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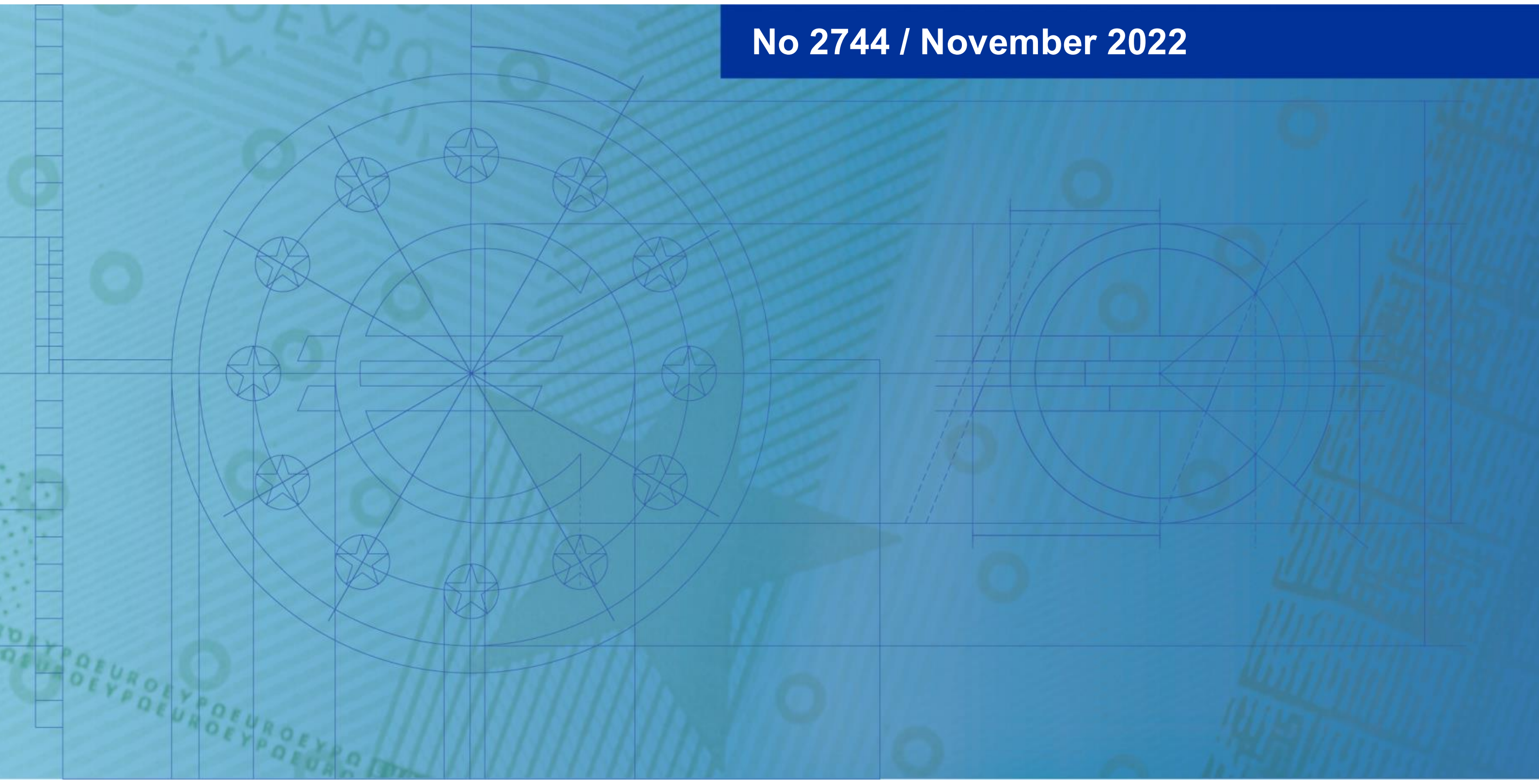
The effects of climate change on the natural rate of interest: a critical survey



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Abstract

This survey reviews the literature about the impact of climate change on the natural rate of interest (r*), an important yardstick for monetary policy. Economic and financial developments can lower r* in scenarios with increasing climate-related damages and uncertainty that reduce productivity growth and raise precautionary savings. Instead, in scenarios that assume innovations and investments induced by transition policies, r* could be affected positively. Orderly climate policies have a pivotal role by facilitating the transition to a carbon-neutral economy and supporting a steady investment flow. We discuss the main models used to simulate the effects of climate change on r* and summarize the outcomes. The downward effects of climate change on r* can be substantial, even taking into account the high degree of uncertainty about the outcomes. Moreover, the downward pressure on r* will further challenge monetary policy in the long run, by limiting its policy space.

JEL classification: E52, Q54
Keywords: interest rate, monetary policy, climate change, natural rate of interest, social cost of carbon

Non-technical summary

Climate change increasingly has been considered an important factor for central banks particularly when considering monetary policy. Climate change, and transition policies to counter it, affect the structure and dynamics of the economy and financial system, posing risks to both price and financial stability. The assets held on central banks' balance sheets also face increased risks related to climate change. Moreover, without prejudice to price stability, monetary policy can support other EU policies, such as environmental policies.

In this paper, we review the literature about the impact of climate change on the natural rate of interest (r*). r* is a theoretical concept which serves as an important benchmark for guiding monetary policy decisions. It is defined as the real rate of interest which allows the economy to operate at its potential while simultaneously keeping inflation at its target. Estimates of r* show that the natural interest rate has declined continuously over the past decades, although a high degree of uncertainty about the level of those estimates remains. If the natural rate is low there is little room for manoeuvre using conventional monetary policy, i.e. changes in the policy rates.

The literature identifies diverse channels at work behind the decline in r*. The most important channels concern shifting demographics, productivity levels, trend growth rates, risk aversion, fiscal and monetary policy reactions, and income inequality. The impact of demographic changes as well as productivity trends on the natural rate have been explored extensively in the literature. However, so far, little attention has been paid to the possible effects of climate change as well as transition policies. This void can partially be explained by the different scope of economic models used in monetary economics versus climate economics. The central bank models (CBMs) usually abstract from environmental variables and their time horizon is mostly limited to the medium run, i.e., up to 5 years. Moreover, these models usually do not explicitly represent the energy sector of the economy. Instead, climate economy models (CEMs) often lack a detailed representation of economic relations, but they include important long run feedbacks from production via emissions to economic damages. We analyse both types of modelling approaches.

Having identified the main channels through which climate change and transition policies could affect r*, we summarize some model outcomes of shocks that run through these channels in the euro area by a CMB and a CEM. CEMs can be seen as complements to CBMs as they propose an alternative perspective. Together these models provide quantitative insights about the effects of climate change on r*. An overarching finding in this literature is that the long-run

effects of climate change on r* can be substantial. These effects are expected to be particularly strong if economic trend growth would drop due to reduced productivity growth and/or in scenarios with serious climate-related physical damages.

Uncertainty associated with adverse scenarios – as well as the transition policies to counter it - plays an important role in the model simulations. As a precaution, households may be more likely to accumulate savings and firms may postpone investments, putting additional downward pressure on market interest rates. On the other hand, the path of market interest rates and r* might depend largely on the thrust and credibility of policies governing the transition to a low-carbon economy.

Government measures are the most obvious and effective way to foster to transition to a climate-neutral economy. An orderly transition can mitigate the economic and financial risks of climate change and thereby also prevent potential downward effects on r*. In addition, active fiscal policy to mitigate climate change might also spur investment demand and thereby put upward pressure on the natural rate. This additional investment demand could offset - at least partially - the negative effects of climate change on r* that we found in our survey.

Given the large uncertainties and numerous assumptions needed to simulate the effects of climate shocks on r*, the outcomes must be interpreted as indicative and tentative, not conclusive. Nonetheless, our survey shows that the possible effects of climate change on the natural rate of interest can be substantial and therefore should be carefully considered.

