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# Economic growth effects of alternative climate change impact channels in economic modeling

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## Abstract

Despite increasing empirical evidence of strong links between climate and economic growth, there is no established model to describe the dynamics of how different types of climate shocks affect growth patterns. Here we present the first comprehensive, comparative analysis of the long-term dynamics of one-time, temporary climate shocks on production factors, and factor productivity, respectively, in a Ramsey-type growth model. Damages acting directly on production factors allow us to study dynamic effects on factor allocation, savings and economic growth. We find that the persistence of impacts on economic activity is smallest for climate shocks directly impacting output, and successively increases for direct damages on capital, loss of labor and productivity shocks, related to different responses in savings rates and factor-specific growth. Recurring shocks lead to large welfare effects and long-term growth effects, directly linked to the persistence of individual shocks. Endogenous savings and shock anticipation both have adaptive effects but do not eliminate differences between impact channels or significantly lower the dissipation time. Accounting for endogenous growth mechanisms increases the effects. We also find strong effects on income shares, important for distributional implications. This work fosters conceptual understanding of impact dynamics in growth models, opening options for links to empirics.

**Keywords:** climate change; damages; economic growth; impact channels; production factors; persistence

## 1. Introduction

Long-term effects on economic growth are among the most significant possible socioeconomic consequences of climate change. Empirical studies find evidence for climatic factors impacting economic production (Burke et al. 2015; Kalkuhl and Wenz 2017), linking lower levels of development with temperature and rainfall conditions (Horowitz 2009; Barrios et al. 2010; Brown et al. 2010; Dell et al. 2012; Carleton and

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Hsiang 2016). Climate extreme events such as tropical cyclones, floods or droughts affect growth trajectories as well, although the literature in this area is extremely diverse (Cavallo et al. 2013; see e.g. Kousky 2014; Berlemann and Wenzel 2016; Noy 2016). Climate change might exacerbate these effects through a higher frequency and intensity of climate extremes (Mendelsohn et al. 2012; Hirabayashi et al. 2013; Prudhomme et al. 2014). Resulting reduced or even stalled economic growth would pose a large challenge in particular to developing countries, but could also lead to distributional effects in wealthy countries by affecting poorer regions within countries or more vulnerable parts of the societies disproportionally. Long-term growth effects would also provide strong arguments for the debate on loss and damage, put into the spotlight recently in Article 8 of the Paris agreement.

However, there has not been much attention on mechanisms for long-term growth effects of climate change in the framework of growth models in climate economics. Lecocq and Shalizi (2007) discuss lessons from the growth literature for climate change impacts and find that both the destruction of production factors and a decrease in factor productivity (focusing on capital and labor) can affect long-run equilibrium growth. Fankhauser & Tol (2005) identify two main pathways for long-term growth effects resulting from climate change impacts: capital accumulation and adjustments of the savings rate. Both papers stress that in particular in a model framework with endogenous technical change these growth effects increase with lower investments due to output reductions as these would also negatively affect investment-related technical change and labor productivity improvements. More complex models are used to study impacts of climate change numerically, in particular integrated assessment models (IAMs, e.g. Hope 2006; Nordhaus 2013; Waldhoff et al. 2014) and computable general equilibrium models (CGEs, e.g. Eboli et al. 2010; Ciscar et al. 2011; Roson and van der Mensbrugghe 2012; Dellink et al. 2014). The former have been criticized recently for, among other points, excluding growth impacts by design and therefore underestimating the long-term costs of climate impacts (e.g. Pindyck 2013; Stern 2013; Burke et al. 2016). Despite a better sectoral and regional resolution as well as the uptake of process-based, sector-specific climate change impacts, the overall macro-economic damages found with CGE models are on the same order of magnitude as those derived with the highly aggregated IAMs (e.g. Dellink et al. 2014). Long-term growth dynamics may not be captured well by CGE models due to missing intertemporal investment dynamics. Driven by the increasing empirical evidence for links between climate and growth, a few recent papers, using the IAM DICE (Nordhaus 2013), have investigated damages affecting total factor productivity or the capital depreciation rate directly, capturing growth effects and resulting in much larger damages, higher social costs of carbon and more stringent mitigation (Moyer et al. 2014; Dietz and Stern 2015; Moore and Diaz 2015). Estrada et al. (2015) found that climate change cost estimates are very sensitive to the inclusion of a persistence parameter, motivated by studies of macroeconomic and financial time series which state that output shocks should have a high level of persistence.

With this paper we extend this literature through a systematic study of possible channels for growth effects in a neoclassical economic growth framework. Focusing on one-time, unanticipated, temporary, factor-specific climate-related shocks on output, capital, labor and labor productivity we address the following questions: How do different types of one-time, temporary macro-economic shocks on production factors affect economic growth in the short, medium and long-run? What are the implications for long-term effects of recurring (cumulative) shocks? Can an endogenous savings rate, or anticipation of the shock, trigger sufficient adaptive investment to significantly diminish the losses? How does this affect optimal climate policy?

One-off shocks could be natural disasters like storms or floods, which already have significant economic consequences in affected countries today (e.g. the Indian Ocean Tsunami 2004, Hurricane Katrina 2005 or Typhoon Haiyan 2013). Climate change is expected to increase the intensity of such events, with potentially large economic consequences (Hsiang and Jina 2014; Hallegatte et al. 2016; Hallegatte et al. 2017). A large body of empirical literature studies the longer-term consequences of such events (see Kousky 2014 for a review), but the economic dynamics and channels remain unclear. We are using one-off shocks as a tool for a clean comparison of the long-term dynamics between impact channels, which is novel in the literature. Our main findings include large differences between the persistence of indirect shock effects within different impact channels, which is explained by different dynamic reactions to the shock, e.g. in terms of after-shock growth rates and savings rate. This paper contributes to the literature by providing a systematic approach in a comparative and calibrated numerical framework, focusing on the relevant impact channels and welfare measures in climate change economics, as well as implications for optimal climate policy. In particular we focus the analysis on the persistence of impacts, including the identification of a direct relation between the persistence of indirect effects of temporary shocks and output effects as well as the analysis of related growth effects. Furthermore, our experiments show that the macroeconomic adaptation mechanisms covered (endogenous savings rate, anticipation) are not able to completely eliminate the economic persistence of shocks.

Our paper is related to models analyzing the implications of macroeconomic shocks on growth. Most relevant works in this area use Real Business Cycles (RBC) models where serially correlated technology shocks affect productivity, investment and labor (Kydland and Prescott 1982; Lucas 1987). The approach followed here is to study impulse response functions and propagation effects of shocks (King and Rebelo 1999; Ramey 2016). Thus, while our analysis could be considered as a special case of an RBC model with an unanticipated technology shock, it differs from conventional RBC analyses in disregarding the risk of shocks. Hence, we assume that climate-induced shocks come as a complete surprise whereas agents in RBC models have rational expectations about shocks and know the random distribution of future shocks. In RBC models, uncertainty about future shocks affects the saving and investment behavior before a shock occurs. Recent works aim at quantifying the welfare and growth effects of macroeconomic volatility, i.e. recurring shocks in productivity, with respect to low-income countries (Pallage and Robe 2003), commodity price volatility and financial sector development (van der Ploeg and Poelhekke 2009), human capital formation (Krebs 2003a) or optimal climate policy (Jensen and Traeger 2014).

There is a vast body of literature on uninsured idiosyncratic risks for heterogeneous households, mostly on labor-income risks, but also for example investment risks (e.g. Bewley 1977; Aiyagari 1994; Huggett 1997; Krusell and Smith 1998; Krebs 2003b; Angeletos 2007). The features of these models, in particular the ex-ante impact of uncertainty, are typically not represented in the neoclassical models used in the economics of climate change (as in this paper) and a review of this literature is far beyond the scope of this paper (but see e.g. Heathcote et al. 2009).

Another strand of literature focuses on shocks within Keynesian economic models that emphasize the role of nominal price levels and the aggregate demand side of the economy. In Keynesian models, supply shocks have different implications on investment, unemployment and economic growth than in neoclassical models due to rigidities in prices and wages as well as heterogeneity in wealth that affects demand (Mankiw 2015). So far, only few works have used a Keynesian framework for analyzing climate change. Rezai et al. (2018), combine Keynesian aggregate demand with an explicit link between productivity, energy use and climate change. Climate damages are represented via effects on the capital depreciation rate and reduce the profit share. They show that in this setup climate change can lead to boom-and-bust cycles and stagnation, only avoided by mitigation. This is an interesting approach, complementary but not comparable to our work. Another group of literature directly focuses on productivity shocks of climate damages using dynamic stochastic general equilibrium models (DSGE): Bretschger & Vinogradova (2014) and Golosov et al. (2014) endogenize macroeconomic volatility by linking the risk of productivity shocks to carbon concentration in the atmosphere. Lemoine & Trager (2014), Cai et al. (2015) and Lontzek et al. (2015) study uncertain tipping points that cause a discrete jump in climate damages (basically TFP is reduced). In their models, agents form rational expectations about the permanent shift of damages due to higher atmospheric carbon concentration. These models, however, follow the DICE model and always use a multiplicative form of damages – climate damages affect total factor productivity and are not biased to specific production actors. The only exception is Bretschger & Vinogradova (2014) who model climate damage as recurrent, uncertain shocks on capital stocks.

In order to conceptualize the different dynamics of climate damages, we focus in our paper on impulse response analysis of single, unanticipated productivity shocks, with differing assumptions on their persistence and biases toward production factors. The insights from this analysis are useful for understanding different dynamic effects of climate damages that are masked by the standard assumption of unbiased TFP damages.

The paper is organized as follows. In the next section we describe our methods and provide an analytical foundation for macroeconomic effects of different impact channels. Section 3 describes the results. Section 4 offers a discussion of a few applications of this work, and Section 5 summarizes key insights and outlines next steps for future research.

## 2. Methods

### 2.1 Study design

We design our study with the following goals in mind: (i) coverage of all relevant impact channels in a standard Ramsey-type growth model in a comparable setting; (ii) use of one-time temporary unanticipated shocks as an approximation for dynamics under uncertainty characterized by climate shocks of low probability and high impact; (iii) coverage of multiple model variations and sensitivity cases related to open questions in the literature, in particular the role of the savings rate as a macroeconomic adaptation mechanism; (iv) analysis of the implications of shocks with varying indirect effects when accumulating through recurrence, and the effect of anticipation as adaptation measure. The study design is summarized in Figure 1.

