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Climate Change Expectations and Endogenous Economic Growth in the DICE Model

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Climate Change Expectations and Endogenous Economic Growth in the DICE Model

Abstract

This paper studies the investment based growth rate effects of climate change. The analysis is based on the Integrated Assessment Model DICE by Nordhaus (2008). I depart from the original model, in that endogenous investments into a knowledge stock drive economic growth. Due to a negative capital accumulation as well as savings effect on the knowledge stock, climate change has a negative impact on gross income that lasts into the long run. In order to be able to quantify the growth rate effects, I calibrate the endogenous growth model version of DICE towards its exogenous growth counterpart. I find that in the exogenous growth model version of DICE, compared to its endogenous growth equivalent, in the social optimum, gross income is over-estimated by 2.3 % in 2100 and by 6.8 % in 2150.

JEL-Codes: O440, Q540.

Keywords: endogenous economic growth and climate change.

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1. Introduction

Climate change is a dynamic problem. Moreover, it is a growing empirical certainty that climate change has long-term, negative growth rate effects. An atmospheric temperature increase, for instance, affects agricultural output through droughts and water shortages instantaneously. More importantly, however, it's dynamic consequences reach far into the future. First, this is through direct impact channels onto the drivers of economic growth. For instance, a temperature increase reduces the productivity of the labor force. And second, this is through an investment based channel. Climate change reduces the rate of returns on investment and, thus, the accumulation of productive assets.

In this paper, I focus on the feedback of climate change expectations on economic growth and I separate a dedicated research and development channel from a mere capital investment channel. In particular, I elicit the size of the effects that climate change has on the investment into research and development, the accumulation of knowledge stocks and consequently the growth rate of the economy. The analysis is based on the endogenization of economic growth in an integrated assessment modelling framework. I quantitatively compare exogenous and endogenous growth model versions of the original DICE model by Nordhaus (2008). To the best of my knowledge, this research and development channel through which climate change affects economic growth has not been analyzed explicitly in the literature before. My results show that in the exogenous growth model version of DICE, compared to the endogenous growth model version, in the social optimum, gross income in 2100 is over-estimated by 2.3% and in 2150 by 6.8%.

There are two main dynamic effects that connect climate change to economic growth in an economy where the productivity term grows at an exogenously given rate. First, this is a capital accumulation effect: when income is reduced, there are fewer resources available for investments into the capital stock. And second, this is a savings effect: in a world with perfect foresight, households adjust their inter-temporal savings plan to the occurrence of damages caused by climate change. A priori it is not clear whether the savings effect is a positive or a negative effect. On the one hand, households have an incentive to smooth their

consumption over time and may save more to make up for future expected losses. On the other hand, the return on capital investments decreases, such that the incentive to invest is lowered. In a reduced model of climate change and Ramsey type growth, Fankhauser and Tol (2005) show analytically that under a relatively broad set of assumptions both, the capital accumulation effect and the savings effect, are unambiguously negative.

This paper goes beyond Fankhauser and Tol (2005) by introducing endogenous investments into the knowledge stock. These investments are separable from investments into the physical capital stock and are the driver of economic growth. In this way, climate change is modeled to have distinct effects on both stocks and the accumulation and savings effect have an impact on both stock variables independently from each other. Implicitly, the social planner decides by how much he needs to reduce carbon emitting investments into capital and knowledge stocks in order to mitigate climate change. As a consequence, the economy grows at a lower rate.

From a modelling point of view, it would be desirable to differentiate between green and dirty technologies and to include directed technical change a la Acemoglu et al. (2012) into the analysis. In the original DICE model, the only other option that the social planner has to mitigate climate change, apart from a mitigation instrument, is to reduce investments into dirty growth. What we would ideally strive for, however, is a transition from dirty to green technologies, which allows for unbounded growth. Nevertheless, even if the model included a green technology, especially in early time periods, the investment based impact channel on the dirty knowledge stock would remain. Only over time, as the economy transitions towards a green technology path, would these negative investment based growth effects cease.