1. Introduction

A growing body of literature examines the effects of climate change and the transition to a sustainable economy on the overall economy and the financial system. Within this context, we focus on a narrower set of studies about the effects on interest rates, and, in particular, the natural rate of interest (r*). In addition to reviewing the main channels linking climate change and r*, we discuss the two modelling strands commonly used to analyse this link: the Central Bank Model (CBM) and the Climate Economy Model (CEM).

Climate change increasingly has been considered an important factor also for central banks to consider, especially with regard to monetary policy (NGFS, 2021). Climate change requires adaptation measures to reduce its impact and transition policies to counter it. Together these factors affect the structure and dynamics of the economy and the financial system. Thereby it potentially poses risks to both price and financial stability (ECB, 2021a and Boneva el al, 2021 and 2022). Moreover, without neglecting price stability, monetary policy can support other EU policies, such as environmental policies (Dikau and Volz, 2021). Climate change and transition policies can affect the economy and financial system through various channels. Mapping those channels is essential for understanding the consequences of climate change and the energy transition for the wider economy as well as various related financial dynamics. Understanding these complex dynamics is essential for central banks and governments to design effective policy measures.

One complication is that r* is a theoretical concept; moreover, several definitions exist. For example, r* might be interpreted as the real long-term interest rate where there is equilibrium on capital markets, or as the real short-term interest rate consistent with equilibrium in the economy. The Swedish economist Knut Wicksell was one of the originators of the concept of r*. According to Wicksell (1898), r* is the interest rate at which the (global) demand for and supply of capital are in balance. From this perspective, r* can also be interpreted as the equilibrium interest rate that corresponds to the marginal product of capital.

Using r* as the real short-term interest rate in the economy plays a prominent role in Central Bank Models (CBM). According to Woodford (2003), the natural rate of interest in CBMs models is the rate at which the economy is in equilibrium while prices are fully flexible. The natural rate of interest r* is not necessarily constant in this equilibrium, but can fluctuate under the influence of several types of shocks, such as aggregated demand and productivity shocks, or changes in the preferences of households. Climate change and the energy transition can also give rise to such shocks.

By examining the difference between the true real short-term market interest rate and a measure of r*, or the ‘interest rate gap’, the central bank can make a judgement on its monetary stance, i.e. the degree to which it should ease or tighten monetary policy. If the policy rate is above (below) the natural rate, monetary policy is too restrictive (accommodative) and the central bank can alleviate excessive pressure on prices by bringing its policy rate more in line with r*. Thereby r* is a benchmark for assessing whether monetary policy is too tight or too loose (Lubik and Matthes, 2015).

When looking retrospectively, several studies documented a protracted decline of real and nominal interest rates and of r* across most countries, primarily driven by long-term demographic and economic factors, plus financial trends (e.g. Rachel and Smith, 2017, Brand, Goy and Lemke 2021, and Feunou and Fontaine, 2021). A low level of r* increases the likelihood of hitting the effective lower bound (ELB) of the policy interest rate. This would lower monetary policymakers’ room for manoeuvre to stimulate economic activity when needed. Under such a scenario, climate change would force central banks to rely more often on non-standard monetary policy measures in the future, while the support from fiscal policy to reach the monetary policy objective becomes more important.

Looking ahead, climate change presents several novel analytical and policy challenges. Diverse studies postulate that climate change might impact productivity growth and risk aversion and therefore future changes in r*. Some clues about this impact are found in the literature on natural disasters. Cantelmo (2020) simulates the impact of natural disasters on physical capital and productivity. Such shocks tend to reduce r* through an increase in risk aversion and precautionary savings. Hambel et al. (2020) show that r* decreases in a range of climate transition scenarios, through the impact of increasing production damages and households responding with higher precautionary savings. A similar conclusion is drawn by Bylund and Jonsson (2020). Their model simulations indicate that weaker growth prospects, greater uncertainty and risk of climate change-related disasters all tend to reduce r*. These effects might become larger and non-linear, in extreme climate change scenarios. Under certain conditions the impact on r* could be substantial.

Despite the fact that climate change is associated with predictions of a decline of r*, research by Benmir et al. (2020) argues that transition policies could have an upward effect on r*. This reversal could at least partially be achieved by a policy introducing an optimal carbon tax that enhances welfare, reduces uncertainty, and lowers risk premia. Such a policy would again raise the average risk-free real interest rate by lowering precautionary savings. New innovations, such as productivity enhancing new emission abatement technology, might also prop up r* by increasing productivity growth and triggering new investments. Moreover, the replacement of capital stock destroyed by natural disasters might give rise to a higher real interest rate in equilibrium (Keen and Pakko, 2011). Pisani-Ferry (2021) underlines that green innovations and investments may improve potential output in the long run but divert resources from expenditures that drive economic growth in the short-run. Moreover, if the transition policy is not credible, Benmir et al. (2020) find that climate risk reduces r* because households become more risk averse when firms fail to internalize the damage caused by their emissions.

Our survey contributes to this expanding literature by presenting an extended literature review of the main channels through which climate change can affect r*. Having identified the main channels through which climate change and transition policies could affect r*, we summarize the model outcomes of shocks that run through these channels in the euro area by a central bank model (CBM) and a climate economy model (CEM). We position CEMs as complements to CBMs: i.e., they provide an alternative perspective which gives some quantitative insights about the effects of climate change on r*. We summarize some main findings in the literature about the effects of climate change and transition policies on r*. One overarching finding is that the long-run effects of climate change on r* can be substantial, particularly if economic trend growth would drop due to reduced productivity growth and/or in scenarios with serious climate-related physical damages. The effect of higher risk aversion depends strongly on habit consumption. Although in some simulations r* is affected positively - particularly in scenarios with productivity enhancing innovations - most simulations indicate that the effects of climate change would reduce r*.

The rest of this paper is structured as follows. Section 2 compares two strands of models (CBMs versus CEMs) with respect to their treatment of r*. Section 3 discusses channels through which climate change can affect r*. Section 4 presents model simulations of the potential impact of climate change on r*. Section 5 discusses the main findings and provides some concluding remarks.

2. Modelling approaches in the literature

In this section, we discuss the main models used in the literature to simulate the wider effects of climate change and transition policy, including those on interest rates. In particular we show how the Central Bank Model (CBM) differs from the Climate Economy Model (CEM) in the way it considers the possible impact of climate change on r*. We identify the main differences by stylized graphical overviews of the channels for this relationship.

The New Keynesian framework - on which the CBM is based - defines r* as the equilibrium real interest rate that would prevail in an economy without nominal rigidities in wages and prices. A helpful starting point is the formulation of the natural rate according to the neoclassical growth model (Ramsey, 1928),

$$r^* = \rho + \gamma\, g + n \tag{1}$$

where *g* is the growth rate of labour-augmenting technological change (or TFP growth), reflecting the expected income growth of economic agents. Parameter n is the population growth rate and γ the consumption elasticity of marginal utility, describing how fast utility changes in consumption. Parameter γ also denotes the smoothing preference of economic agents, related to their aversion to income and consumption shocks. If agents have a high smoothing preference, they will adjust their debts or savings to smooth consumption in response to changes in g. This can be achieved through financial transactions, which determine the responsiveness of the interest rate to changes in g. The inverse of γ is the intertemporal elasticity of substitution in consumption, or the willingness of economic agents to shift consumption across time. Parameter ρ is the pure rate of time preference. It reflects the patience of economic agents to consume. The more patient agents are, the more they save and the lower becomes r*. Both CBMs and CEMs use the Ramsey equation for defining the long-term real interest rate.

