: A shock to Market-based Policy

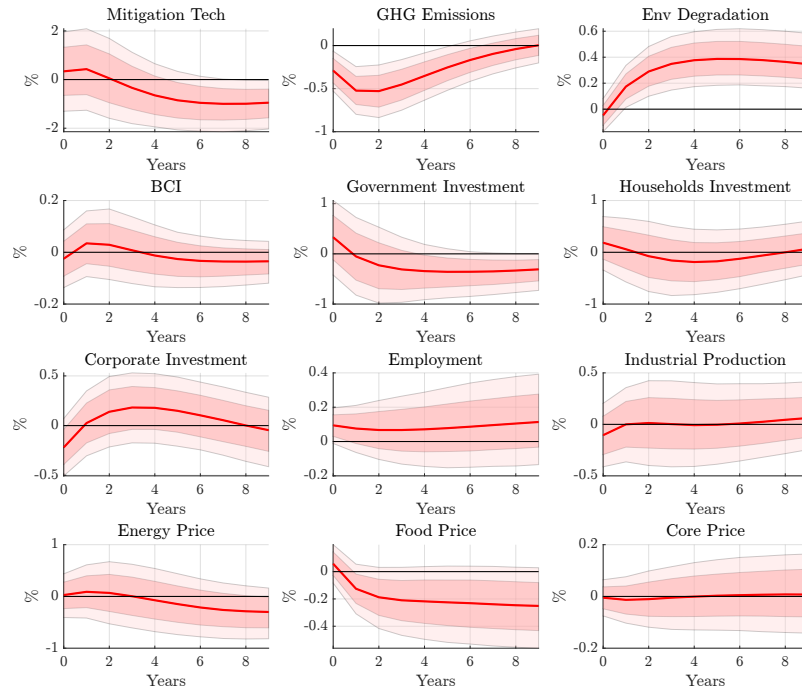


Figure A.13: A shock to Non Market-based Policy

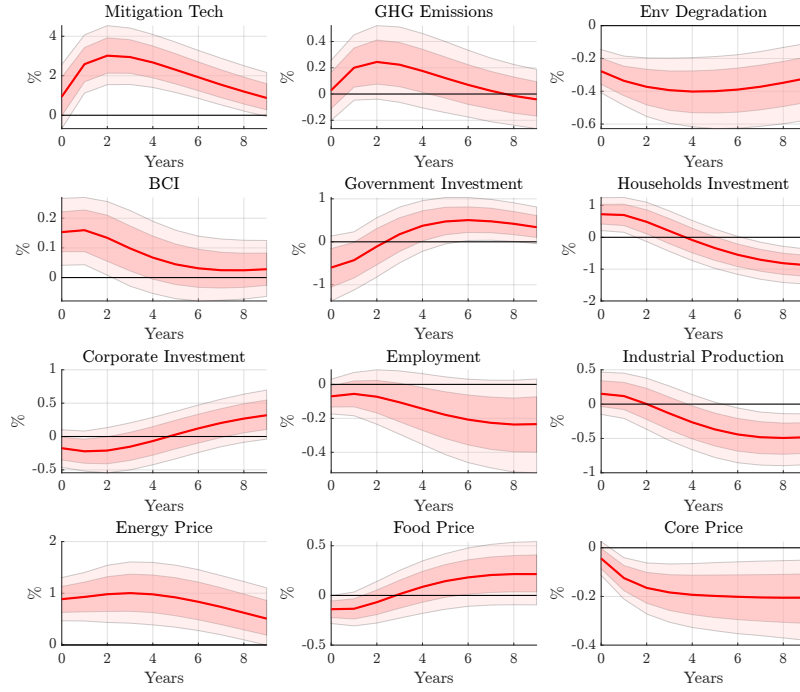


Figure A.14: A shock to Tech Support Policy

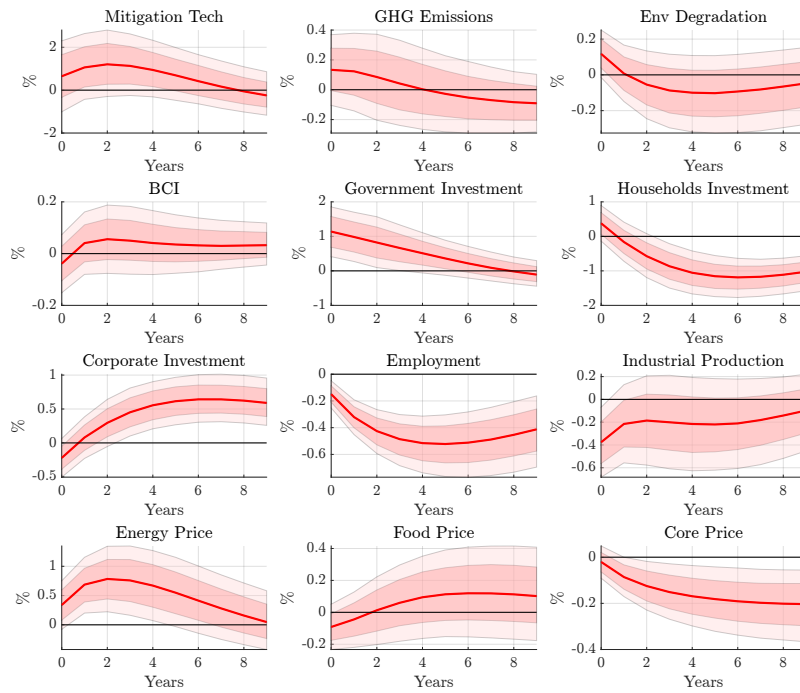


Table 3: Forecast Error Variance Decomposition

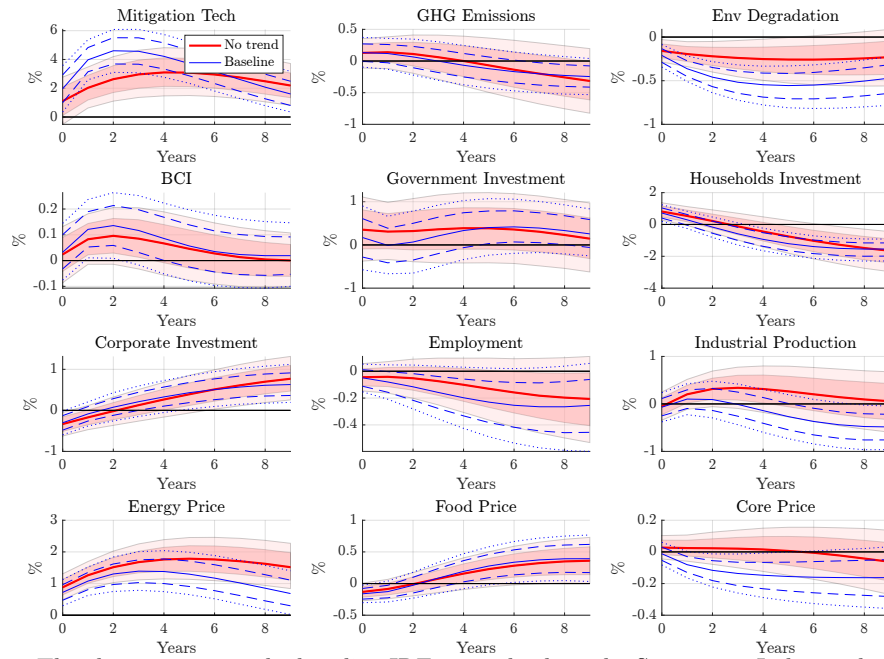
		Env Policy	Mitigation Tech	GHG Emissions	Env Degradation	Global Commodity Price	BCI	Government Investment
Env Policy	1 y	1.00	0.01	0.00	0.01	0.02	0.00	0.00
	5 y	0.90	0.09	0.00	0.07	0.17	0.01	0.00
	10 y	0.80	0.11	0.01	0.11	0.21	0.01	0.01
Mitigation Tech	1 y	0.00	99.26	0.09	2.46	2.02	0.67	0.30
	5 y	3.16	81.60	0.32	3.27	12.83	1.98	0.97
	10 y	3.38	69.71	0.90	3.75	11.77	1.93	1.15
Env Degradation	1 y	0.00	0.00	0.00	90.97	1.11	5.63	0.10
	5 y	0.85	1.59	1.96	83.06	2.72	5.09	0.77
	10 y	2.60	3.32	4.76	70.91	4.37	4.78	1.59
Market-based EPSI	1 y	100.00	0.10	0.79	0.11	0.10	0.10	0.14
	5 y	95.12	0.40	3.46	2.80	0.39	0.33	0.50
	10 y	92.10	0.86	3.26	4.78	1.04	0.52	0.83
Non Market-based EPSI	1 y	100.00	0.19	0.09	2.17	3.33	0.95	0.34
	5 y	92.36	3.66	0.74	4.74	10.73	1.42	0.67
	10 y	84.71	4.50	0.89	6.00	12.46	1.47	1.23
Tech support EPSI	1 y	100.00	0.12	0.18	0.40	0.57	0.11	1.18
	5 y	82.18	0.69	0.39	0.49	4.15	0.41	2.08
	10 y	70.23	0.79	0.61	0.56	3.89	0.55	2.07
		Households Investment	Corporate Investment	Employment	Industrial Production	Energy Price	Food Price	Core Price
Env Policy	1 y	0.01	0.01	0.00	0.00	0.01	0.01	0.00