I calibrate the endogenous growth component towards its exogenous growth counterpart such that gross output in both models is a near perfect match. The value of this exercise lies in the comparability between exogenous and endogenous growth mechanisms and how they are affected by the climate externality. I solve three scenarios as have previously been described by Rezai (2011), each with an exogenous as well as an endogenous growth component. The social optimum scenario is identical to the original by Nordhaus. In this

scenario, the social planner is able to mitigate climate change in two ways. First, he can invest in the reduction of carbon emissions and, second, he can shift his spending away from the carbon-emitting capital and possibly knowledge stock. The latter is coherent with the savings effect. In the constrained optimum scenario, the social planner cannot actively mitigate to reduce climate damages. Therefore, even more investments are shifted away from carbon emitting capital and knowledge stocks and, consequently, the economy grows at an even lower rate than in the social optimum scenario. The constrained optimum scenario is equivalent to the "business as usual scenario" by Nordhaus. Yet, as in this scenario the climate externality is fully internalized, Rezai argues that it does not correspond to a business as usual scenario. Therefore, he suggests a new business as usual scenario, where the climate externality is not internalized and the private return on investment is not affected by climate change. In this scenario, I find positive growth effects due to an over-investment into both stock variables.

2. Literature review

There is a growing empirical literature which analyses the effects that climate change has on economic growth. Dell, Jones, and Olken (2012) assess historical panel data on within-country temperature fluctuations and find that temperature shocks overall have a lasting impact on income per capita and economic growth, but especially so in developing countries. In a meta analysis Dell, Jones, and Olken (2014) substantiate this result by analyzing potential drivers of this negative growth effect, such as agricultural output, labor productivity and mortality rates. In a similar context, Hsiang and Jina (2014) find empirically valid evidence that windstorms exert negative growth rather than level effects on income. Burke, Hsiang, and Miguel (2015) find a global non-linear effect of temperature on productivity levels. Their findings suggest that country-level production is concave in temperature and that it peaks at an average annual temperature of 13°C . Further, the authors estimate a distributed lag model and find that only temperatures at the hot end of the temperature distribution suggest negative growth effects. Looking at the whole tem-

perature distribution, this study does reject neither level nor growth effects of temperature on GDP.

Given these empirical findings, the question arises, how these foremost negative impacts of climate change on economic growth can best be implemented into the integrated assessment modelling framework. For instance, in the original DICE model the damage multiplier on the level of gross output is the only mechanism through which climate change has an effect on growth. This effect operates indirectly through a reduction of investments into the capital stock. This is a rather narrow story on how climate change affects economic growth.

Using the DICE model, Dietz and Stern (2015), Moyer et al. (2014) and Moore and Diaz (2015) construct different versions of the original model, where climate damages have a direct and negative impact on capital stocks or productivity levels. Unsurprisingly, they find a much higher social cost of carbon and a stronger negative impact on economic growth than the original DICE model does. The magnitude of the effects is strongly dependent on the underlying model assumptions. Furthermore, Fankhauser and Tol (2005) and Dietz and Stern (2015) suggest to introduce endogenous growth to the DICE model. In these model versions, either overall investments are equally divided between physical capital and knowledge stocks or the size of the knowledge stock is tied to the size of the physical capital stock, such that investments into the latter also increase the size of the former. In this way, the savings and the accumulation effect regarding physical capital and knowledge stocks are inseparably connected to each other. There are no standalone and endogenous investments into research and development, as I suggest in this paper. Again, these model versions yield higher negative impacts of climate change on economic growth, while their quantitative size is strongly dependent on the underlying model assumptions. Interestingly, Dietz and Stern find that the importance of their growth assumption diminishes, when climate damages are assumed to be more severe.

To the best of my knowledge, endogenous investments into a knowledge stock or productivity levels, which drive economic growth, has not been addressed in the context of other Integrated Assessment Models (IAMs) before. There are at least three IAMs, which entail endogenous technological change. However, in these models economic growth is driven by an exogenously given time series of total factor productivity. These models are the ENTICE model by Popp (2004), which is a modified version of the DICE model, the WITCH model by Bosetti, Massetti, and Tavoni (2007) and the DEMETER model by Gerlagh and Zwaan (2003) and Gerlagh, Zwaan, et al. (2004). The economies of these models include two or more competing energy technologies. In the spirit of directed technical change, investments into the efficiency of these energy technologies is endogenous.