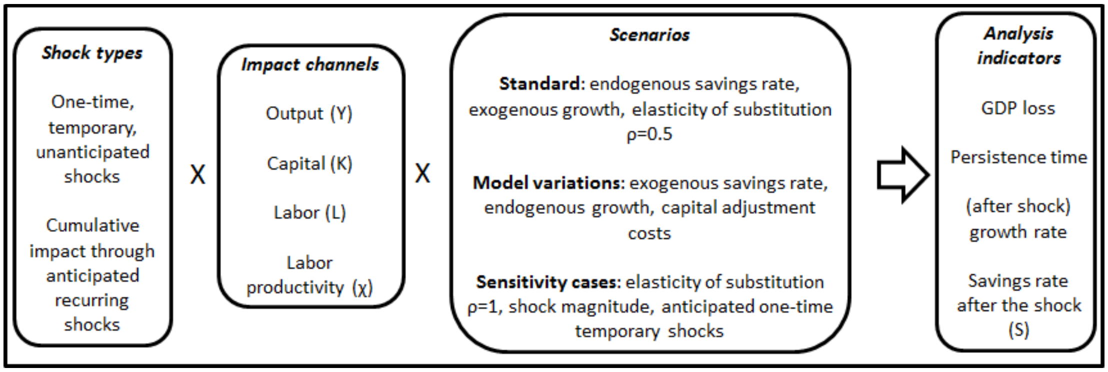

**Figure 1:** *A summary of our multidimensional study design.*

### 2.2 Analytical insights

As a basis for the numerical work we first summarize expectations on the dynamics resulting from shocks in different impact channels gained from a standard analytical approach based on a Ramsey model (see also Barro and Sala-i-Martin 2004; Fankhauser and S.J. Tol 2005; Lecocq and Shalizi 2007). We use a neoclassical production framework $F(K, \chi L)$ with the production factors capital (K), labor (L) and labor-augmenting technological progress $\chi$ growing with a constant exogenous growth rate x. As labor and labor productivity both grow with constant exogenous growth rates, there is no distinction between the dynamics of a shock on either. For simplicity we therefore refer to labor productivity only in the remainder of this section.

As in the standard Ramsey model, the capital stock increases in investment and decreases with the natural depreciation rate. Consumption equals production minus investments. The social planner chooses the investment path which maximizes intertemporal utility. If labor productivity and population grow at constant rates, the economy will exhibit a balanced growth path (see Barro and Sala-i-Martin 2004), i.e.

in the long-run, per-capita GDP and consumption grow at the growth rate of labor productivity, x. The balanced growth path is basically a steady state of the transformed dynamic system where state variables like capital are expressed in intensive form, i.e. divided by effective labor, as $\bar{k} \coloneqq \frac{K}{\chi L}$. While the capital per effective worker, $\bar{k}$, converges to the steady state level $\bar{k}^*$ in the long-run, the economy will in the short run exhibit positive growth of $\bar{k}$ if $\bar{k} < \bar{k}^*$ and negative growth of $\bar{k}$ if $\bar{k} > \bar{k}^*$. The speed at which the economy converges to the steady state can be expressed by the convergence speed parameter $\beta$ which is, in turn, affected by the specific choice of the production and utility function. Empirically, convergence growth is typically between 2 and 3 percent, implying that the economy needs 25-35 years to eliminate half of the initial income gap to the steady state income level (Barro and Sala-i-Martin 2004). In this model setting, shocks may affect the factor endowments capital K or (effective) labor χL as well as total factor productivity (output). There are basically two different effects possible: First, a shock may change the steady state of the economy, implying a persistent impact. Second, a shock may only widen the gap of the economy to its (unchanged) long-run steady state. In the latter case, the impact of the shock will diminish over time as the economy converges back to its original steady state. Additionally, both effects could occur simultaneously.

**Table 1: Overview of the analytical results. x is the productivity growth rate (equal to the growth rate of per capita output in the steady state), β is the convergence speed, Ω is the shock in the respective channel, Γ is the income share of the respective production factor. A * indicates the steady state value, a ^ the value after the shock and a bar the value per effective worker. Both Ω and Γ have values between 0 and 1 for all shocks. The right column refers to the lessons drawn for the alternative growth dynamics for labor and labor productivity used in the simulations.**

| | **Output shock (TFP)** | **Capital stock shock** | **Labor productivity shock with constant productivity growth rate** | **Dissipating labor productivity shock (productivity growth rate increases after the shock)** |
|---|---|---|---|---|
| **Growth rate after shock** | $g_Y = x - \beta \ln(1-\Omega)$ > x | $g_K = x - \beta \ln(1-\Gamma_K \Omega_K)$ > x | $g_A = x + \beta \ln\left(\frac{1-\Omega_A}{1-\Gamma_A \Omega_A}\right)$ < x | $g_{L/A}$ > x due to increased factor growth rates |
| **Effective capital after the shock** | $\hat{\bar{k}} < \bar{k}^*$ due to capital accumulation effect → S increases | $\hat{\bar{k}} = (1-\Omega_K)\bar{k}^* < \bar{k}^*$ → S increases | $\hat{\bar{k}} = \frac{\bar{k}^*}{(1-\Omega_A)} > \bar{k}^*$ → S decreases | $\hat{\bar{k}} = \frac{\bar{k}^*}{(1-\Omega_A)} > \bar{k}^*$ → S decreases (though increases in the long run) |
| **Long-term GDP effect** | $\hat{Y}^* = Y^*$ | $\hat{Y}^* = Y^*$ | $\hat{Y}^* = (1-\Omega_A)\, Y^*$ | $\hat{Y}^* = Y^*$ |
| **Expected persistence** | Low as it is a temporary shock | Higher as $g_K<g_Y$ | Permanent shock | Higher than for Y/K channel due to the initial decrease in savings rate |

The standard neoclassical growth framework allows us to study the immediate output growth rate response and the long-term GDP effect of unbiased technology shocks (output, or Y channel, shocks), as well as shocks biased towards capital (K channel), labor (L channel) or labor productivity (χ channel). The results hold for all types of neoclassical production functions, and are shown in Table 1. For the derivations please see the Appendix. All shocks are assumed to be unanticipated and temporary, however through the assumption of an exogenous productivity growth rate, the labor (productivity) shock is effectively perfectly persistent.

There is a clear distinction between the Y and K channel on the one side, and the labor productivity channel on the other side. For Y and K shocks, there is no long-term GDP effect, and the shock dissipates completely. This is due to an increase in the after-shock growth rate compared to the counterfactual case without shocks, caused by an increase in the savings rate S as part of the reoptimization after the shock. The growth rate increase is initially larger for the Y channel than for the K channel, but the increase of the savings rate is larger in reaction to the direct effect on capital stock compared to the smaller indirect effect for a Y channel shock.

A shock on labor productivity on the other hand leads to a permanently lower long-term GDP. Despite the temporary shock, the labor productivity is permanently lowered due to the constant exogenous growth rate, which causes a permanent persistence of the shock. However, in the steady state, effective consumption and capital (i.e. consumption/capital per effective worker, e.g. $\bar{k}^* = \frac{K^*}{\chi L}$ where the * indicates the steady state) will stay constant despite the lower productivity, which means the long-run steady-state capital stock is lowered, leading to a permanently lower GDP. This means a lower savings rate and output growth rate during the transition to the lower long-term capital and GDP levels.

A permanent persistence of a shock on labor productivity might be an extreme case. Also, the growth rate of labor productivity is unlikely to be constant but could increase after a shock through higher investments to alleviate the long-term GDP reduction. In this case we would expect the after-shock dynamics to be similar to the capital channel, with a higher after-shock output growth rate and a dissipation of the shock. However, directly after the shock, the savings rate response for a shock on labor productivity, independent of the growth formulation of that factor, is different from that of a capital or output shock. As the effective capital stock after the shock initially exceeds the steady state effective capital stock, since $\hat{\bar{k}} = \frac{\bar{k}^*}{(1-\Omega_A)} > \bar{k}^*$, there is an initial reduction in the savings rate and therefore an increased indirect damage effect in addition to the shock itself. Only when labor productivity grows again over time due to the increased growth rate, this overcapitalization is reduced and an increase in the savings rate follows. Therefore, even when the productivity shock dissipates, we expect a higher persistence than for the output and capital channels.

A main implication of this stylized model is that climate shocks, even if they exhibit the same immediate reduction in GDP, may exhibit completely different growth and long-term dynamics (persistence). Particularly, with respect to damages on labor productivity, it is important to understand whether a recovery due to increased investments in human capital or innovation is possible to prevent permanently lower GDP levels.

The analytical study has its limits. As there is no general analytical solution for the convergence speed parameter, we cannot compare or quantify half-life time and transition dynamics after different types of shocks in detail. Furthermore we would like to include more realistic assumptions for labor and labor productivity growth, study model modifications like endogenous growth, and investigate the cumulative impacts of recurring shocks. We therefore employ numerical modeling for the main part of the paper; the setup is described in the following section.

### *2.3 The numerical model*

Our growth model builds on the latest version of the DICE model, DICE-2013R (Nordhaus 2013). DICE provides an appropriate framework for our analysis due to the elegance and simplicity of its macroeconomic core, i.e. the standard neoclassical growth model. Like other integrated assessment models, DICE has been subject to criticism, for example related to its choice of mitigation cost function, damage function, discount rate and climate sensitivity (Ackerman and Stanton 2012; Stern 2013). In general, neoclassical growth models typically contain a simplistic representation of technological change (Serban Scrieciu et al. 2013), consider all markets to be in equilibrium and assume perfect information (Atkinson and Hackler 2010). Moreover, modeling of climate damages on the level of economic value lacks a representation of growth reducing damages and low probability high impact events like catastrophes and tipping points (Stern 2016). While this criticism is valid, our study actually tackles on of the important shortcomings, namely the representation of growth damages. Other critical aspects, e.g. on market clearance and perfect information, are left for future research.