	5 y	0.02	0.01	0.01	0.00	0.06	0.01	0.01
	10 y	0.06	0.03	0.02	0.02	0.08	0.02	0.02
Mitigation Tech	1 y	0.83	0.13	0.09	0.09	1.20	0.34	0.68
	5 y	2.30	0.58	0.82	0.46	7.43	3.52	0.73
	10 y	5.97	1.72	1.25	1.35	7.27	5.80	0.91
Env Degradation	1 y	0.79	0.33	0.09	1.93	0.38	0.17	0.51
	5 y	1.19	0.49	0.43	1.97	1.77	0.92	1.79
	10 y	1.34	1.22	0.60	1.92	3.80	1.91	2.61
Market-based EPSI	1 y	0.11	0.30	0.40	0.12	0.08	0.13	0.08
	5 y	0.35	0.55	0.39	0.30	0.28	0.84	0.23
	10 y	0.48	0.61	0.54	0.43	0.58	1.31	0.32
Non Market-based EPSI	1 y	0.97	0.20	0.25	0.15	2.18	0.51	0.22
	5 y	1.04	0.47	0.45	0.49	3.90	0.51	2.46
	10 y	2.30	1.01	1.15	1.76	4.65	0.92	3.45
Tech support EPSI	1 y	0.27	0.30	1.07	0.76	0.33	0.23	0.11
	5 y	1.73	1.60	6.67	0.69	1.98	0.35	1.62
	10 y	4.66	4.00	7.47	0.85	1.88	0.50	2.84

A.8 Robustness

Table 4: Residuals correlation matrix

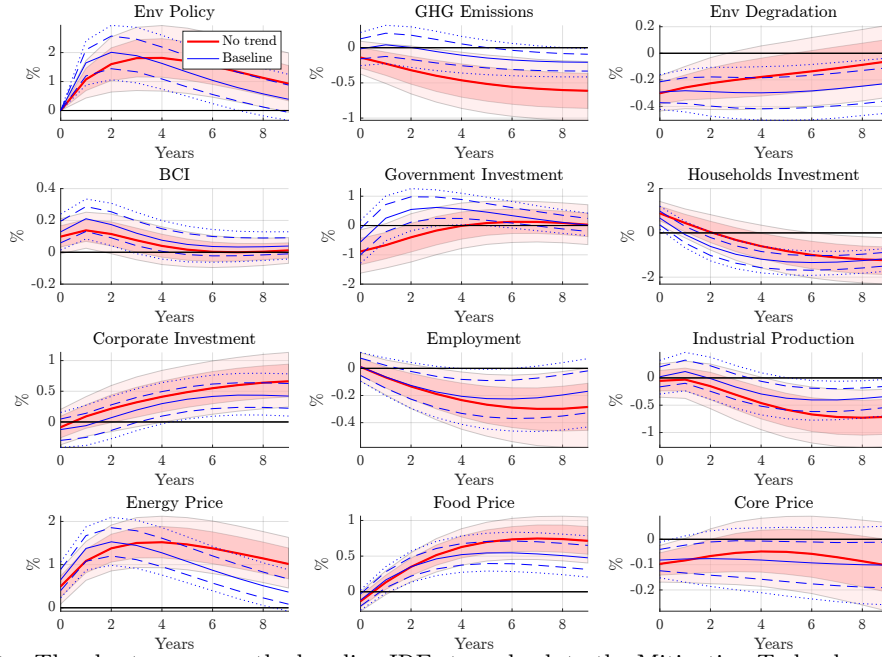
	Env Policy	Mitigation Tech	GHG Emissions	Env Degradation
Env Policy	1.00	0.08	0.04	-0.11
Mitigation Tech	0.08	1.00	0.00	-0.17
GHG Emissions	0.04	0.00	1.00	0.22
Env Degradation	-0.11	-0.17	0.22	1.00
Global Commodity Price	0.14	0.15	-0.02	-0.14
BCI	0.02	0.08	-0.06	-0.25
Government Investment	0.02	-0.05	0.07	0.01
Households Investment	0.10	0.10	0.06	-0.10
Corporate Investment	-0.07	-0.04	-0.06	0.06
Employment	-0.03	0.01	-0.13	-0.04
Industrial Production	-0.02	0.00	-0.11	-0.16
Energy Price	0.12	0.12	-0.03	-0.10
Food Price	-0.08	-0.07	0.01	-0.01
Core Price	-0.01	-0.08	0.01	-0.05