3. Scenarios of the DICE model

The DICE model is a widely used IAM. It is based on a Ramsey type economy. Economic activity causes carbon emissions, which, through climate forcing, increase the global surface temperature and the temperature of the water systems. Damages due to global warming are modeled as a fraction of economic output, which is lost to household income. In all scenarios, the social planner and households have perfect foresight.

In the *social optimum scenario* the social planner is able to mitigate climate change in two ways. First, he can invest in the reduction of carbon emissions and second, he can shift his spending away from the carbon-emitting capital stock. I rename the original base scenario by Nordhaus and call it the *constrained optimum scenario* (following Rezai (2011)). This scenario solves for the social optimum, where direct investments into the mitigation of carbon emissions are not possible. Nevertheless, the externality is fully internalized. The only way for the social planner to mitigate climate change in this scenario, is to reduce investments into the capital stock. The third scenario is the *business as usual scenario*. This scenario has a decentralized solution. The climate externality is not internalized, because each household perceives his own contribution to the overall reduction of carbon

emissions as marginal. The private return on investment exceeds the social return on investment. When introducing endogenous growth to the DICE model, growth is no longer driven by an exogenously given parameter of technological advancements, but it is driven by the endogenous decision of the economy's agents to invest in their own productivity. Agents divide their income between consumption and savings, which are sub-divided into investments into the physical capital stock and investments into research and development. Future output is increased by higher investments in general, be it into the physical capital stock or into the knowledge stock. As a consequence, in the optimal and in the constrained optimal scenario, the savings and the capital accumulation effects are even stronger in the endogenous growth setting and, thus, negative growth effects caused by climate change become larger. In the business as usual scenario with endogenous growth, households overinvest into the knowledge stock and, therefore, have to endure more damages from climate change. Eventually, the damages become so big that they overcompensate any positive effect that a higher knowledge stock has on income.

3.1. The original DICE model

Social planner problem I use the latest version of DICE, which is the DICE2016R model. The code of the original model can be downloaded from the web page by Nordhaus (2016). The model is solved in discrete time and for sixty time intervals of five years. The first time period starts in 2015. The social planner problem is a fully centralized problem where the climate externality is fully internalized. At the heart of the model is a neo-classical growth model. The social planner maximizes the discounted sum of utilities from consumption:

$$\max \sum_{t=0}^T \left\{ \frac{1}{(1 + \rho)^{T_{\Delta}t}} T_{\Delta} L_t U(c_t) \right\} \quad (1)$$

Time intervals are denoted by t . T_{Δ} represents the length and T the absolute number of time intervals. The social discount rate ρ equals 1.5 %. Population size, L , grows over time at an exogenously given rate (see the appendix for more detail). Consumption, c_t , is

expressed in per capita terms.

Per-period utility, U , carries the form of constant relative risk aversion (CRRA). The inter-temporal elasticity of substitution, ϵ , is 1.45.

$$U(c_t) = \frac{c_t^{1-\epsilon} - 1}{1-\epsilon} - 1 \quad (2)$$

The production function is Cobb-Douglas with labour-augmenting productivity, A . In this paper, I use the words productivity level and knowledge stock interchangeably and I assume that both have a relation of one to one. The production value, Y , equals gross income. The output elasticity of capital, K , is denoted by α and equals 0.3.

$$Y_t = (A_t L_t)^{1-\alpha} K_t^\alpha \quad (3)$$

The capital stock is raised by investments and is lowered by depreciation at a rate, δ , of 10 %.

$$K_{t+1} = I_t T_\Delta + (1 - \delta)^{T_\Delta} K_t \quad (4)$$

A certain fraction of gross income is lost to damages, Ω , which are convex in the atmospheric temperature, $TATM$. A further fraction is lost to the cost of abatement, Λ , which increases exponentially in the emission control rate, MIU . Investments, I , thus, equal the difference between net income and consumption.

$$I_t = Y_t (1 - \Omega(TATM_t) - \Lambda(MIU_t)) - C_t \quad (5)$$

$$\Lambda_t = \varphi_t MIU_t^{2.6} \quad (6)$$

$$\Omega_t = 0.00236 TATM_t^2 \quad (7)$$

Nordhaus assumes that due to exogenous and costless technological advancements, the efficiency of abatement, φ_t , increases over time¹ until eventually the cost of abatement goes down to zero.