The DICE model uses a Cobb-Douglas production function where the elasticity of substitution between labor and capital equals one. Recent works have criticized the use of the Cobb-Douglas function, and provide empirical evidence that the elasticity of substitution between labor and capital is substantially lower than one (Antras 2004; Chirinko 2008; Juselius 2008; Smith 2008; Chirinko and Mallick 2017). Using a substitution elasticity smaller than one will have three major implications: First, it allows studying the differential impact of factor-specific climate damages on production. Under a Cobb-Douglas production function, a shock on labor or capital will always have a proportional effect compared to a TFP shock with the magnitude related to the labor-income shares. Second, with an elasticity of substitution below one, climate damages affecting specific factors may create stronger impacts on production as it becomes more difficult to substitute for factor-specific damages. Third, as shown by Swan (1964) and Phelps (1967), permanent technological change must be expressible in labor-enhancing form for a balanced growth path to exist.

Therefore, growth models include technological change as labor enhancing to replicate stylized empirical facts on (constant) long-run economic growth.[5]

Our production function has the form

$$Y_t^G = a_0[\alpha K_t{}^{\sigma} + (1-\alpha)(\chi_t^L L_t)^{\sigma}]^{1/\sigma} \tag{1}$$

where technical progress $\chi_t^L$ is purely labor-augmenting. We assume a substitution elasticity of ρ=0.5, giving $\sigma = \frac{\rho-1}{\rho} = -1$. The parameters α and $a_0$ are obtained via a calibration procedure for the first time step as outlined in Klump & Saam (2008) to reproduce the initial income shares of 30 and 70% for capital and labor, respectively. Assuming $\chi_{t=1}^L = 1$, the calibration yields $a_0$=1.4 and α=0.89. As in DICE all parameters represent global parameters. In our standard case productivity grows exogenously following the DICE productivity equation given by

$$\chi_{t+1}^L = \frac{\chi_t^L}{1-g_t^L}. \tag{2}$$

This is a logistic equation with declining productivity growth over time, with the exogenous growth rate given by $g_t^L = g_0^L \exp(-\delta^L \Delta t\ (t-1))$. $\delta^L = 0.006$ and $g_0^L = 0.114$, calibrated to produce a GDP trajectory matching DICE-2013R with the Cobb-Douglas production function, where GDP grows from 64 to 1570 trillion US$2005 between 2010 and 2200. Section 3.2.3 discusses the influence of the change in the production function on our results.

Motivated by the findings by Fankhauser & Tol (2005) we also study a model variation with endogenous productivity growth. It is implemented following the method by Dietz & Stern (2015), where

$$\chi_{t+1}^L = (1-\delta^{\chi})^{\Delta t} \chi_t^L + \gamma_1 \left(\Delta t I_t^{\chi}\right)^{\gamma_2}. \tag{3}$$

In this case $\delta^{\chi}$, the net depreciation rate for productivity, represents productivity depreciation stemming from erosion or displacement of skills as well as autonomous productivity growth, e.g. from institutional innovation. $\delta^{\chi}$ is assumed to be positive and smaller than the capital depreciation rate ($\delta^K = 0.1$). The driver of productivity growth is a non-internalized spillover of capital investment into knowledge. Its functional form $a(I_t) = \gamma_1 \left(\Delta t I_t^{\chi}\right)^{\gamma_2}$ is chosen to capture the decline of productivity growth in standard DICE in the initial periods, satisfying the conditions a'>0 and a''<0 (with $\gamma_1 > 0$ and $\gamma_2 \in (0,1)$). The constants are calibrated to ensure that output in the baseline run without damages is similar to the standard DICE baseline run, resulting in values of $\gamma_1 = 0.01$ and $\gamma_2 = 0.6245$ with $\delta^{\chi} = 0.006$. This non-internalized formulation by definition lacks the adaptive mechanism allowing targeted labor-augmenting investment increases to recover productivity levels which would provide an advantage for endogenous growth. Therefore it is expected to increase damages.

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[5] In case of a Cobb-Douglas production function (as in the DICE model), however, total factor productivity enhancing technological progress can be transformed to an equivalent labor-enhancing representation. With a Cobb-Douglas production function, a balanced growth path can therefore exist if technological change increases TFP.

The exogenous specification of the labor productivity growth rate by definition implies perfect persistence of one-time productivity shocks as labor productivity is permanently shifted to a lower level while the exogenous growth rate stays the same (as discussed in Section 2.2). On the contrary, a permanent effect of a one-time shock is not possible for the formulation in eq. ( 3 ), as the actual growth rate of productivity is changing in response to the shock. This is not only an effect of the endogenous investment spillover but also occurs when the driver of productivity growth is given exogenously as $P_t^{\chi}$ (demonstrated in the Appendix, Section A.3.1). Perfect persistence might be considered as an extreme case. Therefore, and to have a direct comparison of the dissipative dynamics in the endogenous growth case, we introduce a second formulation for exogenous productivity growth with varying persistence $1-\delta^{\chi}$ as follows

$$\chi_{t+1}^{L,d} = (1-\delta^{\chi})^{\Delta t}\chi_t^{L,d} + P_t^{\chi}. \qquad (4)$$

$P_t^{\chi}$ is calibrated to produce the same productivity growth path as given by eq. ( 2 ).
We study the effects of biased damages acting directly on the production factors, i.e. affecting labor and capital stocks as well as labor productivity. Shocks on capital may arise from extreme events like storms or floods. The damage is imposed directly in the capital motion equation as

$$K_{t+1}^{*} = \Omega_{t+1}^{K}K_{t+1} = \Omega_{t+1}^{K}[(1-\delta^{K})^{\Delta t}K_t + \Delta t I_t] \qquad (5)$$

where I are investments. This specification again introduces persistence of shocks of magnitude $1-\delta^{K}$. The initial value for the capital stock is $K_0$=135 trillion US$2005. In addition to this direct damage, indirect damages resulting from all macroeconomic channels manifests itself through the capital accumulation, via lower investments following lower GDP. At the same time, investments can be raised in response to (or anticipation of) impacts when the savings rate is endogenous.

Population (and by assumption labor) grow asymptotically in DICE towards a level of 10.5 billion people. This asymptotic growth is different from the labor productivity growth and results in differences between the labor and the productivity channels, contrary to the analytical case discussed in the previous section. We separate labor and population, applying the shock only on the labor force entering the production equation, while the total population remains unchanged:

$$L_{t+1}^{*} = \Omega_{t+1}^{L}L_{t+1} = \Omega_{t+1}^{L}L_t\left(\frac{10.5}{L_t}\right)^{\mathrm{n}}, \qquad (6)$$

where n is the exogenous population growth rate, calibrated to match the UN population projection for 2050. Note that the shock on labor increases the labor growth rate in this formulation, due to the asymptotic exogenous growth assumption (see Figure S1), therefore the shock is dissipative. Shocks on labor could arise, for example, from emigration (Coffman and Noy 2011), heat stress or people dropping out of the work force due to health effects.

For labor productivity we use both the perfectly persistent and the dissipative formulation, based on equations ( 2 ) and ( 4 ) respectively:

$$\chi_{t+1}^{L,p\,*} = \Omega_{t+1}^{\chi}\chi_{t+1}^{L,p} = \Omega_{t+1}^{\chi}\frac{\chi_t^{L,p}}{1-g_t^L} \tag{7}$$

and

$$\chi_{t+1}^{L,d\,*} = \Omega_{t+1}^{\chi}\chi_{t+1}^{L,d} = \Omega_{t+1}^{\chi}[(1-\delta^{\chi})^{\Delta t}\chi_t^{L,d} + P_t^{\chi}] \tag{8}$$

On the individual level, a highly persistent productivity reduction could for example result from childhood stunting (Horton and Steckel 2013). An example for a dissipating effect would be lower productivity due to a heat wave (Kjellstrom et al. 2009). Both versions are illustrated in Figure S2.

In order to ensure direct comparability between the impact channels the channel-specific damage factors $\Omega_t^X = \frac{Y_t^{N,X}}{Y_t^G}$ ($Y_t^G$ gross output before damages and $Y_t^N$ net output including damages) are set to result in the same relative output effect of the shock, i.e.

$$\Omega_{\mathrm{t}} = \frac{Y_t^{N,Y}}{Y_t^G} = \frac{Y_t^{N,\chi\_L}}{Y_t^G} = \frac{Y_t^{N,K}}{Y_t^G} = \frac{Y_t^{N,L}}{Y_t^G} \tag{9}$$

where $\Omega_{\mathrm{t}}$ is an exogenous damage factor. As damage is applied as flow damage in the output channel, $\Omega_t^Y = (1-\Omega_t)$ holds. For the other channels the comparability approach yields

$$\Omega_t^K = \left[(1-\Omega_{\mathrm{t}})^{\sigma} - (1-(1-\Omega_t)^{\sigma})\frac{(1-\alpha)(\chi_t^L L_t)^{\sigma}}{\alpha K^{\sigma}}\right]^{1/\sigma} \tag{10}$$

and

$$\Omega_t^L = \Omega_t^{\chi} = \left[(1-\Omega_{\mathrm{t}})^{\sigma} - (1-(1-\Omega_t)^{\sigma})\frac{\alpha K_t{}^{\sigma}}{(1-\alpha)(\chi_t^L L_t)^{\sigma}}\right]^{1/\sigma} \tag{11}$$

(see Appendix). This formulation of the damages as stock damage for the production factors ensures that we include growth-relevant indirect effects of damages. As the standard GDP damage formulation is a pure flow effect, those dynamics are largely neglected, aside from some indirect capital effects. Of course production factors can also be affected by flow damages, however in our comparative setting these simply yield the same result as the damage in the output channel and are therefore not included here.

## 3. Results

In the discussion of the results we first focus on the effects of a one-time, temporary, unanticipated, exogenous shock in the different impact channels, ensuring comparability and allowing the cleanest analysis of the resulting dynamics. We also discuss in detail the model variations using a fixed savings rate and endogenous growth, and then expand our results briefly for the sensitivity of anticipated shocks and variations in the elasticity of substitution. We then move on to applying recurring cumulative shocks over time including climate feedback, and discuss the importance of the dynamic macroeconomic effects of temporary shocks for the case of persistent shocks. We also discuss long-term growth rates and income share effects and finally focus on optimal abatement pathways for the different impact channels.