Figure A.15: A shock to Environmental Policy



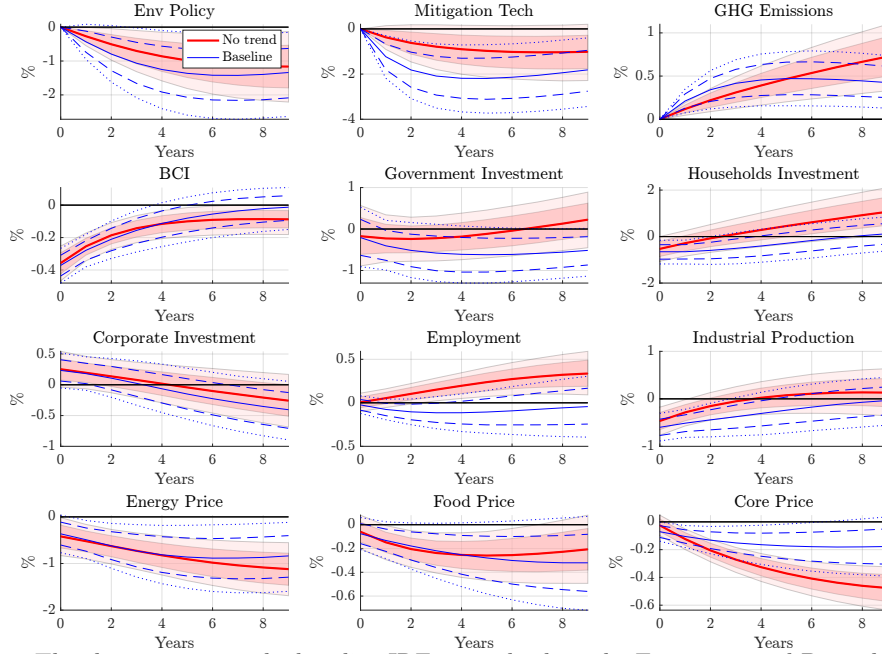
Note: The chart compares the baseline IRFs to a shock to the Stringency Index with those obtained in a model specified without the linear trend.

Figure A.16: A shock to Mitigation Technologies



Note: The chart compares the baseline IRFs to a shock to the Mitigation Technology with those obtained in a model specified without the linear trend.

Figure A.17: A shock to Environmental Degradation



Note: The chart compares the baseline IRFs to a shock to the Environmental Degradation with those obtained in a model specified without the linear trend.

Figure A.18: A shock to Environmental Policy

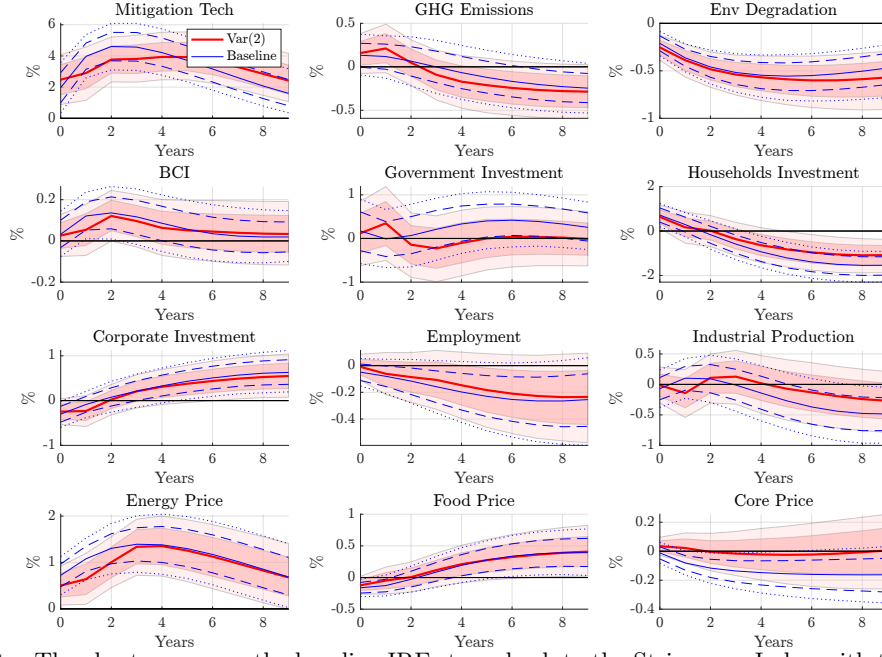


Figure A.19: A shock to Mitigation Technologies

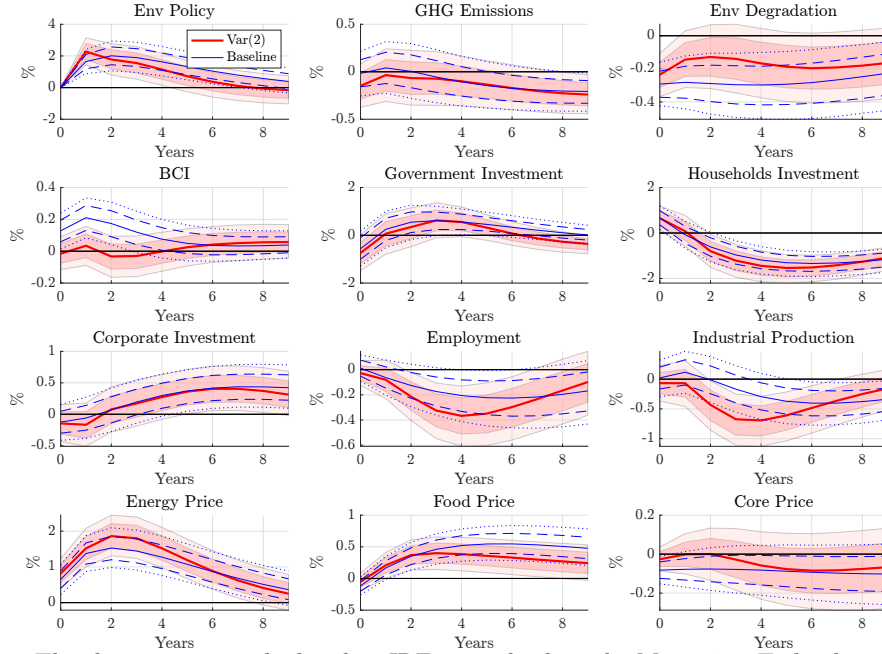
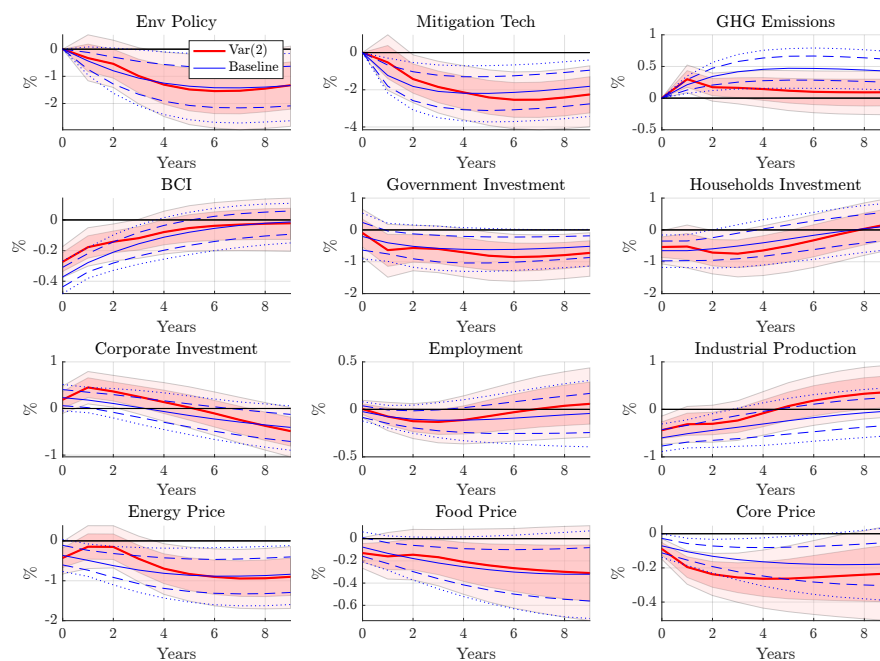
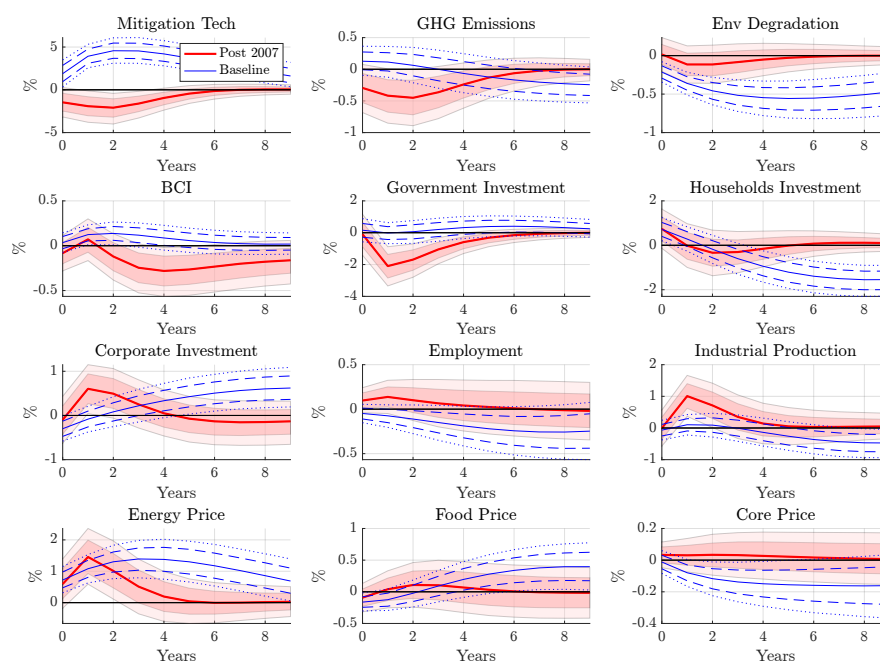