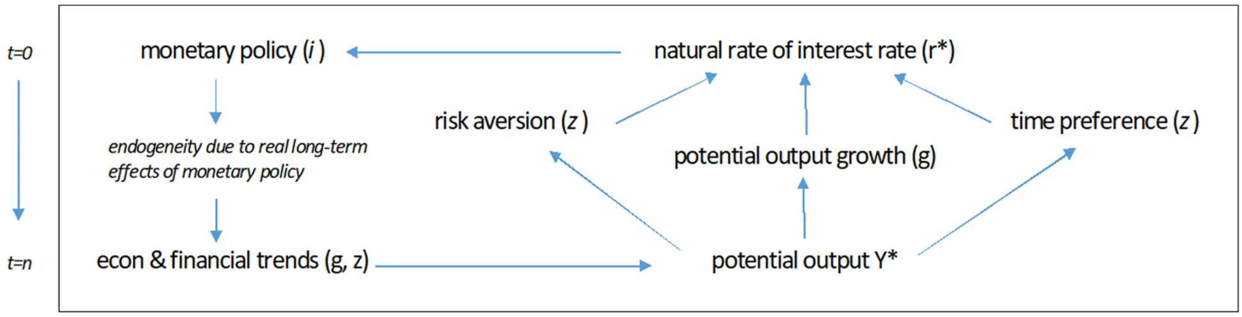
2.1 Central bank models (CBM)

The natural rate of interest is a determining factor in CBMs. A CBM for r* is the semi-structural model of Laubach and Williams (LW, 2003; see Holston, Laubach and Williams (HLW, 2017) for a novel specification and readily available quarterly estimates). It assumes that r* is a function of two random walk processes, the trend growth rate of potential output, g_t, and a time-varying unobserved component, z_t,

$$r_t^* = g_t + z_t \tag{2}$$

With variable *g* the expected growth rate of potential output, of which TFP growth is a main driver. Thereby it reflects expected income growth of economic agents, like in the Ramsey model. Variable z_t captures the effects of the other factors in the Ramsey model: i.e., the time preference and substitution (or smoothing) parameters. Hence variable z_t includes behavioural factors that determine borrowing and saving by economic agents. Through these financial channels the changes in agents' preferences can influence r*. Figure 1 presents these relationships in a stylized framework of a CBM.

Figure 1. Diagram of central bank model (CBM)



An aspect that has become all too relevant since the global financial crisis of 2008 (GFC) is that the lower r*, the tighter the policy space for central banks to provide monetary accommodation and the higher the risks of hitting the ELB.[1] So r* directly affects monetary policy (arrow at the top of Figure 1, pointing from r* to *i*). Besides, monetary policy can have an impact on r* as well (left-hand side of Figure 1). This refers to the effect of monetary policy on productivity growth, via hysteresis effects and the influence on the allocation of capital. In Section 3.7 we explain how such channels make r* endogenous on monetary policy.

Since r* is not directly observable, central banks rely on several types of model estimates of r*.[2] One of the most widely used is the LW (2003) model. It is based on a semi-structural model which filters r* out of the (short-term) market interest rate and potential output estimates. The research by LW (since extended by HLW (2017)) shows that estimates of the natural rate of interest are highly inaccurate and can vary widely depending on the model specification. Another strand of CBMs are time series models, which proxy r* as the long-term trend in real interest rates. This trend is filtered out of the data, as in Johanssen and Mertens (2018). Other CBMs are general equilibrium models, in which r* is the interest rate at which the economy is in equilibrium while prices are fully flexible (e.g. Del Negro et al., 2017). The natural rate of interest is not necessarily constant in this equilibrium but can fluctuate due to shocks in aggregate demand and productivity or due to changes in preferences. Instead, shocks to the risk premia are usually assumed to be exogenous, which limits the explanatory power of general equilibrium models for r*.

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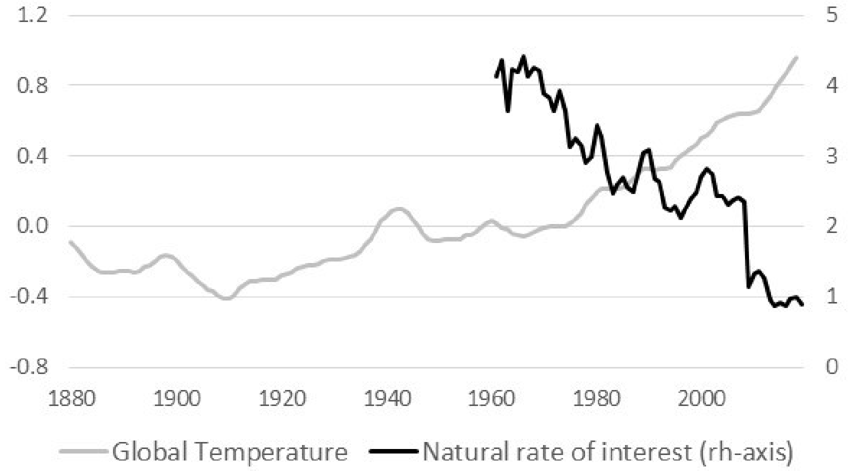
[1] This adds to the uncertain impact of climate change on output gap measures: since productivity and inflation trends may change, cyclical deviations become more uncertain.

[2] (Borio, 2021) even raises doubts on the usefulness of r* measure to guide monetary policy, *"…depending on how it is employed, the concept has the potential of leading policy astray…".*

Like climate change, the decline of r* is a trend-based, long-term, and global phenomenon (Figure 2). Brainard (2019) suggests a (future) link between both factors. As an illustration, the figure below shows a global proxy for r* as modelled by LW, together with an indicator of global warming.

Figure 2. Global warming and r*



Note: Temperature on earth (smoothed range, deviates from average temperature in 1951-1980 (source: NASA). Natural rate of interest of US, UK, EA, Canada (unweighted average, Laubach & Williams)

Another limitation is that CBMs are backward looking and do not consider the adverse impacts stemming from climate change (see for instance Brand et al., 2018, and Brand et al., 2021): however, both *g* and *z* could potentially be impacted by it. In part, this has to do with a horizon difference in CBMs and CEMs. The “long-term” for central banks is shorter than the “long-term” for climate scientists (who usually calculate in time units of five years). Moreover, CBMs have limitations that make them inappropriate for simulating the macro-financial effects of climate risks in a comprehensive manner, in particular the absence or limited representation of the energy sector. Recently, central banks and financial institutions have started to develop tools to better understand the macroeconomic effects of climate change (see ECB, 2021b for an overview).

2.2 Climate economy models (CEM)

CEMs, such as the leading Dynamic Integrated Climate Economy (DICE) model by Nordhaus (2013[3]), consider the effects of climate damage on the discount rate, a proxy for r*. The obvious channel for this relationship runs via potential economic growth *g*, as visualized in Figure 3. In

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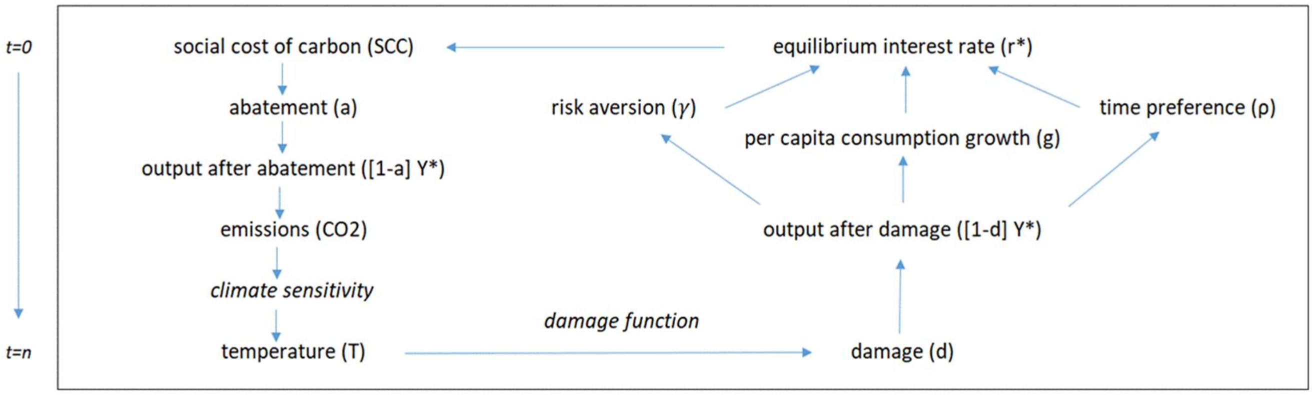
[3] Dynamic Integrated model of Climate and the Economy (DICE) is a neoclassical and deterministic growth model that also includes equations from climatology.