### *3.1 One-time temporary shocks: standard case*

We start out by applying a one-time, temporary, unanticipated shock of a 15% output loss in 2050. The channel-specific damage factors are $\Omega^{Y}_{t=2050} = 0.85$, $\Omega^{K}_{t=2050} = 0.62$ and $\Omega^{L}_{t=2050} = \Omega^{\chi}_{t=2050} = 0.8$. The GDP shock of 15% is chosen for illustrative reasons but it also represents a high-impact extreme event. For example, Hsiang and Jina (2014) find income reductions of 15% at the 99th percentile of cyclones intensity. Based on empirical GDP-temperature responses, Burke et al. (2015) estimate global warming to reduce global GDP by 23% by 2100. Values around 10% and 15% are therefore often used in the literature to model high impact outcomes like tipping points (Nordhaus and Boyer 2000; Bretschger and Vinogradova 2014; Golosov et al. 2014). Note that the results are not sensitive to the strength of the shock (discussed further in the Appendix, section A.3.2).

Figure 2 shows that the long-term implications vary strongly between the channels, along the lines expected from the analytical insights (see Section 2.2) and in line with the growth literature[6]. Shocks in the output and capital channel have relatively small indirect, long-term effects, explained by their increased after-shock growth rate and the increase in the savings rate. The shocks on labor and labor productivity (in the dissipating formulation) do dissipate over time, though it is a slow process. In both cases, as expected, we have an initial drop in the savings rate due to the overcapitalization of the system, and the recovery from the shock is delayed by about 15 years. Then, as explained above, the dissipation is driven by higher savings rates caused by the increased labor and productivity growth rates due to the respective growth formulation of the factor, resulting in increased GDP per capita growth rates. However, at the same time the increase of the growth rates is limited by their exogenous formulation. No targeted investment for their increase, i.e. adaptation directly in the damage channel, is possible, which also limits the dissipation speed.

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[6] The convergence dynamics are as expected from the Ramsey model (see Barro and Sala-i-Martin 2004) and the results also show the different transition and long-run dynamics depending on the persistence of shocks (see, e.g. King & Rebelo 1999 for simulations of single TFP shocks with different degrees of persistence in the RBC framework).

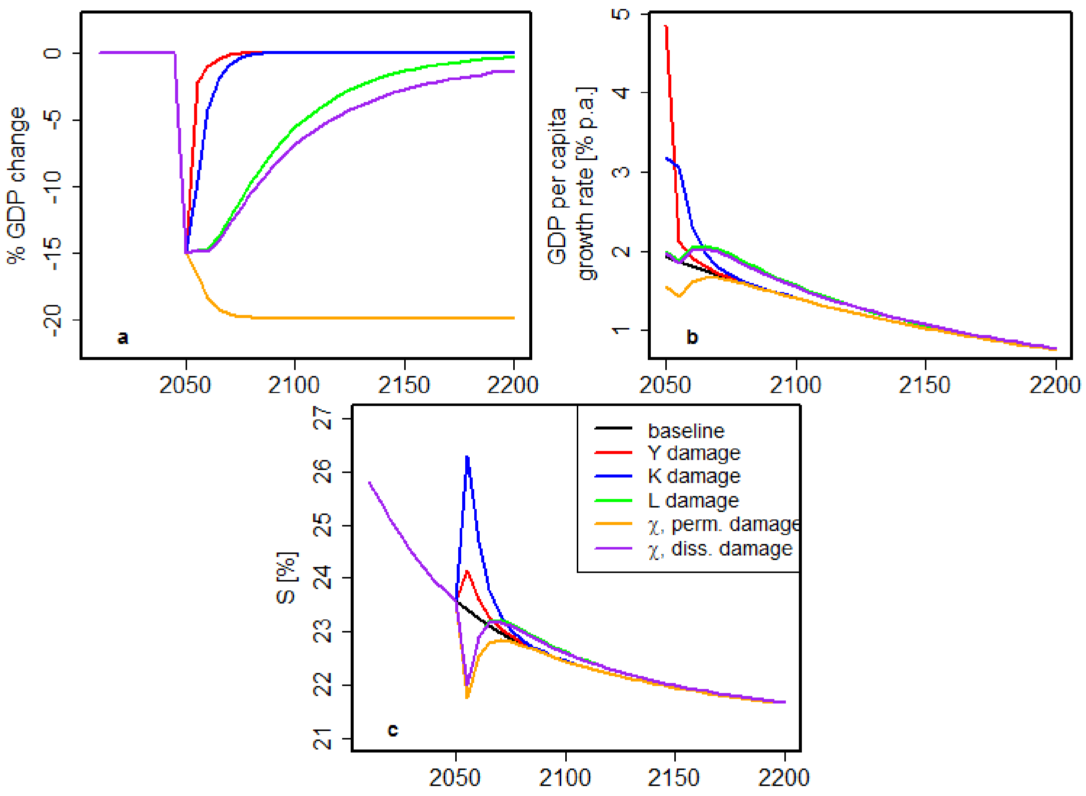

**Figure 2:** *GDP change (panel a), the GDP per capita growth rate after the shock (panel b) and the savings rate (panel c) in a comparative shock test for different damage channels (colors).*

The final case, the permanent productivity damage, is by definition a permanent level effect – the counterfactual GDP per capita growth rate is reached soon after the shock, but the GDP level stays permanently below the pre-shock level, at $\Omega^{\chi}_{t=2050} Y^{baseline}_{t}$ which is reached after about 15 years. This corresponds directly to the productivity case as discussed in the analytical section. Note that none of the effects are actually growth rate effects, i.e. the long-term GDP per capita growth rate stays the same for all impact channels, although the overshoot remains for a relatively long period for the labor and dissipating productivity channels. It is difficult to imagine a one-time shock which could lead to a permanently lower growth rate. However recurring shocks over a long period of time may have such an effect.

### *3.2 Model variations and sensitivities*

In this section we study the influence of two economically important mechanisms – the savings dynamics and endogenous productivity growth. Previous literature has used different assumptions for them but does not include explicit comparisons of their respective effects. Furthermore we look at the effect of the elasticity of substitution. For further sensitivity dimensions (the strength of the shock, the effect of anticipation, capital adjustment costs) please see the Appendix.

### *3.2.1 The savings rate*

A fixed savings rate does not allow investment adjustments as shown in Figure 2, i.e. it impedes adaptation to the shock effects which is undertaken to increase welfare driven by consumption. This affects especially the output and capital channel, where the savings rate effect is largest, and leads to higher damages in both cases (Figure 3).

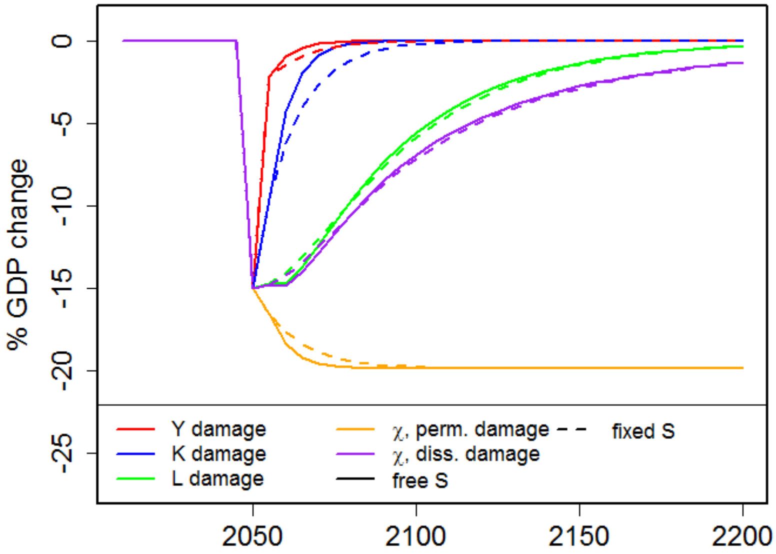

**Figure 3:** *The influence of a fixed savings rate (dashed lines) on the system dynamics, compared to the original runs with an endogenous savings rate (solid lines) in the different damage channels (colors).*

For the other channels a fixed savings rate actually reduces GDP loss for a time after the shock as the previous initial reduction of investment, reducing the immediate consumption drop, (Figure 2c) is not allowed. Over the long run the loss is slightly larger as well, though the difference is small, with the exception of the permanent productivity channel. The loss of the positive adaptation effect in the Y and K channels influences the indirect effects of the shock much more than the avoidance of the additional capital loss in the L and χ channels. However, the larger pattern of dynamical differences in the different impact channels is rather insensitive to the endogeneity of the savings rate. In particular, the adaptive effect of an endogenous savings rate does not significantly speed up the dissipation, with the exception of the capital channel (see also Figure 6). The re-optimization after the shock balances consumption loss and investment increase, taking into account that it is a one-time temporary shock and a long-term recovery will take place. When the shock is anticipated, in an additional adaptive effort the investments are increased right before the shock for all impact channels. However, again, this is limited as the shocks will either dissipate in the long-run or the GPD loss is unavoidable (the permanent productivity channel). The effects of the anticipation do not significantly alter the dynamic transition results, with largest effects for the capital channel (see Appendix Section A.3.2).

### *3.2.2 Endogenous growth*

When productivity growth is driven endogenously by investments, this adds another channel by which indirect effects can compound the original shock. Results are shown in Figure 4, including the effects on productivity (panel b). For all channels, the endogenous growth leads to larger damages (dashed lines vs. solid lines), in agreement with the results by Fankhauser & Tol (2005). For both the output and the capital channel the effect remains visible over the whole simulation time, albeit very small (less than 0.5% GDP loss compared to the counterfactual case). However, contrary to the savings rate effect, endogenous growth impacts most strongly the labor and productivity channel. The reason for this is the stronger compounding effect, acting through both capital and productivity over the longer dissipation time in these channels.