Figure A.20: A shock to Environmental Degradation



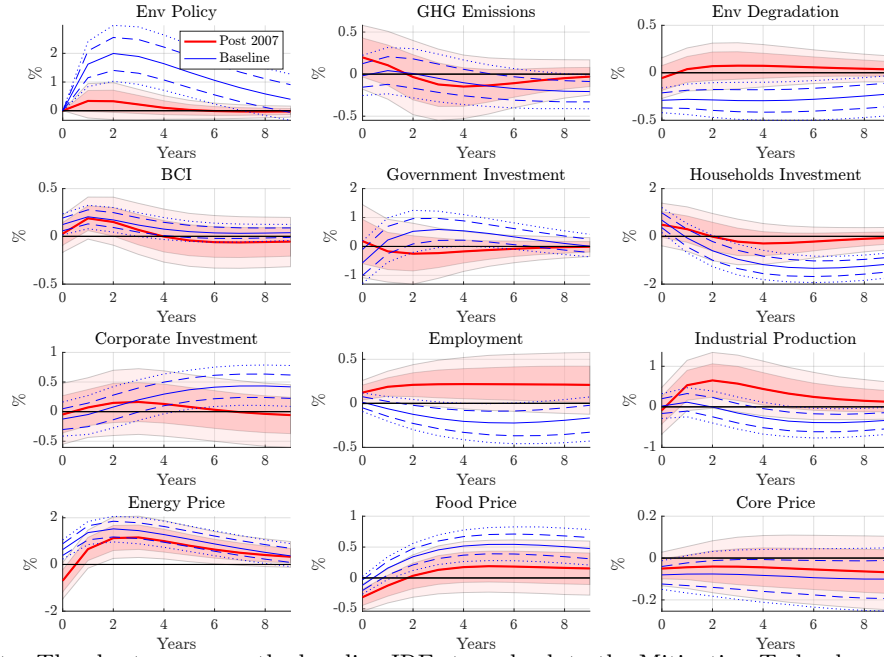
Note: The chart compares the baseline IRFs to a shock to the Environmental Degradation with those obtained in a model specified with 2 lags.

Figure A.21: A shock to Environmental Policy



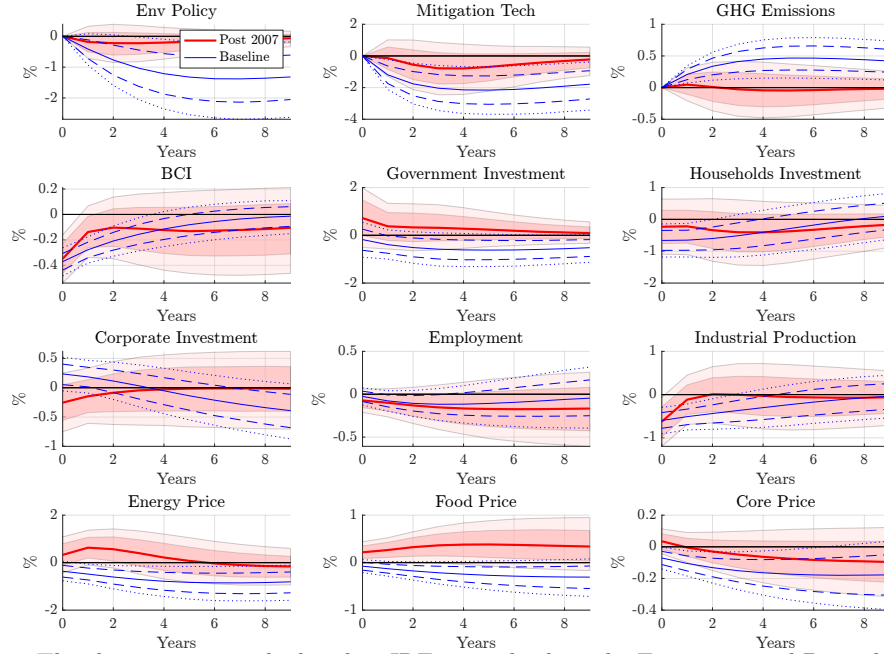
Note: The chart compares the baseline IRFs to a shock to the Stringency Index with those obtained in a model estimated over the sample 2007-2019.

Figure A.22: A shock to Mitigation Technologies



Note: The chart compares the baseline IRFs to a shock to the Mitigation Technology with those obtained in a model estimated over the sample 2007-2019.

Figure A.23: A shock to Environmental Degradation



Note: The chart compares the baseline IRFs to a shock to the Environmental Degradation with those obtained in a model estimated over the sample 2007-2019.

The following charts, from A.24 to A.26, compare baseline IRFs with IRFs obtained in a model where Environmental Degradation has been placed first in the climate block.