CEMs, climate change has a negative impact on *g* through physical damages in a damage function which negatively affects potential output (bottom arrow in Figure 3). The costs of the transition (abatement) to a carbon neutral economy also lower potential output, by reducing disposable income at least in the early stages and so reducing per capital consumption growth (left-hand side of Figure 3). Moreover, damage and transition costs lower the return on capital, which causes a decline in investment demand and reduces output. Because temperatures increase gradually, the dampening effect on per capita consumption growth is also gradual.

Figure 3. Diagram of climate-economy model (CEM)



Feedback effects play an important role in the standard CEM (lhs of Figure 3). Higher output produces more greenhouse gas emissions, which feeds back negatively on the economy. This effect runs through the impact of rising cumulated emissions on temperatures, which in turn is the main input of the damage function. Over time, this effect decreases during the transition to a carbon neutral economy. It indicates the intertemporal trade-off between the costs of improved carbon pricing in the short run and limiting physical damage in the longer run.

Parameter ρ (pure rate of time preference) also plays an important role in CEMs. In an intergenerational set-up it reflects how agents assess the value of current consumption relative to the consumption of future generations. In CEMs, parameter ρ is used as the discount rate that determines the Social Cost of Carbon (SCC), i.e. the current discounted value of future damages (in terms of changes in wealth) of emitting one ton of carbon today, scaled by the marginal welfare effect of an extra unit of consumption. The lower ρ, the higher the SCC and in that sense ρ is also called an “ethical discount rate”. Bauer and Rudebusch (2020) find that the decline of the discount rate has substantially boosted the estimated economic loss from climate change and the SCC. Stern (2007) argues normatively that future damages should not be discounted at all (i.e. $\rho = 0$). We will elaborate on this in more detail in Section 5.

Critics of current climate economy models include Weitzman (2009), who emphasizes their fundamental uncertainty, and Bolton et al. (2020), who point at unpredictable interactions and non-linear effects that could trigger tipping points and following from that, damages might be severely underestimated. Such factors are usually not considered in climate-economy models, which tend to be deterministic. Most IAM/DICE models do not take into account economic and climate risk and instead focus on parameter uncertainty. In reality, uncertainty about future economic and climate conditions substantially affects the choice of policies for managing interactions between the climate and the economy. Cai and Lontzek (2019) develop a framework of dynamic stochastic integration of climate and economy (DSICE), showing that the social cost of carbon is substantially affected by both economic and climate risks and is a stochastic process with significant variation. Therefore, the uncertainties and possible inaccuracies in modelling future climate damage, as well as the simplification of the representation of the climate system and the economy, call for caution about interpreting the outcomes of CEMs.

3. Literature review of main channels

Besides the above factors influencing r* in the Ramsey model, the empirical literature has identified several other factors of interest. The main drivers of the decline in r* include demographic factors, declining trends in productivity related to secular stagnation (see amongst others, Rachel and Summers (2019), Brand et al. (2018), Rachel and Smith (2017) and Auclert and Rognlie (2018)), and rising income and wealth inequality.[4] These factors tend to increase savings and reduce investments thus exherting a downward effect on r*. More recent research casts a new light especially on demographics and inequality. We found some additional contributions regarding the impacts of risk aversion -- working through the impact of preferences on the elasticity of intertemporal substitution -- and saving preferences, as well as fiscal policy.

3.1 Demographic trends

Most advanced economies are experiencing a demographic transition, reflecting low fertility rates, rising life expectancy, and changing composition of age cohorts. Brand et al. (2018) find that the net effects of these trends has reduced real interest rates in the euro area by around 1 percentage point since the 1980s. When extrapolating demographic trends, it is foreseen that real interest rates can be expected to fall by a further 0.25-0.5 percentage points by 2030.

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[4] While these papers are by necessity backward looking, some extend their predictions. This section links these additional factors affecting r* also to climate change.

For the US, estimates of the effect of demographics on interest rates over the 1970–2015 period range from a decline of less than 100 basis points (Gagnon et al. 2021) to a more severe decline exceeding 300 basis points (Eggertsson et al., 2019). Hence, there is substantial range estimating the magnitude of the demographic driver. On one side, Auclert et al. (2021) foresees that ageing will be accompanied by higher wealth-to-GDP ratios and capital deepening, lower asset returns, putting further downward pressure on real interest rates and widen global imbalances. Such effects will be large and heterogeneous across countries. Hence, according to Auclert et al. (2021) demographics will continue contributing to the trend decline in r* (a prediction, also shared by Gagnon et al., 2020).

On the other hand, some studies predict that future demographic developments might contribute to lowering saving rates while lifting interest rates. One is the hypothesis of a “great demographic reversal” by Goodhart and Pradhan (2020). A worsening dependency ratio, with a sharply increasing proportion of elderly and retired people will lower savings ratios of the whole economy and hence bring about rising interest rates. This follows from the assumption of age-specific savings rates that decline in old ages as retirement thresholds are crossed (Summers and Carroll 1987, Auerbach and Kotlikoff 1990, Bosworth et al. 1991). Thus, demographics and an increasing number of elderly pushes down aggregate savings, which in turn lifts interest rates.

There is a growing literature on the effects of climate change on migration which was surveyed by Cattenao et al. (2019). They find that climate change and its negative impact on income variability does not automatically lead to more migration, but rather climate change often acts as an effective constraint to migration. Acute manifestations of physical risks like hurricanes or floods tend to result in temporary displacements and the affected households and firms would often return to their original venues. Chronic physical risks like droughts or rising sea levels instead cause more permanent migratory outflows, often because original locations cannot be rebuilt. However, rising temperatures can also reduce international migration from poorer countries, since liquidity constraints could become more binding. While Cattenao et al. (2019) conclude that alarmist projections of future migration levels triggered by climate change are unrealistic, other scenarios of large climate-related labour supply shocks which could drive r* are also possible.

ECB (2021b) presents some arguments about how climate change could trigger migration flows and thereby affect labour supply. In the case of an outflow, an adverse impact on labour supply leads to a higher capital / labour ratio which reduces the marginal product of capital in the steady state and thus r*. The impact of climate change could differ across countries, as labour supply might rise in some countries due to immigration flows. These effects are uncertain at best and could manifest themselves over very long horizons. Summing up, the net impact of climate change on demographic trends is thus prima facie ambiguous: while it might discourage labour supply, thus exacerbating the downward effect on r*, it could also have an upward effect on r* by reversing the current trends towards higher life expectancy and changing the age composition of the population in favour of younger cohorts.[5]

3.2 Changes in productivity

Rising temperatures might impact labour productivity (Tol, 2009). "Comfort" temperature for humans lies between 18-22 degrees Celsius. Extreme temperatures above or below this level can have important effects on mortality, health and, in turn, labour supply and productivity (Seppanen et al., 2006). Existing evidence finds that productivity levels can decrease in the short-term by 2% per degree above comfort temperature (Heal and Park, 2016). Day et al. (2019) provide a survey of studies that have analysed the impact of global warming on labour productivity. All these papers find substantial reductions in productivity for temperature increases above certain thresholds.[6] They also present a range of possible adaptation policies to address the productivity slowdown and weaken its impact. Sectoral shocks may also vary in intensity, e.g., agricultural productivity might be affected by climate change via changes in crop yields.

With regard to physical risks, the increasing frequency of extreme weather events (acute physical risks) and deterioration of the environment (chronic physical risks) will affect the capital stock directly, if productive assets are damaged, or become useless, more often than under current climate conditions. This is comparable to an accelerated obsolescence rate of capital. It leads to a shift in resources from innovative activities towards reconstruction, adaptation and prevention of further damages as described by Batten et al. (2020) and Kahn et al. (2019).[7] Dietz and Stern (2015) suggest that damages to the capital stock will also diminish knowledge production and knowledge spillovers hence lowering the long-term growth rate of the economy. Ojeda-Joya (2022) simulates the economic effects of global warming with a state-space semi-structural model where lower productivity growth also dampens the natural interest rate.

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[5] In addition, it cannot be ruled out that migration policies will be adopted to dampen the impact on demographics.