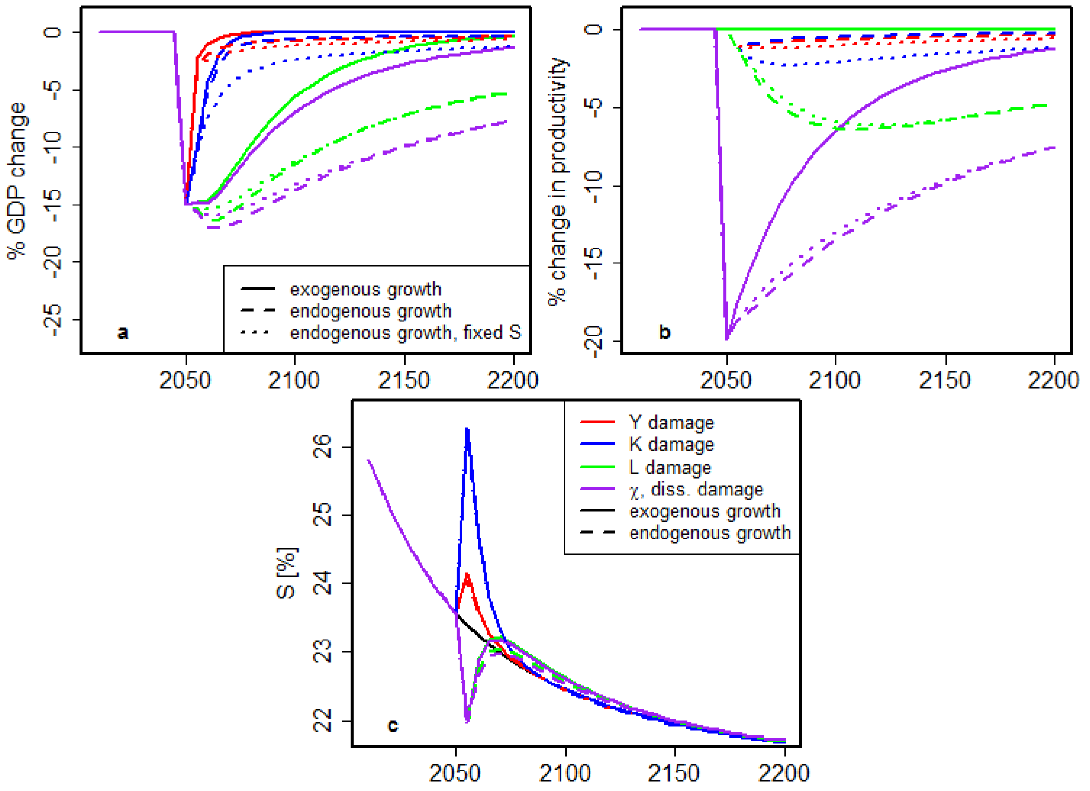

**Figure 4:** *The effect of endogenous growth (dashed lines) compared to the standard setting (solid lines) and endogenous growth with a fixed savings rate (dotted lines). Panel a shows the GDP effect, panel b that on productivity itself (where there is no effect for the Y, K and L channel in the standard runs with exogenous productivity) and panel c the savings rate comparing the exogenous growth with the endogenous growth setting (solid vs. dashed lines).*

In addition, the increase of the savings rate after the shock compared to the baseline is smaller than in the case with exogenous growth (Panel c). The difference between an endogenous and a fixed savings rate is stronger in the case of endogenous growth (dotted vs. dashed lines), as it affects both capital accumulation and productivity growth. This is in particular visible for the capital channel, as can be expected. The effect of endogenous growth is partially driven by its implementation as productivity-enhancing spill-over effect without the possibility to adapt via targeted investment into productivity. Models with other formulations of endogenous growth, e.g. through innovation activities, also find strong negative growth impacts (Donadelli et al. 2017). While innovation in adaptation may also reduce the costs of climate impacts, these innovation activities crowd out other innovation activities. This interplay affects long-run growth.

### *3.2.3 The elasticity of substitution*

As we discussed in Section 2, our standard setup uses a CES production function with an elasticity of substitution of 0.5. Standard DICE relies on a Cobb-Douglas function and we explore the difference in this section. Figure 5 shows that the higher elasticity of substitution leads to lower convergence growth after a shock and even to lower permanent GDP for labor productivity shocks. Hence, damages are higher (dashed lines) in all channels (Panel a). This is intuitive when keeping in mind that the driver for the optimization is consumption, not output. A better substitutability between production factors therefore allows a lower convergence speed (Turnovsky 2002; Klump and Saam 2008). This means a smaller adaptive response through investment adjustments, which can be seen from the much smaller change in the savings rate as shown in Figure 5b. Another reason is the decreasing capital share in the CES case, from the initial value of 0.3 (the same as for the Cobb-Douglas setting) to 0.265 in 2200. This reduces the influence of the after-shock capital dynamics on the long-term GDP path, leading to lower overall damage.

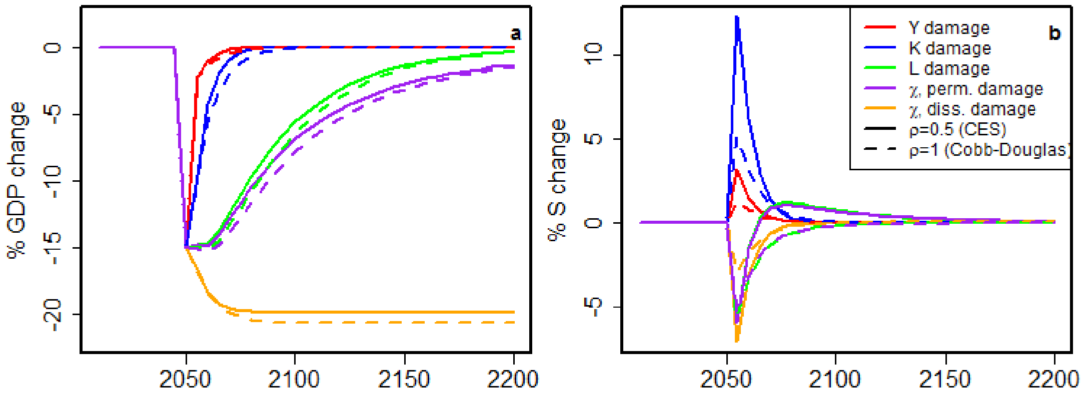

**Figure 5:** *GDP loss (panel a) and change in the savings rate S (panel b) for the different impact channels comparing the standard CES case with elasticity of substitution=0.5 (solid lines) with a Cobb-Douglas case (elasticity of substitution=1, dashed lines).*

### *3.2.4 Persistence of indirect shock effects in terms of the half-life time*

The persistence of indirect shock effects is a useful measure to synthesize the results of the shock analysis. To measure persistence we use the half-life time which is the time until 50% of the shock has dissipated, i.e. the GDP has returned halfway to its original value. Results are shown in Figure 6. The case of a permanent productivity shock is not included as it has infinite persistence by definition. Half-life times are smaller than 10 years for the output and capital channels. The persistence of the indirect effects of labor and dissipating productivity channel shocks is significantly stronger, with half-life times of around 40-50 years and significantly more in the case of endogenous growth. As described above this is due to a combination of effects: a slow recovery as a consequence of the exogenous growth rates of the factors, an additional GDP reduction through the reduction in savings rate as an immediate reaction to the shock and a compounding effect through capital accumulation throughout the longer dissipation period. In terms of the sensitivity cases, Figure 6 illustrates again that endogenous growth has the largest impacts for the labor and dissipating productivity channels. An already slow dissipation is further reduced due to compounding of the damage through an extra feedback loop. A fixed savings rate has, relatively, the strongest effect for the capital channel. These different persistence characteristics influence strongly how the system reacts on recurring shocks, as we discuss in the following section.

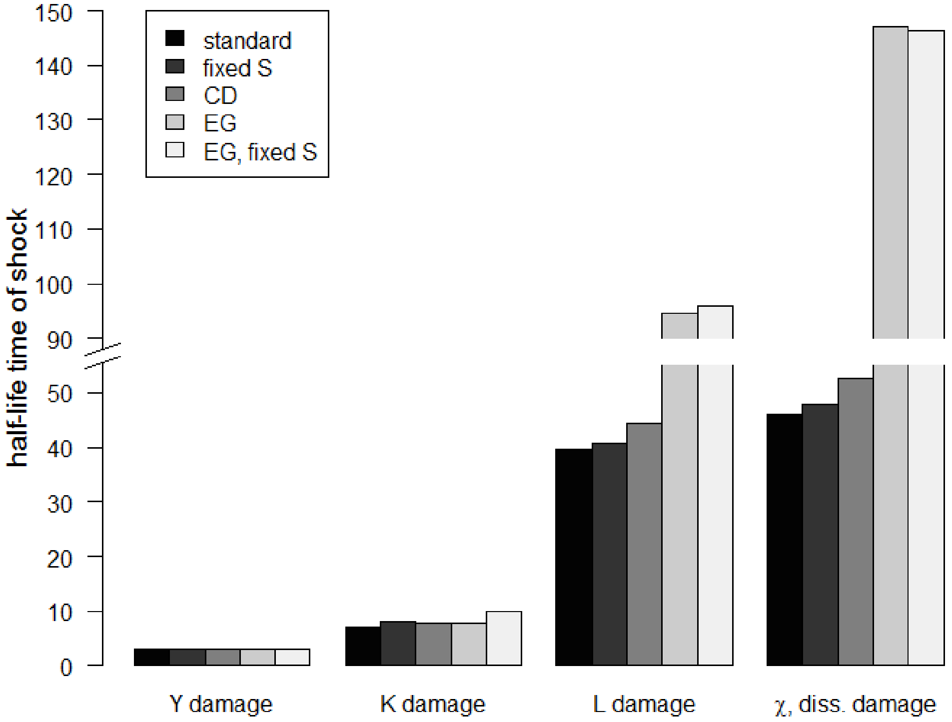

**Figure 6:** *Half-life time of the shock as a measure of how quickly it dissipates, for the different impact channels and sensitivity cases.*

### *3.3 The effects of recurring cumulative shocks*

Many climate change impacts do not occur as one-time shocks but either as recurring shocks or as slowly increasing changes over time with increasing temperature. This can be expressed through a damage function, applying increasing shocks over time. We use the standard DICE damage function expressed as $\Omega_t = \zeta T_t^2$. In order to retain some level of comparability between the channels we recalibrate the damage function to yield the same GDP effect at a warming level of 2.5°[7]. This is chosen as it is the calibration point for most damage functions in the literature (Arent et al. 2014, Figure 10.1) and the DICE damage function relies on such a literature survey (Tol 2009). The resulting values for the damage parameter are $\zeta^{Y}=0.00267$ (as in DICE2013R), $\zeta^{K}=0.00895$ and $\zeta^{L,\chi}=0.003715$. All damages are now fully anticipated and endogenous[8]. In the following we discuss the effects in the standard setup (exogenous growth, endogenous savings rate, elasticity of substitution 0.5), for details of the model variations see the Appendix (Figures S6-S8).