Figure A.24: A shock to Environmental Policy

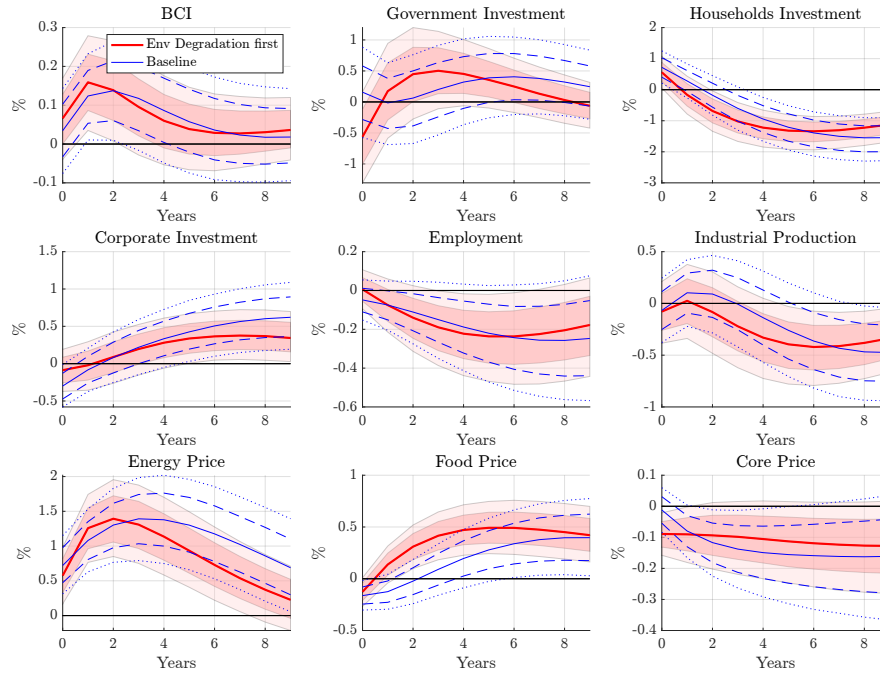


Figure A.25: A shock to Mitigation Technologies

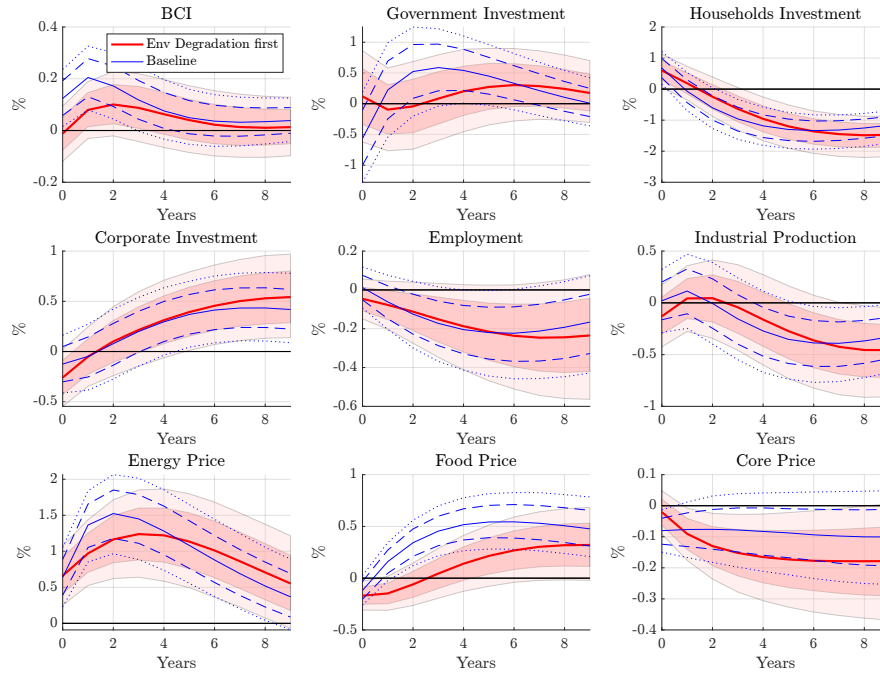
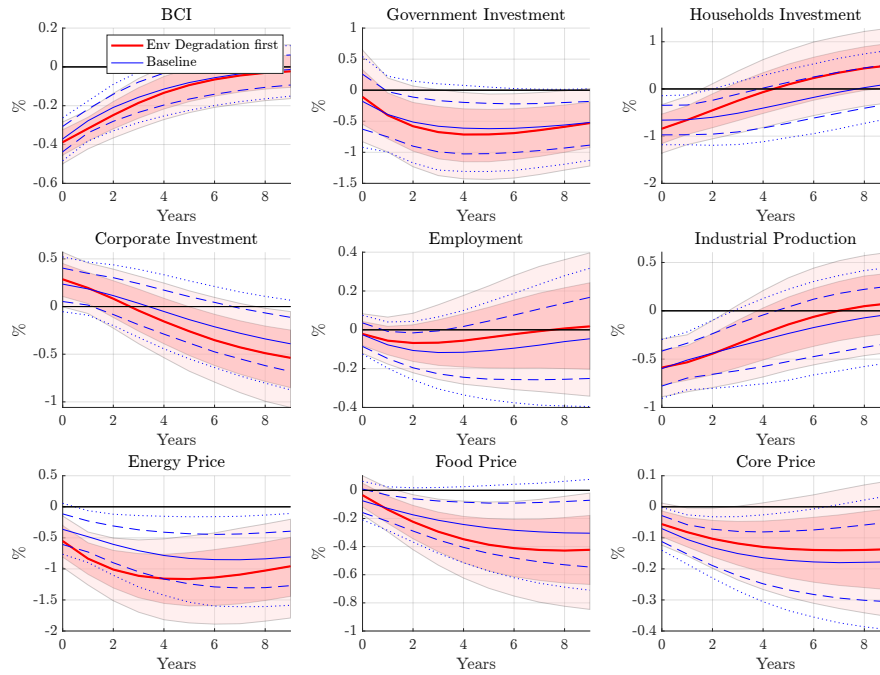


Figure A.26: A shock to Environmental Degradation



The following charts, from A.27 to A.29, compare baseline IRFs with IRFs obtained in a model where the macroeconomic block has been ordered before the climate block.