[6] Presumably in the absence of adequate insulations, heaters or cooling, shading, air-conditioning and other measures.

[7] Keen and Pakko (2011) argue that the need to replace capital stock destroyed by natural disasters should raise the real interest rate in equilibrium: i.e., they assume that real returns on investments in new technology may increase after a disaster.

On the other hand, in the Ramsey model, higher productivity growth (parameter g in eq. (1)) increases households expected future income, reducing their need to save in order to sustain a chosen future consumption path. Lower savings then translates into a higher marginal product of capital and thus higher r*. Firms might be more willing to invest when the marginal product of capital increases. The consequent higher demand for investments could drive up r*, too. Climate change can also affect technology in several contrasting ways. It is important to distinguish the effects of physical risks (chronic and acute) from those of transition risks.

With unabated climate change (e.g., in a disorderly, delayed transition scenario as presented in NGFS, 2021), transition risks are also increasing over time, because the demand for policies to mitigate climate change might rise or consumers could eventually decline to buy carbon intensive goods and turn erstwhile productive investments into stranded assets. Hence, both physical and transition risks can lead to increasing rates of capital depreciation, thereby reducing the capital stock and its productivity. Over time, there might be higher R&D and rapid innovation (the “Porter Hypothesis”).[8]

Climate policies will change the relative price of energy inputs, which will affect the type of technologies that are developed (Acemoglu et al., 2012). Pisani-Ferry (2021) also points at an intertemporal trade-off, by underlining that green innovations and investments may improve potential output in the long run but divert resources from expenditures that drive economic growth in the short-run. While the transition requires more investment in climate-neutral innovations, these innovations might not automatically raise productivity.[9]

Instead, for additional investment to have an upward effect on productivity growth and hence on r*, the marginal product of capital should be higher than the marginal cost of capital. In fact, productivity gains of technological innovations are inherently uncertain, because they have not been tested and proven before. The transition towards a climate-neutral economy will require innovations in energy generation, in mobility and in other core processes of the production sector. In the gradual process of establishing new standards of de-carbonized production, some initial investments in innovative technologies will be lost, as competing alternatives will prevail, but the clearer the new standards will emerge, the more investors’uncertainty will fall.

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[8] Whereas some economists postulate that stricter environmental regulations would impose additional costs to firms and lower production and innovation, the so called “Porter hypothesis” (Porter, 1991) conjectures that environmental regulations might instead enhance competitiveness, thereby augmenting productivity. Porter asserts that negative externalities lead to misallocation of resources therefore regulations that help internalize these externalities should be welfare enhancing. In this sense, regulation could be a driver of innovation and productivity. Empirical studies find support for an increase in innovative activities (more patents), but no positive impact on productivity (Calel et al., 2016).

[9] Their aim is to allow the production of goods with less carbon emissions, not with fewer inputs.

Some firms might not be able to afford the I investments for new technologies and will be forced out of the market. This could affect productivity either way: negatively as it might diminish the productive capital stock in the economy and thereby lower the ratio of output to invested capital or positively as those firms which are able to succeed might be more productive than their less fortunate competitors. OECD (2006) also emphasizes the possibility that climate-related regulations might act as entry barriers in certain markets and thereby reduce firm dynamics.

Summing up, the effect of climate change on total factor productivity, and hence r*, is ambiguous. Physical risks will accelerate the write-down of capital stock and lead to less productive investments in abatement efforts to reduce damages. In addition, the increase in global temperatures will likely have a negative impact on labour productivity. Adaptation policies to soften these effects are feasible, they will likely trigger additional investment demand, thereby raising r*. Generally, R&D and innovations may be fostered as part of the energy transition, also creating demand for investment and driving up the interest rate. Climate policy will be a main determinant of these trends. Nevertheless, the transition is likely to increase the uncertainty about productivity trends.

3.3 Trend growth

The literature suggests a close relationship between climate change and GDP losses, as higher temperatures adversely affect several channels of the economy including labor productivity (Day et al., 2019), agricultural yields (Schlenker and Roberts, 2009), and industrial output (Cashin, et al., 2014). Empirical studies provide rough estimations for the total potential impact of climate change scenarios on the trend growth rate *g*. A literature review by Howard and Sterner (2017) shows that the economic damage of 0.7 - 4.3°C temperature increases until 2100 - compared to pre-industrial levels - can range from +0.1 to -23% of GDP. This worst-case impact is comparable to the -25% cumulative GDP impact estimated by the NGFS (2021). In the same NGFS scenarios, the cumulative impact of transition risk until the year 2100 ranges from a positive impact (net zero 2050 scenario) to around minus 2-3% GDP (delayed transition scenario). Alestra et al. (2020) simulate the impact of GDP damage due to climate change and the GDP impact of mitigating measures for 30 countries, by taking a long-term supply-side view. They find that at the 2100 horizon, the global GDP loss ranges from 7 - 12%, depending on the scenario.

These estimate ranges of damage and transition risk combined translate into an (annual) trend growth effect (*g*) ranging from 0 to -0.45%.[10] The maximum estimated annual effect on *g* (estimated at -0.45%), may remain within the current uncertainty bands of natural rate estimations for the euro area (Brand et al., 2019). However, the non-linear relation between climate change and the economy implies that the uncertainties about r* will compound over time. The uncertainty is right-skewed, with negative outcomes being more likely than positive outcomes (Tol, 2018). Tipping points, which are associated with temperature increases beyond the 3-4°C range, can exacerbate the economic impact exponentially (Howard and Sterner, 2017).

3.4 Risk aversion and savings

Another channel through which climate change affects the natural rate is an increased risk aversion working through the impact of preferences on the elasticity of intertemporal substitution. In the Ramsey model, risk aversion is captured by the smoothing preference of economic agents (parameter γ) which determines the sensitivity of r* to *g*. Hence risk aversion is akin to the aversion to income and consumption shocks. If climate shocks affect future income prospects (through variable *g*), agents that want to smooth consumption across time will save more today. Higher savings will reduce r* through an increase of the supply of savings. Climate change may also raise uncertainties and lead to an increase of the risk premium. Such finance-related impacts are captured in parameter *z* in eq. (2) of the Laubach and Williams model for r*.

Climate change, adaptation to it, and the transition to a carbon neutral economy may go in tandem with higher economic tail risk (Batten et al., 2020). Such risks are associated with fundamental uncertainty, as it depends on physical, social, and economic systems that involve complex interactions, non-linear dynamics, and chain reactions (Bolton et al., 2020). Both physical and transition risks are inherently fat-tailed events, not reflected in past data, with a potentially unlimited downside exposure (Weitzman, 2009). Hence, climate change will be a source of more frequent, intense, and persistent shocks in the economy that are difficult to disentangle. The related fundamental uncertainty will lead to a reduced willingness to invest and a greater propensity to save. These financial channels, captured by variable *z* in eq. (2), can lower r*.

Time-varying risk aversion has been documented by several studies. The major drivers behind these variations in the risk attitude of economic agents are changes in the macroeconomic

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[10] For example, a 23% decline of GDP volume in 2100 (85 years from 2015, at which we date the research by approximation) equals an annual growth rate of -0.3%.

environment and not necessarily idiosyncratic negative shocks experienced by individuals. Dohmen et al. (2016) and Guiso et al. (2018) present evidence for increasing risk aversion in the aftermath of the 2008 global financial crisis. Cameron and Shah (2015) provide experimental evidence from Indonesia that individuals who have experienced natural disasters exhibit a higher degree of risk aversion because they adapt their expectations about the occurrence probability of such events. This perceived increase in further natural disasters reduces their willingness to accept additional separate risks. Sakha (2019) reports the results from repeated risk experiments in Thailand, where negative agricultural shocks like droughts or floods increased the risk aversion of households. She also finds that a negative assessment of their well-being increases individuals' risk aversion.