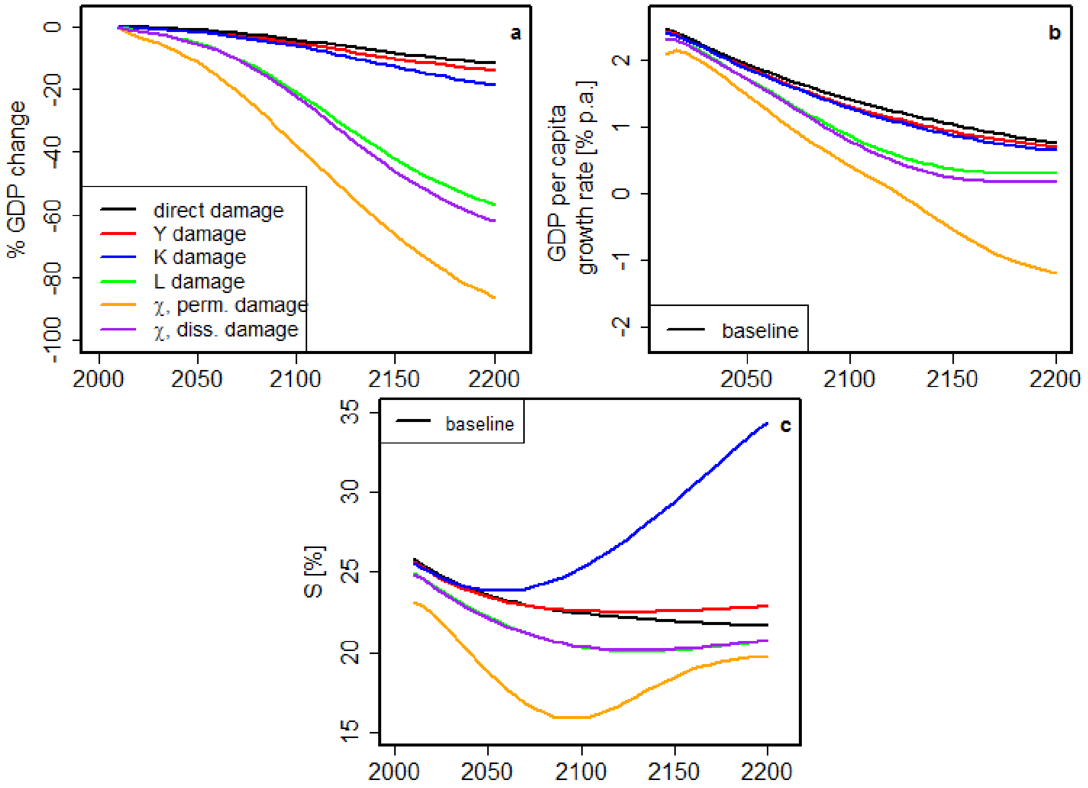

**Figure 7:** *GDP loss (panel a), GDP per capita growth rate (panel b) and savings rate (panel c) in the standard setup with recurring cumulative shocks for the different*

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[7] Note that the quantitative comparison of impact channels is inherently problematic because different concepts of damage functions have to be calibrated consistently with a clear and operational definition based on the same point. The calibration definition applied here applies a static criterion to replicate a GDP loss at a certain temperature increase. However, the different impact channels lead to vastly different transient results on GDP as temperature increases over time. Alternatively, a definition considering the transient effects could be formulated, but there are no estimates available consistent with such a transient definition. Therefore, future research on climate impact and macroeconomic damages needs to consider the transient features rather than static damages that relate significant temperature increases to significant GDP losses without considering cumulative effects over time.

[8] Thus, the model framework is essentially that of the DICE model with modified production functions and damages with varying biases and persistence. Contrary to the climate DSGE models cited in the introduction, we abstract from uncertainty in damages.

*damage channels (colors).*

As the system experiences recurring shocks at every time step in this setup, there is no recovery as was the case for a one-time temporary shock. Rather damages cumulate steadily (Figure 7). The different degrees of persistence for the various impact channels drive the amount of damage, leading to largest effects for the labor and productivity channels (Figure 8). The very large damages in the productivity channel with permanent damage stem from the accumulation of shifting productivity to lower levels (as seen for a one-time temporary shock), which eventually results in declining productivity, accompanied by negative GDP per capita growth rates after 2125 (right panel). For the other channels in 2100 we see a reduction in growth rate between 7 and 44%. Note that these numbers do not represent actual damages to be expected under climate change. The damage function we apply here is an aggregate function over multiple impact sectors, for the individual impact channels we would in principle need a channel-specific damage function, which are not available. In the study by Dietz & Stern (2015), only a fraction of the damage is applied on capital or TFP, it is however pointed out that there is no actual literature basis for selecting this fraction. In our case, with the goal of a comparison between the channels, we do not strive to obtain realistic cost estimates but rather highlight the comparative differences between the channels.

Due to the endogeneity of the damage there is an interplay between the adaptation option of increasing investments and higher damages caused by higher emissions, in particular in the long term due to locked-in temperature increases. For the channels with lower persistence (Y and K) this results in increases in the savings rate compared to the baseline case, while for labor and productivity damages savings rates are lowered (though increased again later on). Note that capital, being driven completely endogenously, has the highest adjustment flexibility of all channels, demonstrated by the large increase in savings.

The comparative behavior of the channels and the overall dynamics are not sensitive to the choice of model discount rate. This was tested using a lower discount rate in line with the "Stern review of The Economics of Climate Change" (Stern 2007), with a variation of DICE as discussed by Nordhaus (2014), setting the initial rate of social time preference per year to 0.1% and the elasticity of marginal utility of consumption to 1.01, lowering the discount rate from 3.6 to 1.5% in 2100. As expected, the lower discount rate enhances the adaptive dynamics with a lowered savings rate initially which is increased later on, therefore triggering stronger initial GDP losses in exchange of lower long-run damages (Figure S8).

Linking the analysis of one-time temporary shocks to the cumulative effect of recurring shocks, we look at the total loss in expected future welfare due to the recurring shocks. As a measure we use the relative change in balanced growth equivalent (BGE), introduced by the Stern Review (Mirrlees and Stern 1972; Stern 2007). The BGE replaces a consumption path starting at a given initial level of consumption with one growing at a constant growth rate but yielding the same utility as the original path. The relative change in BGE between the baseline and the various damage cases therefore measures, independent of the assumed constant growth rate, the fraction of consumption to be paid to switch from the scenario with lower BGE to that with higher BGE (Anthoff and Tol 2009; Lorenz et al. 2012).

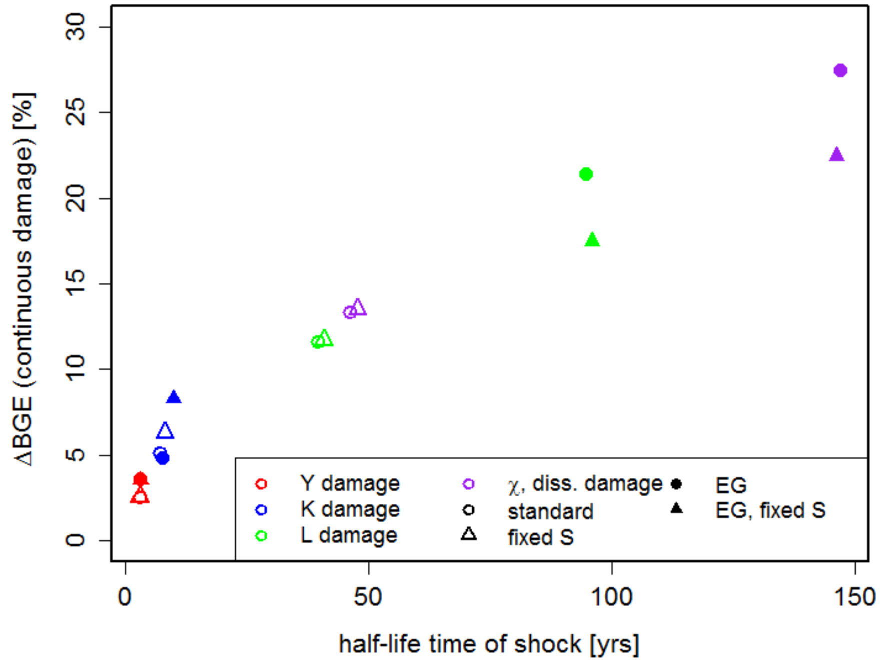

**Figure 8:** *Correlation between the half-life time of a one-time temporary shock with the absolute relative change in balanced growth equivalent (BGE) for recurring cumulative shocks. The case of the permanent productivity damage is left out since that channel has a permanent level effect by definition (infinite persistence time).*

Figure 8 shows that the persistence of the indirect effects of one-time temporary shocks, measured as the half-life time, is a main driver for the change in BGE in the corresponding scenarios with recurring shocks and accumulating effects. The link weakens a bit for the scenarios with endogenous growth and shocks in the labor and productivity channels, though the increase is consistent.

Figure 9 summarizes the results for the model variations and sensitivity experiments in the case of recurring cumulative shocks showing the change in BGE, as well as the corresponding average GDP per capita growth rate (2010-2200) compared to the baseline growth rate (for more details see Figures S6-S8). For the permanent productivity damage the damages have the highest impact by far, as expected. In general the dynamic differences between the impact channels in the different cases agree with the results seen for one-time temporary shocks. Endogenous growth results in higher damages in particular in the labor and productivity channels due to the negative effect the decreased savings rate has also on productivity growth. For the capital channel with its increased savings rate however, endogenous growth results in a reduction of the damage. In turn, a fixed savings rate in the case of endogenous growth increases damage in the capital channel but decreases it for the other channels, as it prevents the adaptive dynamics. The effects on the average long-term growth rate mirror the strength of the damage. For the capital channel with endogenous growth the combined effect of the increased savings rate on GDP and productivity results in a higher growth rate than in the case with exogenous growth.