Figure A.27: A shock to Environmental Policy

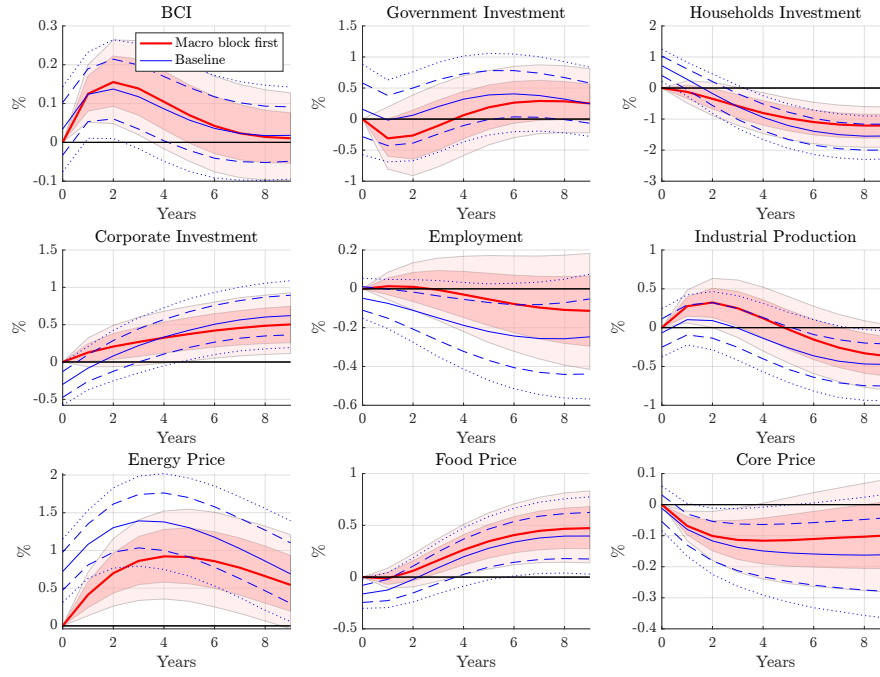


Figure A.28: A shock to Mitigation Technologies

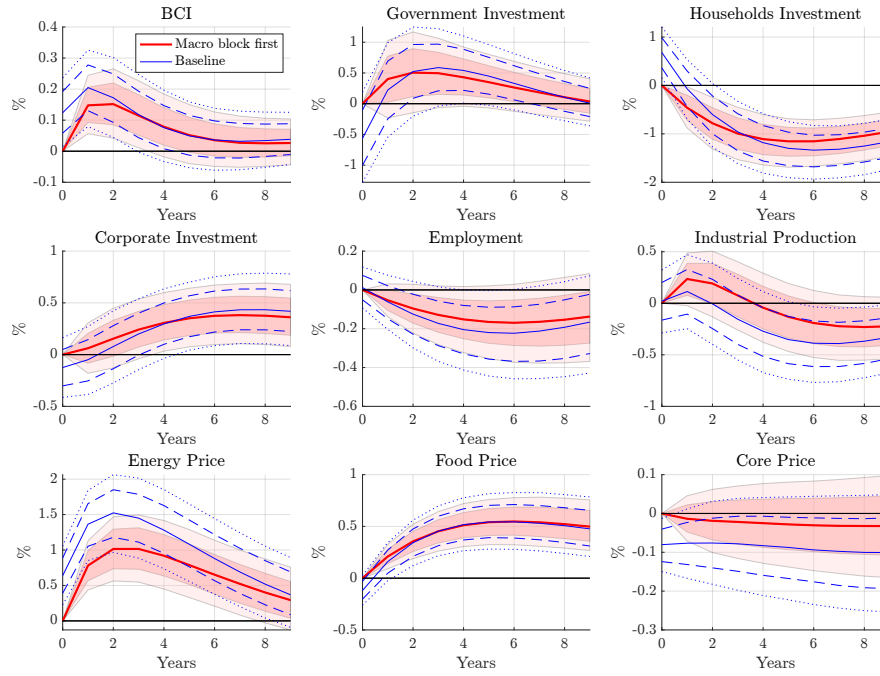
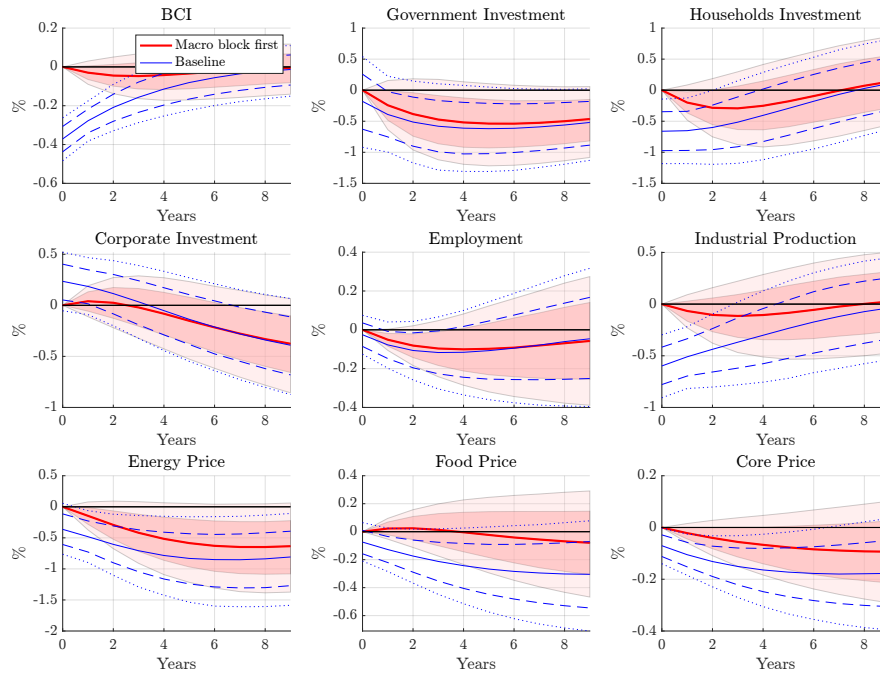


Figure A.29: A shock to Environmental Degradation



The following charts, from A.30 to A.32, compare baseline IRFs with IRFs obtained in a model where the Environmental Degradation has been replaced by Temperature Anomalies.