Another contributing factor could be higher demand for safe assets, reinforced by climate change related uncertainty. Analysing the impact of rare disasters (i.e., wars in the 20th century) on asset markets, Barro (2006) finds that as more frequent disasters magnify uncertainty about the future, households demand more and safer assets. For instance, an increase of uncertainty about asset valuations in the transition to a carbon neutral economy may increase the demand for safe assets. As a result, the premium that market participants are willing to pay for holding safe assets is likely to rise, putting downward pressure on r*. This refers to the safe asset channel, which asserts that safe assets hold a convenience yield, or scarcity premium, that lowers the bond yield (see e.g. Del Negro et al., 2017; Caballero and Fahri, 2019).

An important consideration is that climate change might have asymmetric effects on risk aversion. Physical risks might affect risk aversion of agents in vulnerable regions and sectors, whereas transition risk can affect risk aversion across a wide spectrum, depending on the scenario of policy adjustments. A scenario of an erratic and uncertain adjustment path will likely elevate risk aversion and market volatility more than a clear and well-communicated climate policy path. Decarbonization policies could also lead to (temporary) disruptions in the supply of energy and commodities; for instance, if mining of certain commodities would be curtailed by stricter regulation. This could lead to increased volatility of commodity prices and raise uncertainty about investment returns and the decarbonization path.

Research shows that investors translate climate related uncertainty into a higher risk premium. Based on a combined asset pricing, endogenous growth model Hambel et al. (2020) find that the risk-free interest rate decreases due to additional precautionary savings needed to cope with global warming. Fernando et al. (2021) associate climate shocks with higher equity risk premia, which according to their simulations could lead to a loss in economic activity each year of up to 2% of GDP in the worst-case scenario. Bolton and Kacperczyk (2020) find that investors in US stock markets also charge a premium for the risk of holding the stocks of disproportionately high carbon emitters. Cevik and Jalles (2020) find that climate change also affects sovereign bond yields. Countries that are more resilient to climate change benefit from lower bond yields and credit spreads relative to countries with greater vulnerability to climate change. This suggests that climate change can increase the divergence between safe and non-safe sovereign bonds. Battiston and Monasterolo (2020) investigate the impact of climate policy scenarios on the valuation of corporate and sovereign bonds, considering endogeneity and deep uncertainty. They find that climate policy scenarios can have a substantial impact on bond yields, which would imply that also r* would be affected.

Summing up, the qualitative and quantitative impact on r* through financial channels is hard to quantify. Empirical research of the impact of climate change on bond yields is scarce. Nonetheless, the limited available research indicates that financial risks of climate change can put further downward pressure on r* through higher premiums. Given that financial markets are forward looking, this effect through *z* likely has a more immediate impact on r* than changing preferences of economic agents related to changing income prospects (reflected in parameter *g*).

3.5 Fiscal policy

Governments have the primary responsibility and the appropriate tools to spur the transition to a carbon-neutral economy and to counter the economic consequences of climate change. If the negative externalities of climate change are insufficiently priced, this market failure can be addressed by taxation and regulatory measures by governments. Climate change will also lead to higher government spending due to the costs of physical damages stemming from extreme climate events and adaptation costs and mitigation investments. Higher public spending could also be related to social security expenditure to cover health, emergency housing, relief efforts and other costs stemming from natural disasters. The commensurate increase of fiscal deficits will likely lead to an increase of government debt and the associated higher demand for savings will exert an upward pressure on r*.

The impact on fiscal sustainability will depend on the timely adoption of concerted climate policies, thus on the thrust of transition scenario. An orderly sustainable transition could support TFP growth by utilizing adequate carbon pricing (through a mix of carbon taxes and tariffs, ETS and carbon permits) with the proceeds being reallocated to support, for example, sustainable infrastructures and innovative projects and R&D. More transition measures would even contribute to higher TFP growth and so have an upward effect on r*. For instance, in the NGFS (2021) simulations the carbon price increase in the transition scenario has an offsetting growth effect owing to carbon revenue recycling. Hence, the quality and composition of fiscal policies in the context of climate policies matters.

Through the safe asset channel, a higher supply of sovereign bonds, related to higher public debt levels, would increase r*. A higher bond supply reduces the scarcity premium, which keeps r* low in a situation with excess savings and a shortage of safe assets in which to invest. In such case, the safe asset channel may also have an upward effect on r*.

3.6 Income inequality

Rising income inequality can lower r* through reduced consumption and increased desired savings (Rachel and Smith, 2017; Auclert and Rognlie, 2016). Climate change is likely to increase income inequality and so reduce r* through these channels. New evidence suggests that rising income inequality might be a more important factor in explaining the decline in r* than demographics. Based on micro data, Mian et al. (2021) weigh the relative importance of demographic shifts versus rising income inequality on saving behaviour in the US from 1950 to 2019.[11] These findings challenge the view that the ageing of the baby boomers explains the decline in r* and might taper off as baby-boomers retire. Garbinti et al. (2018) report similar inequality trends for France for the after-war period. Albers et al. (2022) analyse the wealth distribution in Germany where, despite a tax policy regime aimed at reducing inequality, the top 10% of households increased their share of national wealth significantly over the past 25 years. In an attempt to quantify the contributions of different channels that lower r* Platzer and Peruffo (2022) use a heterogenous agents OLG model with non-homothetic preferences tcontrolling for changes in intra- and intergenerational inequality. They find that the effect of rising inequality had dampened the natural rate as much as lower productivity and demographic changes.

The literature that identifies inequality as a driver of r* does not yet include climate change related risks in the analyses. However, the impact could be substantial, disproportionately for poorer countries and communities more affected by acute and chronic effects, thus exacerbating their economic vulnerabilities and increasing global income inequality. Climate change will also exacerbate inequality: the impact of high temperatures is non-linear; poor countries specialised in sectors affected by climate change have less capacity to adapt (IMF, 2017). Some studies show that such impact could have permanent adverse economic growth effects (e.g. Dell et al.,2012). Other research shows that countries with higher income

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[11] They find that saving rates are significantly higher for high income households within a birth cohort relative to middle and low income households in the same cohort. Plus, in each cohort there has been a large rise in income shares for high income households since the 1980s.

inequality tend to have higher levels of per capita GHG emissions (Islam and Winkel, 2017). This hints at a feedback effect from inequality to climate change.

3.7 Endogenous monetary policy

New Keynesian models commonly assume that monetary policy does not have long-term effects on the real economy and hence does not influence r*. Monetary policy smooths the fluctuations of the economy around its long-run growth trajectory but does very little to affect the trend itself (Woodford, 2003). In this view, monetary policy only has temporary real effects, in the transition to the new steady state after a shock. Even more so, as climate change originates from the cumulated stock of carbon emissions monetary policy should not have a structural impact on climate change.[12]

However, some recent studies argue that monetary policy can have very long-term effects, such as on expectations (Hansen et al. 2015; and Hansen et al. 2018)) and that r* might be endogenous to monetary policy (Rungcharoenkitkul et al. 2021; Jordà et al., 2020; Borio et al., 2019; Gopinath et al., 2017). This refers to the potential impact of monetary policy on productivity growth, via hysteresis effects and the impact of the real interest rate on the allocation of capital. If monetary policy would indeed affect economic trend growth (*g*), it would also have an impact on climate change via the feedback effects of potential output on carbon emissions (such feedback effects are part of CEMs such as DICE, as seen in Figure 3).

Another channel through which monetary policy could have an impact on climate change is the influence on capital allocation. Prolonged accommodative monetary policy can slow-down the energy transition, if higher polluting energy-intensive industries benefit relatively more from monetary policy stimulus (Schoenmaker, 2021). This is, for instance, the case with asset purchase programmes of the ECB, which are based on the concept of market neutrality. It implies that the allocation of asset purchases follows capital market benchmarks, which are dominated by more polluting firms, because these are relatively capital intensive.[13] This carbon bias in the purchases of corporate bonds may imply that monetary policy does not achieve efficient outcomes (Schnabel, 2020). Ultimately this bias can reduce productivity in the economy and so (through parameter *g*) also contribute to lower r*, which will then be endogenous to monetary policy via climate change in the long run. According to the Climate

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[12] Ferrari and Nispi Landi (2020) show that green QE has very limited impact in reducing the stock of emissions and, hence, in pursuing climate objectives (a similar conclusion is reached for interest rate policies by Ferrari and Pagliari, 2021).