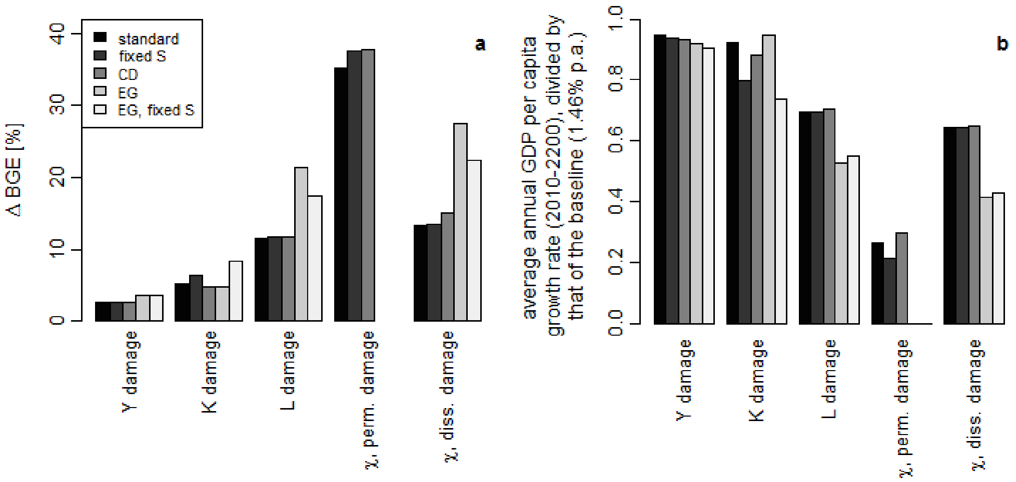

**Figure 9:** *Panel a shows the change in BGE for the standard runs with exogenous growth and endogenous savings rate and the model variations (fixed savings rate, a Cobb-Douglas production function (CD), endogenous growth (EG) and endogenous growth with a fixed savings rate (EG, fixed S)). Panel b shows the corresponding GDP per capita growth rate effect, using the mean annual growth rate 2010-2200 compared to the baseline growth rate.*

### *3.4 Optimal climate policy in the presence of factor-specific damages*

Ultimately, the key question is how optimal climate policy will look like under different types of damages. We investigate this using the standard DICE abatement scheme based on a highly convex reduced-form cost function given by $\Lambda(t) = \Theta_1(t)\mu(t)^{\Theta_2}$ where $\mu$ is the emissions reduction rate. A backstop technology replaces all fossil fuels once a certain carbon price is reached (344$ per ton $CO_2$ in 2010 in standard DICE). Results are shown in Figure 10. As expected and in good agreement with the literature (Dietz and Stern 2015; Moore and Diaz 2015), higher damages lead to stronger mitigation. In particular our case with permanent productivity damage is very well comparable to the growth damage discussed by Moore and Diaz. While emissions keep rising until 2055 for the output channel and until 2045 for the capital channel, they are reduced immediately for the labor and productivity channels, leading to peak warming of 2° in the former and 1.62° in the latter case. Emissions are eliminated by 2125 for the output channel (carbon price in 2015 is 63.7 US$/tC), but already by 2040 in the case of permanent productivity damage (with a 2015 carbon price of 523.2 US$/tC). The increasing social costs of carbon over the channels are due to the increasing damages but also related to the lower endogenous discount rate stemming from slower economic growth. Note that, while the strong mitigation reduces damages tremendously, the remaining damages in the labor and productivity channels are still quite high (a GDP loss of around 10% in 2100) and in the permanent productivity channel GDP keeps decreasing due to the growth effect. Endogenous growth does not influence the optimal policy results very much.

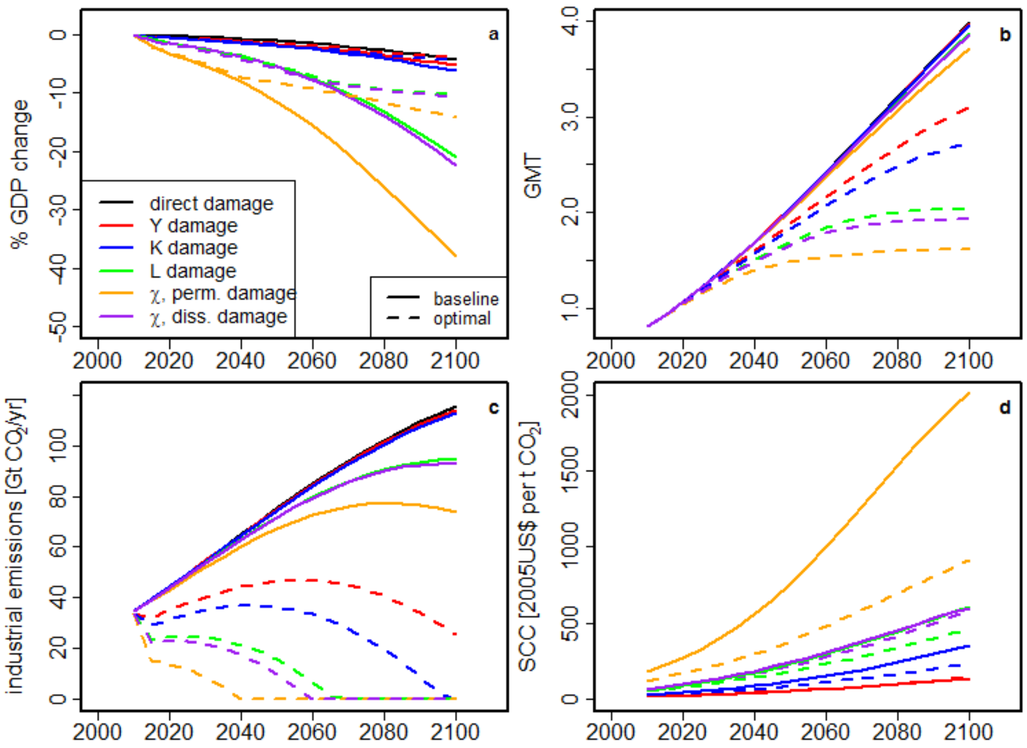

**Figure 10:** *GDP change (panel a), global mean temperature change (panel b), industrial emissions (panel c) and social cost of carbon (panel d), comparing baseline and optimal policy case (solid vs. dashed lines) for the different damage channels (colors) in the standard case (endogenous savings, exogenous growth, endogenous damage function).*

## 4. Discussion

Our results agree well with existing analyses using DICE-based models that have focused on specific and partial aspects of our analysis. While the use of a CES production function is important for our analysis of damages on production factors and increases model realism as discussed in section 2.3, the different elasticity of substitution only affects the magnitude of the effects, not the results on persistence or on the respective channel effects, as shown in section 3.2.3 and Figure S6, therefore allowing a comparison to other work. The strong effect of productivity damage including possible growth effects are in line with the results by Moyer et al. (2014), who study the effect of an increasing fraction of the damage being applied to TFP. When comparing damages on productivity to capital stock damages we agree with Dietz and Stern (2015) in finding a stronger effect for the productivity channel, although in their case there is no direct comparability between the channels as they use different endogenous growth specifications and different fractions of damage are applied in the channel. Our optimal policy results under permanent productivity damage agree very well with the results by Moore and Diaz (2015) as in both cases there is a growth effect. Our results regarding the compounding effect when including endogenous growth are in good agreement with Fankhauser and Tol (2005).

In the following we will focus on a few applications and extensions of the results. The first relates to distributional consequences of damages. The second is a suggestion on how to link to empirical results by "fingerprinting" impact channels. Finally, we discuss an agenda for the actual quantification of channel-specific impacts.

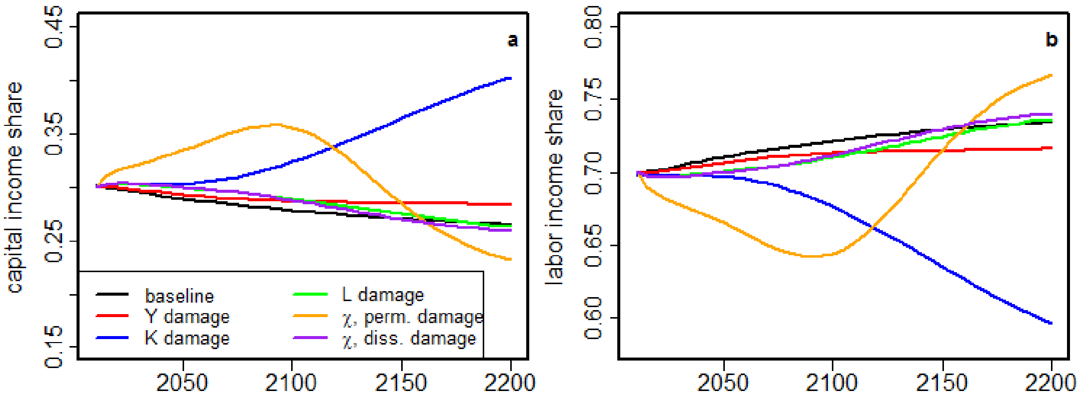

**Figure 11:** *Capital (panel a) and labor (panel b) income shares for the different damage channels.*

In a CES setting, the income shares are not fixed but depend on the development of the production factors. We can therefore study the effect of factor damages on the income shares (Figure 11). This allows a first indication of distributional effects within economies when individuals differ with respect to the ownership of production factors. There is a distinction in behavior for the capital and output channels on the one hand and labor and labor productivity on the other hand. For damages on income and capital, the capital income share increases steadily over time, quite substantially in the latter case. When labor or labor productivity is affected, the income share of capital increases at first but peaks and declines later. While this change is relatively small for loss of labor as well as dissipating productivity damage, it is quite pronounced for permanent productivity damage. Such a redistribution could result in further indirect economic implications for example via possible institutional consequences.