Figure A.30: A shock to Environmental Policy

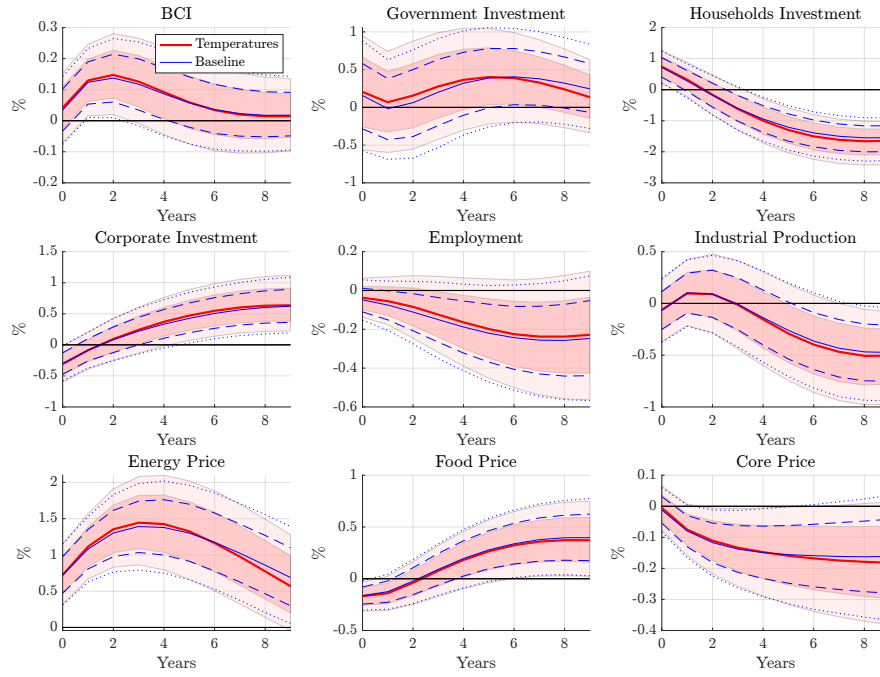


Figure A.31: A shock to Mitigation Technologies

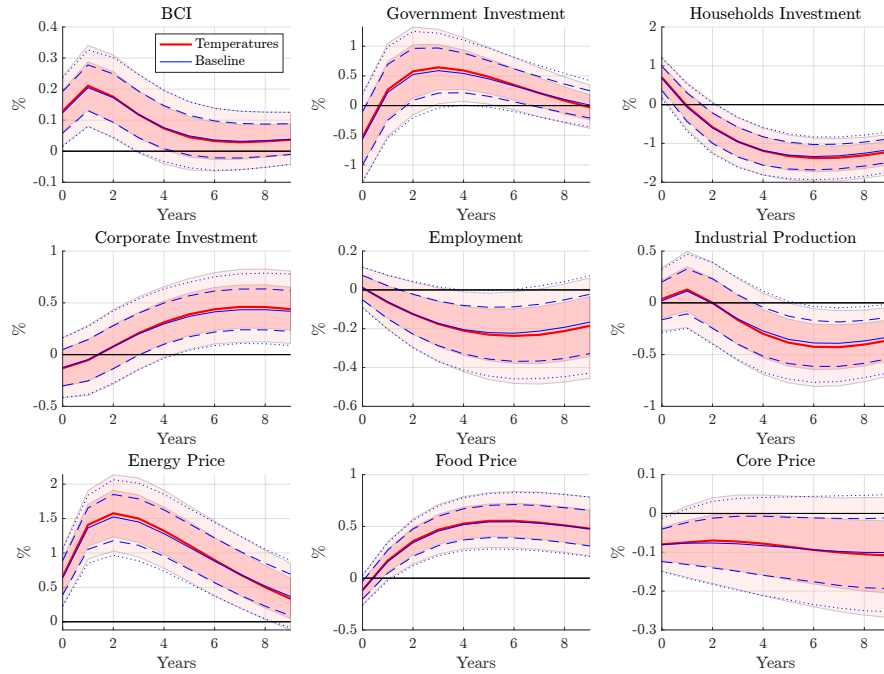
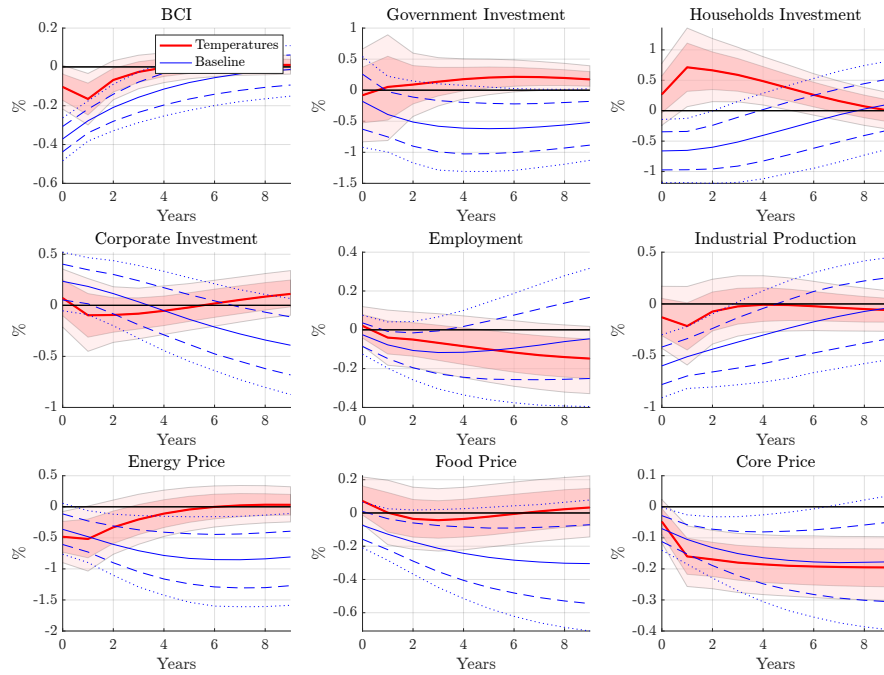


Figure A.32: A shock to Temperature Anomalies



The following charts, from A.33 to A.35, compare baseline IRFs with IRFs obtained in a model where the Industrial Production has been replaced by GDP.