[13] This effect is probably smaller when the economy is more service-oriented.

Action Plan the ECB will adjust the framework guiding the allocation of corporate bond purchases to incorporate climate change criteria, in line with its mandate (ECB, 2021c).

Monetary policy can support climate transition policies by creating accommodative financing conditions for sustainable firms and activities. These lower the costs of capital, by supporting a reallocation of production factors from brown to green sectors and fostering the financing of innovative green projects. Such an allocation process will be stimulated by adequate carbon pricing. This reduces possible adverse climate-related effects of monetary policy on productivity and can turn the interaction between monetary policy and potential GDP growth in the desired direction.

Concerted climate policies in an orderly transition scenario (NGFS, 2021) have the potential to transform the macroeconomic and financial environment. Therefore, central banks might need to change their response functions to meet their mandate in the “new normal”. Such a transition is unlikely to be smooth and to the extent that it affects inflation dynamics, they cannot be ignored by monetary policy (Boneva el al., 2021). Such yet unseen scenarios offer a ground to argue that central bank should engage in “proactively” integrating climate change considerations in their policies (see Ferrari and Nispi Landi, 2021 and Benmir and Roman, 2021). Active fiscal policies designed to meet climate objectives might also affect the volatility of output and inflation which, in turn, might lead to changes in the optimal policy rule of central banks (Ferrari and Pagliari, 2021).

Summing up the various effects of monetary policy on r* should not be overemphasized, as they may cancel out over the cycle. Nevertheless, there are various channels through which monetary policy is not neutral about climate change. Monetary policy can influence the greening of the economy through the effects on capital allocation and these effects depend on governments’ climate policies that determine relative prices in the economy.

4. Model simulations of the channels

Having surveyed the main channels through which climate change and transition policies could affect r*, we now summarize some simulation outcomes of shocks that run through these channels in the euro area in order to provide an overview of the possible quantitative effects.

As a start, we follow the approach of Bylund and Jonsson (2020). They simulate the outcomes of r* with different values of the parameters – calibrated for the Swedish economy - of the

Ramsey model. This allows for a quantification of the possible effects of climate change through various channels, based on the key equation for r* in the CBM. The analysis is limited to the impact on the long-run (steady state) real interest rate. We calibrated the parameters of their model, focusing on Sweden, to transpose it to the euro area.

The results of the simulations are summarized in Table 1. As we have calibrated various parameter levels for the different scenarios, we find that in r* reacts most pronounced to changes in trend growth *g* as well as the probability of disaster *p* and the impact of disaster *b*. In these scenarios, climate change has a rather direct impact on the production capacity of the economy relative to the other scenarios, which simulate different reaction modes by households and firms. The rising uncertainty often associated with climate change would particularly show its effect on r* only when combined with habit formation, otherwise the impacts are fairly negligible. So even if individuals perceive a higher degree of uncertainty about climate risks as they react by increasing their risk aversion, this would not move r* by much in the simulations.

Table 1: Effects of shock simulations on r* with a CBM model

scenario levels	*lower trend growth*	*increasing uncertainty*	*increasing uncertainty with habit formation*	*higher probability of disaster*	*higher impact of disaster*
Low	-0.5	<0.1	-0.1	-1.0	-1.3
medium	-1.0	<0.1	-0.1	-1.9	-1.9
high	-2.0	<0.1	-0.4	-2.9	-2.7

Notes: impacts on r are measured as percentage point deviations from the baseline scenario. The scenarios are simulated with different variants of the Ramsey equation, following Bylund and Jonsson (2020). Lower trend growth (g) is simulated by the basic equation* $\boldsymbol{r}^* = \boldsymbol{\rho} + \boldsymbol{\gamma}\,\boldsymbol{g} + \boldsymbol{n}$*, with* $\boldsymbol{g}$*= 1.5% and 1%. Increasing uncertainty is simulated by the Ramsey equation extended with parameter* $\boldsymbol{\gamma}^2$ *as measure of the risk aversion of economic agents and parameter* $\boldsymbol{\sigma}^2$*, representing the consumption shock (*$\boldsymbol{r}^* = \boldsymbol{\rho} + \boldsymbol{\gamma}\,\boldsymbol{g} - \frac{\gamma^2}{2}\boldsymbol{\sigma}^2$*), with* $\boldsymbol{\gamma}^2$*= 0.5, 1 and 2 and* $\boldsymbol{\sigma}^2$ *= 0.0002 and 0.0004. The effect of habit formation (S) is simulated by* $\boldsymbol{r}^* = \boldsymbol{\rho} + \boldsymbol{\gamma}\,\boldsymbol{g} - \mathbf{0.5}\left(\frac{\gamma}{S}\right)^{\mathbf{2}}\boldsymbol{\sigma}^2$*, with* $\boldsymbol{S}$*= 0.45, 0.3 and 0.15. The impact of probability (p) and impact (b) of disasters is simulated by* $\boldsymbol{r}^* = \boldsymbol{\rho} + \boldsymbol{\gamma}\,\boldsymbol{g} - \boldsymbol{pb}/(\mathbf{1} - \boldsymbol{b})$*, with p=12% and p=36% and b=5, 7.5 and 10% GDP. All scenarios assume parameter* $\boldsymbol{\rho}$ *= 0.*

Secondly, we use the CEM model DICE to conduct dynamic simulations of climate-related shocks that run through the main channels as identified previously. DICE is an integrated assessment model (IAM) developed by Nordhaus (2013).[14] It is the workhorse model in

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[14] We use the DICE-2016R version.

climate-change economics. While most climate variables and relationships in the model are global, we include euro area data for the economic and demographical variables that are not common across regions. This enables us to simulate the impact of climate shocks on r* of the euro area. Therefore, we use DICE as a projection model, i.e. an equilibrium model that generates paths of variables following a shock (Nordhaus, 2013). As is common in IAMs the time interval in DICE is 5 years and variables are projected for multiple decades in the future. We project outcomes up to the year 2100, as this horizon fits with most climate policy objectives and is distant enough to capture long-term equilibrium effects on r*.

DICE takes into account possible non-linear effects of climate change on economic variables (that could be very substantial). For instance, temperature impacts output via the damage function, which includes an exponential term. This allows for simulating non-linear effects which may occur beyond certain tipping points about changes in the ecosystem. Such non-linearities will also affect r* through their impact on economic variables. Since the uncertainty about the outcomes is large, due to assumed parameter values, non-linear effects amongst others, we are more interested in the direction of the effects and the relative impact on r*, rather than in the precise quantitative outcomes.

What we present are scenario outcomes that indicate the ranges of expected changes caused by global warming. To do so, we assume different values for key parameters of the DICE model. It is important to focus on the tails of the outcome distribution as the uncertainty around the expectations make the occurrence of tail risks more likely. Krogstrup and Oman (2019) emphasize that climate change increases uncertainty to new levels, because the tail risks include catastrophic and often irreversible events like the thawing of permafrost which could release huge amounts of GHGs and thereby intensify climate change even further. Therefore, they suggest a risk management approach inspired by Value-at-Risk (VaR) models which means maximizing one’s objective function subject to the risk of catastrophic irreversible climate change remaining below a before agreed level.

The simulations are conducted by shocking the parameters of DICE that determine the impact of climate change on the discount rate (r*) via changes in TFP growth, risk aversion and physical damages. The outcomes display the sensitivity of r* to changes in key model parameters. While the outcomes provide partial insights into the effects of changes in TFP growth, risk aversion and damages, they are useful to inform policymakers about possible paths of r* following different sets of shocks.

Table 2 summarizes the results of our DICE simulations for different parametrizations of the scenarios. The results are presented in terms of deviation from the baseline outcome in the year 2100. We find that even the most severe temperature increases as envisaged by the IPCC's SSP5-8.5 scenario (which predicts an increase in global temperatures of 4.4°C by the end of the century) would result in a relatively modest decrease of r* of less than 0.3 pp (in this scenario total output falls by nearly 6%). The effect of increasing risk aversion of economic agents has a much greater impact on the natural rate. The low scenario in Table 2 presents the outcome of a benign shock (i.e., lower risk aversion), taking into account that at least in theory the impact of climate change on risk aversion is ambiguous. An increase in risk aversion due to climate change would lower r* by as much as 2.5 pp.