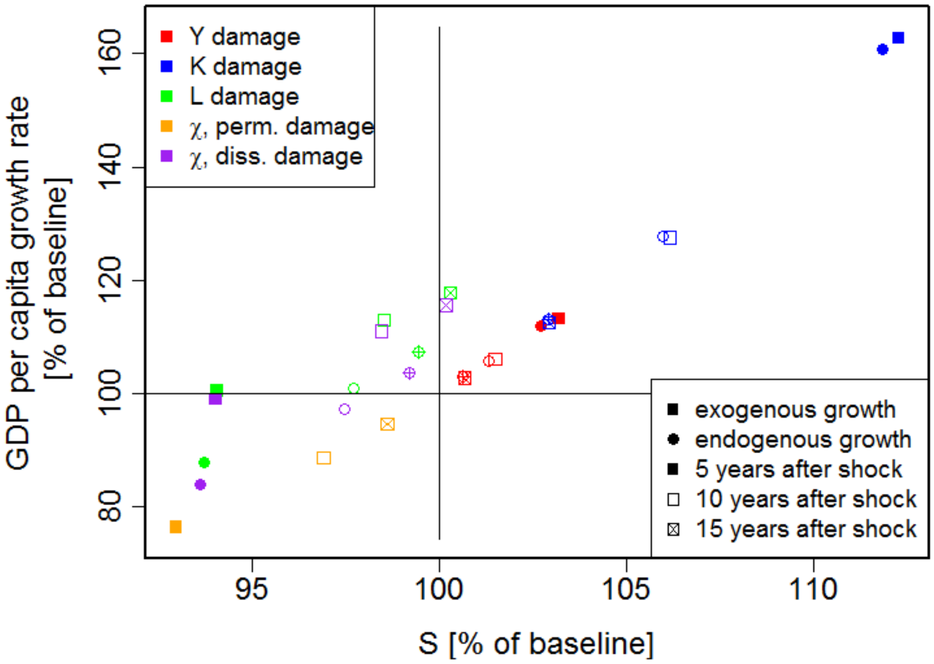

**Figure 12:** *Typology of the macroeconomic system dynamics in terms of savings rate and per capita GDP growth rate 5, 10 and 15 years after the shock (symbols) in the different impact channels (colors), expressed as % of the baseline values.*

As already discussed in the introduction, there is extensive empirical research on climate impacts, attempting also to identify impact channels. However, by design these studies more often focus on the macroscopic link between climate and output (Dell et al. 2014). Our results on the dynamic differences between the impact channels could be used for identifying measurable fingerprints of impact channels. A typology of fingerprints as attempted in Figure 12 might allow, with the help of measuring an additional variable like the savings rate, to infer the channel from the location of the measurement in the space of savings rate and after-shock growth rate in empirical studies. Capital and output impacts are located in the upper right quadrant (increased savings rate and growth rate after the shock). Labor and productivity damages with exogenous growth are initially located in the upper left quadrant (smaller savings but increased growth rate), and then move to the upper right quadrant 15 years after the shock. With endogenous growth, labor and productivity impacts start out with both lower savings and lower growth rate (lower left quadrant), moving towards the upper right, but the permanent productivity impact channel remains in the lower left quadrant. As time passes, all impact channels cluster back towards the origin, as was also shown in the detailed discussion of the after-shock dynamics in Section 3.

Finally, this work provides the basis for linking the macro-economic modeling of impacts to both the empirical and the impact modeling communities, as a logical next step is the quantification of actual channel-specific impacts based on empirical relations or results from impact models. While this is already done by some CGE models (see e.g. Ciscar et al. 2011; Roson and van der Mensbrugghe 2012; Bosello et al. 2013), those types of models lack the intertemporal investment dynamics included in a growth model. This raises a number of channel-specific questions. Does a specific impact have a pure flow effect or long-term indirect implications? What types of adaptation are associated with it? How can high-resolution results from empirics/impact models be aggregated to the coarser levels of an economic model? How do impacts in different channels interact? Where possible, a validation of the response of the economic model to a given impact should be undertaken and extensions of the models are likely necessary (e.g. by production factors or even multiple sectors). This type of application requires close interaction of the different scientific communities and essentially a targeted research agenda towards a better representation of impacts in macro-economic models.

The most interesting channel for further work is the labor productivity channel. The high persistence of impacts in this channel suggests a great multiplying effect of observable impacts that work through the macroeconomic system. Empirical studies find increasing evidence for impacts of climate on labor productivity and human capital[9]. Examples for the former are lowered work intensity or reduced cognitive performance resulting from heat stress, reduced working hours in temperature-sensitive sectors like construction or agriculture, manufacturing impacts or early life impacts reducing productivity in later life. Examples for human capital impacts include impacts on human morbidity and mortality as well as migration. Studies linking climate with aggregated output effects indicate that labor effects are an important channel (Hsiang 2010; Dell et al. 2012; Deryugina and Hsiang 2014; Burke et al. 2015). This could be because even if effects on individuals are modest, the number of affected individuals is potentially high, leading to substantial aggregate impacts. Furthermore, there are related losses downstream in the production chain. However, there are a number of adaptation options as well, e.g. through reallocation of labor (Colmer 2018), investment in human capital and innovation. The interaction of impacts and adaptation and the resulting persistence of labor productivity impacts is a very interesting subject for further research as our results comparing the different channels are very sensitive to this.

## 5. Summary and conclusions

In this paper we conduct the first comprehensive analysis of factor-specific impact channels in a comparative and calibrated numerical neoclassical Ramsey-type growth framework. A key aspect of our analysis is the persistence of indirect shock effects. Contrary to the RBC literature, we do not have a persistence parameter, but instead specifically differentiate the different impact channels. While a standard one-time temporary impact on output has limited indirect long-term dynamic effects, damages acting directly on production factors allow us to study the dynamic effects triggered through the accumulation process of those factors. As increasingly detailed

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[9] See Carleton and Hsiang (2016) for an extensive review of further references.

projections of biophysical climate impacts as well as empirical relationships between climate and economic factors become available, a better understanding of the macroeconomic dynamics of damages can help to improve the representation of empirically-founded damage estimates within structural economic models on a channel-specific level. From this work we draw five main insights on the impact dynamics while differentiating immediate impacts, transitionary growth impacts, long-run level effects, long-run growth effects and distributional effects on factor incomes.

First, using both analytical and numerical methods, we show that the long-term effects caused by a shock of the same magnitude (in terms of immediate GDP effect) but applied in the various channels differ strongly in their dissipation time and after-shock dynamics (such as changes in the savings rate and the after-shock growth rate). The numerical results agree well with the analytical predictions, though the analytical discussion had to remain limited. We find that the persistence, measured as half-life time, of the indirect effects caused by a one-time temporary shock is a key determinant of the cumulative damages incurred through recurring shocks, measured in terms of welfare effects through the change in BGE. Persistence also strongly affects the accompanying economic growth effects. Clearly, it is insufficient to define climate change impacts simply as output effects, as this misses important long-term dynamic and growth effects.

Second, in our modeling framework the shocks fall into two families – the output and capital shock with relatively small long-term impacts and the labor and labor productivity shocks where persistence of the indirect effects is much higher. They also display different sensitivity to model variations. Endogenous growth exacerbates mainly the impacts for labor and productivity, while in particular the capital channel is highly sensitive to the endogeneity of the savings rate. While an endogenous savings rate reduces damages somewhat, this is insufficient to have a significant effect, in particular on the differences between the channels. The other sensitivities we tested (elasticity of substitution, capital adjustment cost, strength of damages) are of less or no importance.

Third, intertemporal investment dynamics prove to be important to establish the differences between the impact channels. In particular in the case of recurring cumulative shocks, the combination of endogenous damage and endogenous savings causes initial investment decreases in particular for the high-persistence channels (L, χ) due to the anticipation of the high long-term damage. On the other hand in the capital channel the long-term savings rate is strongly increased to compensate for damages. However, even though both macroeconomic adaptation mechanisms (endogenous savings rate and anticipation of impacts) work to attenuate damages, long-term damages are not fully compensated for, in particular in the case of recurring shocks with stronger persistence.

Fourth, higher damages in combination with slower economic growth lead to increasing social costs of carbon and more stringent mitigation. Global mean temperature increase stays below 2° for the labor and productivity channels. Nevertheless, in these channels significant damages remain despite the strong abatement effort.

Finally we discuss two applications of this work. First, it allows, through its use of a CES production function, to study the effect of the damages on the income shares of the production factors and therefore of distributional implications of the damages. While damages initially increase the income share of capital in all channels, it decreases again in the long run for the labor and productivity channel. Redistribution is significant for damage in the capital and the permanent productivity channel. Second, we propose a typology of fingerprints of impact channels along the dimensions of savings rate and GDP per capita growth rate, as a possible way to access results of empirical studies, mostly relating climate factors with GDP, for use in macroeconomic modeling. Bridging the current gap between the two research fields is a key requirement to improve our understanding of how climate change impacts progress from the physical to the economic and societal level – a necessity for meaningful projections of future damages.

There are multiple avenues of future research building on this work. An important open research question is on the level and effectiveness of adaptation. On the empirical side, an open question is how much adaptation is realistically expected, based on historic data (see e.g. Burke et al. 2015; Burke et al. 2016). On the modeling side, there is a lack of understanding of the dynamics of macroeconomic adaptation mechanisms. In this work we have focused on the endogenous savings rate coupled to the anticipation of future damages, but there are many more mechanisms. The endogenous growth formulation could be improved to reflect its adaptation potential through targeted investment into productivity growth, which probably would have a strong influence on the dynamics of the impact channels in that setting. Other endogenous growth formulations, e.g. with human capital or specific R&D investments, might also open other adaptation channels. Another mechanism is structural change, i.e. the use of a multi-sectoral growth model (Desmet and Rossi-Hansberg 2015; Kalkuhl and Edenhofer 2016). Adaptation can also happen through links between regions, i.e. through trade, migration or international financial flows. This would require a model with regional detail capturing those mechanisms. Of particular interest regarding all of those adaptation mechanisms is that they are not necessarily positive, but could also increase damages through maladaptation or simply the propagation of damages e.g. along supply chains.

Another direction for future work is the introduction of additional production factors. Two would be of particular interest – human capital and land. Human capital could constitute one of the most important channels for long-term growth effects. Examples include stunting in children or extended education gaps after natural disasters (e.g. Horton and Steckel 2013). Land, a non-reproducible production factor, is highly relevant for distributional effects of impacts, as it is very vulnerable to climate change (Rosenzweig et al. 2014). At the same time, there are recent claims that increasing land rents are at least partially responsible for trends in the wealth-income ratio, returns to capital and rising inequality (Stiglitz 2015), making this a channel of potentially large economic and distributional consequences resulting from climate change.

Investigating potential effects of climate change on long-term economic growth is a crucial gap in damage assessments. It is highly relevant for policy makers with a focus on setting mitigation targets and looking for reliable estimates of the social cost of carbon. Furthermore, it is crucial for better assessing the adaptation gap and in general the overall economic costs of climate change in particular in developing countries. Closing it requires conceptual studies on the dynamics of economic growth under climate change impacts, such as the one presented here, in conjunction with new efforts to improve the quantification of impacts. This analysis aims to advance a joint research effort in this direction.

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