Figure A.33: A shock to Environmental Policy

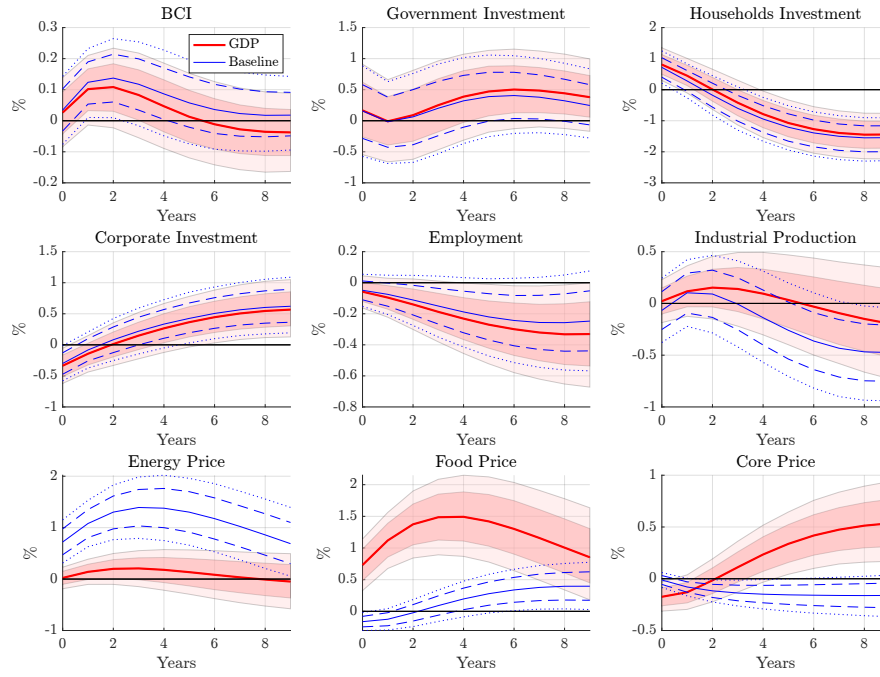


Figure A.34: A shock to Mitigation Technologies

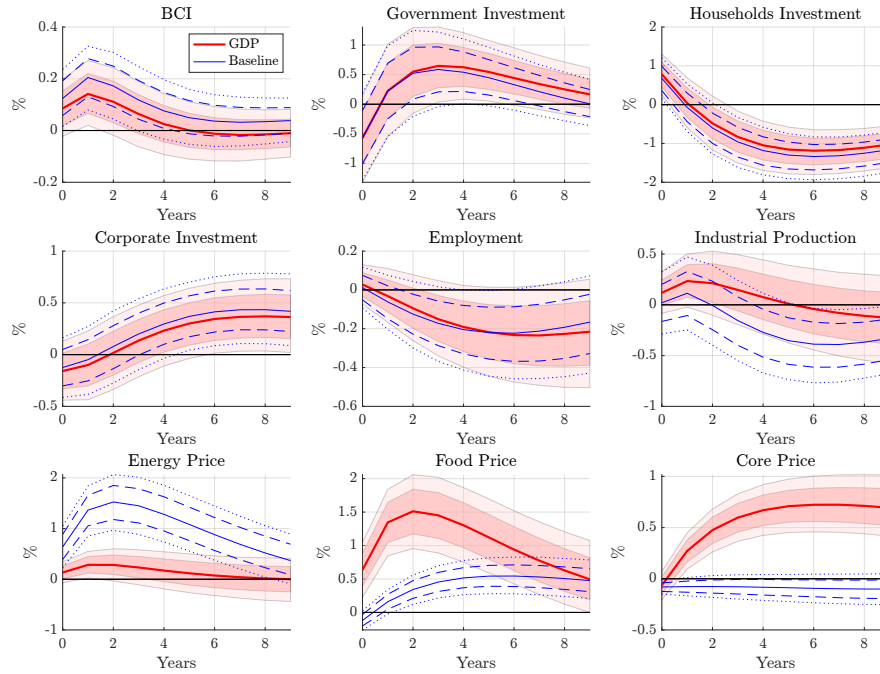
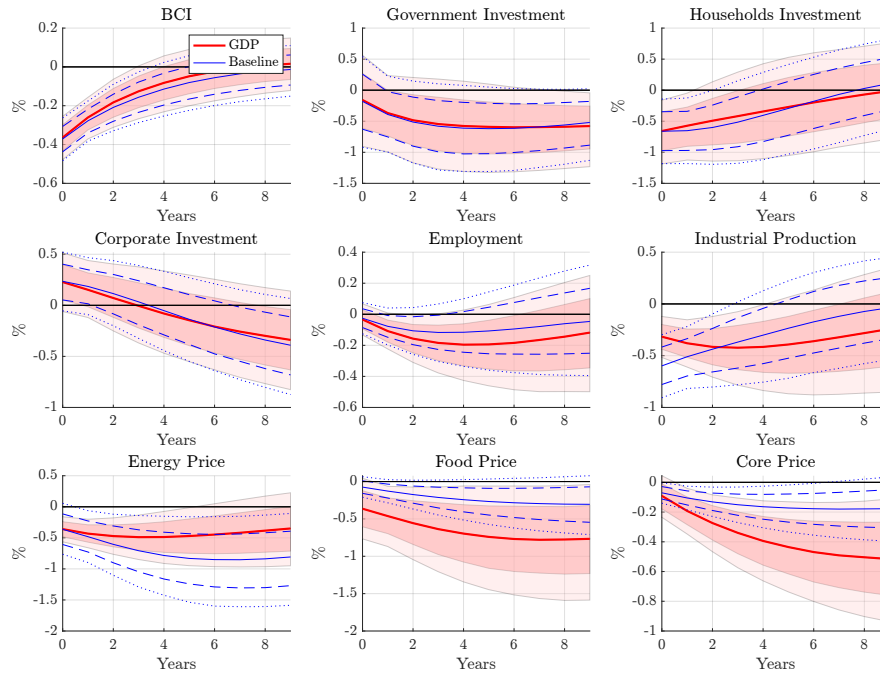


Figure A.35: A shock to Environmental Degradation



The following charts, from A.36 to A.38, compare baseline IRFs with IRFs obtained in a model specified in first difference.

Figure A.36: A shock to Environmental Policy

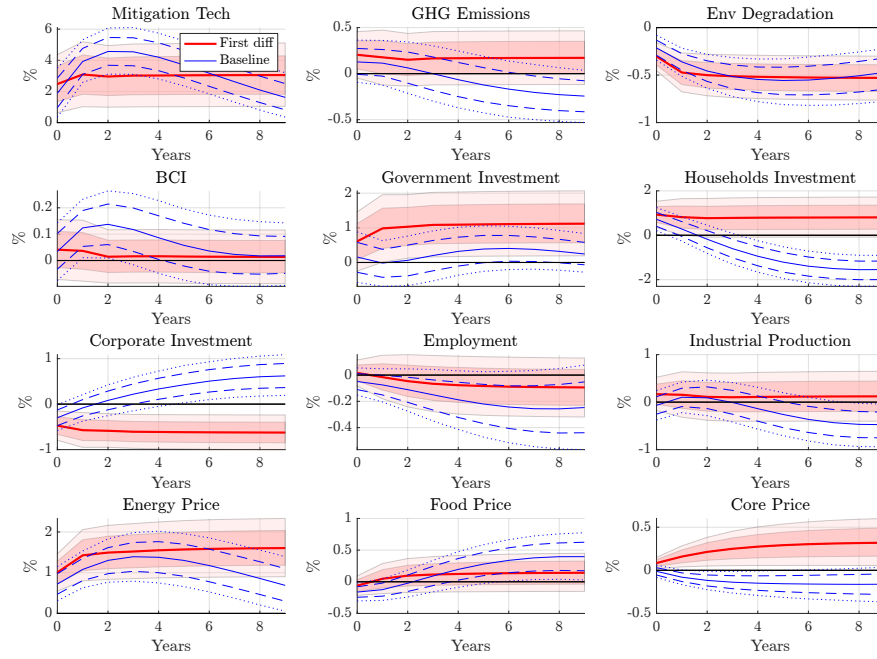


Figure A.37: A shock to Mitigation Technologies

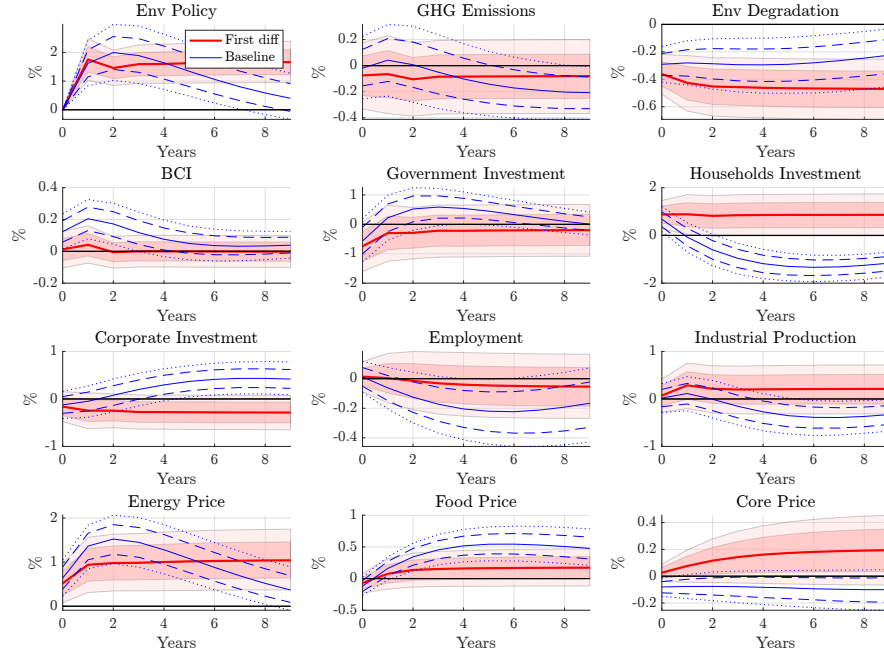


Figure A.38: A shock to Environmental Degradation