The TFP shocks have been calibrated as a change in the rate of technological progress. While the low-level scenario presents a positive shock as we assume a slower decline than in the baseline, the medium and high level are both negative shocks. Tripling the decline in TFP growth in the high scenario reduces r* in 2100 by up to 1 pp. Finally, we calibrated the effects of changes in the damage function. These changes imply different sensitivities of the economy to physical risk scenarios. In contrast to other simulations, we do not include a positive shock scenario here. The high-level damage scenario would result in a decline of r* by 0.5 to 1 pp compared to the baseline, which goes in tandem with an output loss of 17% in 2100.

Table 2: Effects of shock simulations on r* with CEM model

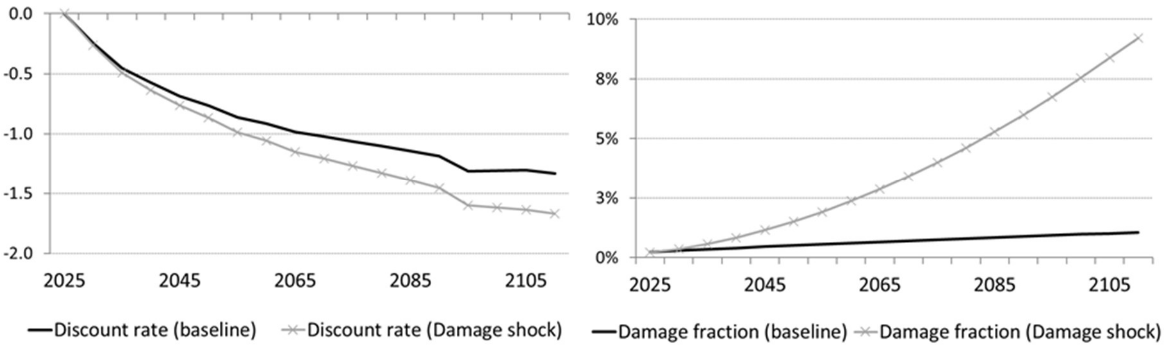
scenario / levels	*increasing temperature*	*increasing risk aversion*	*increasing TFP shocks*	*increasing damage function*
low	0.0 – 0.1	0.0 – 0.5	0.0 – 0.5	0.0 – -0.5
medium	0.0 – -0.1	-0.5 – -1.0	-0.5 – -1.0	0.0 – -0.5
high	0.0 – -0.5	-2.0 – -2.5	-0.5 – -1.0	-0.5 – -1.0

Notes: impacts on r are measured as percentage point deviations from the baseline scenario in 2100; because the results of the simulations are surrounded by significant uncertainty, we display only ranges. The low temperature scenario corresponds to the SSP1-1.9 by IPCC, the medium scenario to SSP2-4.5 and the high scenario to SSP5-8.5; the low risk aversion scenario to a risk aversion parameter of $\gamma = 1$, medium risk aversion $\gamma = 2$ and high risk aversion to $\gamma = 2.5$ (baseline $\gamma = 1.45$). For the low TFP shock we assumed $A_{gd} = 0.0025$, for the medium TFP shock 0.01 and for the high TFP shock 0.015. The damage function scenarios deviate from the baseline with $a_3 = 4$ (low scenario), $a_3 = 5$ (medium scenario) and $a_2 = 0.0044$ and $a_3 = 5$ (high scenario).*

Comparing the results of the DICE simulations in Table 2 with the steady state simulations in Table 1, we find quite significant differences. The increase in temperatures even to the most elevated levels under the IPCC scenarios yields a rather modest decrease in *r** according to the DICE model, whereas the higher probability of disaster, which is a corollary of higher temperatures, reduces *r** by up to 2.9 pp in the steady state simulations. This difference in outcomes is illustrative of the high uncertainty surrounding any effects of climate change on economic variables. Pindyck (2013) has already stressed the fact that the climate sensitivity of IAMs is surrounded by a high degree of uncertainty and that assumptions about the discount rate and risk aversion can have very decisive effects on projected outcomes. Also, the DICE model has been criticized for rather implausibly low effects of rather high temperatures, among others by Dietz and Stern (2015).

To illustrate the degree of uncertainty we present in Figure 4 the effects of changes in the damage function of DICE on r*. The damage function determines the output losses d from higher temperatures T in the model, according to $d = a_1 T + a_2 T^{a_3}$. Originally, the model uses a quadratic term to link damages to temperatures (a_3 = 2), but since the effects are highly uncertain, we use different specifications. If we assume a_3 = 5 the damages increase significantly by the end of the century, but the resulting impact on r* is rather negligible.

Figure 4. Different specifications of damage functions in DICE



Notes: *the left-hand panel shows the deviation of projected r* from its original level in the baseline scenario and under a different specification of the damage function. The right-hand panel depicts the effects of the different specifications of the damage function on expected output up to the year 2105. Despite very significant damages of more than 8% of annual output by the end of the century in the damage shock specification, the natural rate is only 0.4 pp. lower than in the baseline specification.*

Increasing risk aversion on the other hand leads to a very strong reaction of *r** in the DICE model, whereas the steady state simulations in Section 5 yield a mere decline of *r** by 0.4 pp if habit formation is included. The TFP shock which corresponds to lower trend growth produces significant effects in both models. Increasing the sensitivity of the damage function in DICE has comparable effects on r* as intensifying the impact of disaster in the steady state simulations. Both simulations yield economically significant results.

5. Discussion

This survey is the first to systematically review the possible effects of climate change on the natural rate of interest. While r* is a theoretical concept, it is used as a benchmark by central banks to assess the stance of their monetary policy and the room for policy manoeuvre. Starting from the Ramsey equation we reviewed the channels through which climate change or policies to mitigate it might affect the determinants of r*, e.g., demography, productivity and risk aversion (working through the impact of preferences on the elasticity of intertemporal substitution). In most cases, we find that climate change would have a rather dampening effect on r*, which implies a narrower room for manoeuvre for central banks. Because climate change is likely to have wider repercussions on economic policies, we also assess the impact of fiscal policies and inequality on r* and the possibility endogenous effects of monetary policy.

We illustrate how the uncertainty associated with climate change impacts – as well as the transition policies to counter it - plays an important role in several simulations. This uncertainty might raise households' precautionary motive to accumulate savings and may induce firms to postpone investment, putting additional downward pressure on market interest rates. On the other hand, the path of market interest rates and r* might depend largely on the thrust and credibility of policies governing the transition to a low-carbon economy. Along this mitigation path, the reallocation of capital across sectors and the impact on firm valuations and risk premia can lead to complex dynamics affecting aggregate variables and ultimately r* (Donadelli et al., 2018).

An additional challenge for the central banks is that the effects of climate change on these drivers may differ across euro area countries both in terms of potency and timing. This opens complicating scenarios for future monetary policy, rendering it more difficult to reach precisely narrow objectives over common policy horizons (e.g. price stability in the medium term). Hence, the uncertain impact of climate change on main r* may call for an increasing flexibility in the monetary policy strategy, both in terms of objectives and time horizon.

Lower levels of the natural rate of interest reduce a central bank's policy space since it increases the likelihood that the ELB becomes binding. This adds to the uncertain impact of climate change on the output gap, which would also imply that guidance from Taylor rules weakens. The reduced policy space for conventional monetary policy might only partly be compensated for by unconventional policy tools like QE. Therefore, it will be important to conduct policies that can help to avoid hitting the ELB, including fiscal policy. Government measures are the most obvious and effective way to foster to transition to a climate-neutral economy. An orderly transition will mitigate the economic and financial risks of climate change and thereby also prevent potential downward effects on r*. In addition, active fiscal policies to mitigate climate change might also spur investment demand and thereby put upward pressure on the natural rate. This additional investment demand could offset - at least partially - the negative effects of climate change on r* that we found. Future research could assess the consequences of different fiscal policy strategies in reaction to climate change on r*.

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