Carbon emissions, E , are the sum of industrial emissions, E_{Ind} , and exogenous emissions from deforestation, E_{Land} . Industrial emissions are a side product to production and they can be lowered in an endogenous effort by investing into the control rate MIU .

$$E_{Indt} = \sigma_t Y_t (1 - MIU_t) \quad (8)$$

σ_t denotes the emissions output ratio².

$$E_t = E_{Indt} + E_{Landt} \quad (9)$$

The carbon cycle consists of three reservoirs, whose transition is interdependent. Carbon emissions first flow into the lower atmosphere and from there they are passed on to the lower and deeper oceans. In equation (10) MAT stands for the carbon concentration in the lower atmosphere, MU represents the concentration in the upper and ML in the lower oceans.

$$\begin{pmatrix} MAT_{t+1} \\ MU_{t+1} \\ ML_{t+1} \end{pmatrix} = \begin{pmatrix} 0.2728 \\ 0 \\ 0 \end{pmatrix} E_t T_\Delta + \begin{pmatrix} 0.88 & 0.196 & 0 \\ 0.12 & 0.797 & 0.0015 \\ 0 & 0.007 & 0.9985 \end{pmatrix} \begin{pmatrix} MAT_t \\ MU_t \\ ML_t \end{pmatrix} \quad (10)$$

There is no limit to the accumulation of carbon in either of the reservoirs and there is no decay rate. Once carbon is added to the carbon cycle, it remains there.

Atmospheric carbon, which is above the equilibrium concentration of $MAT_{EQ} = 588GtC$, drives the temperature of the atmosphere through radiative forcing, $FORC$. Forcing due to other greenhouse gases, $FORC_{EXt}$, evolves exogenously³.

¹See the appendix for an exact representation of the efficiency of abatement term.

²See the appendix.

³See the appendix.

$$FORC_t = 3.6813 \frac{\log\left(\frac{MAT_t}{MAT_{EQ}}\right)}{\log(2)} + FORC_{EXt} \quad (11)$$

The climate system is modeled as a cycle as well, where energy is passed between the atmosphere, $TATM$, to the oceans, $TOCEAN$.

$$\begin{pmatrix} TATM_{t+1} \\ TOCEAN_{t+1} \end{pmatrix} = \begin{pmatrix} 0.1005 \\ 0 \end{pmatrix} FORC_t + \begin{pmatrix} 0.8718 & 0.0088 \\ 0.025 & 0.975 \end{pmatrix} \begin{pmatrix} TATM_t \\ TOCEAN_t \end{pmatrix} \quad (12)$$

Constrained optimal problem In this scenario, the social planner has perfect foresight and fully internalizes the climate externality. However, he has no instrument for direct climate change mitigation at hand. Thus, Nordhaus sets $MIU_t = 0$. Consequently, in this scenario the economy arrives at the social optimum under the constraint that direct investments into mitigation are not possible. The problem remains the same as the social planners problem with an additional constraint.

Business as usual problem In this scenario, households perceive their own contribution to the sum of all carbon emissions as marginal. Therefore, they have no incentive to mitigate, neither through direct investments into the reduction of carbon emissions, nor by avoiding the use of carbon-emitting capital. The private return on capital and R&D investments exceeds the social return and, as a consequence, the agent over-invests. Although industrial emissions are caused in the process of production, they are substituted by an exogenous emissions term:

$$E_t = E_{Landt} + E_{Exgt} \quad (13)$$

The computation of this scenario is carried out iteratively. The vector of initial carbon emissions over time is set to an arbitrary, but plausible, value. Using these values, climate damages are calculated accordingly and the growth model is solved. In the following round,

carbon emissions are adjusted to those values, which households would have emitted given their gross output from the first round. The model is solved sequentially and in rounds until the vector of exogenous carbon emissions has converged to the vector of industrial carbon emissions.

The economic intuition behind the business as usual scenario and its computational solution are a simplified version of the business as usual scenario suggested in Rezai (2011) and Shiell and Lyssenko (2008). These authors suggest to divide the economy into N dynasties, who are each endowed with equal capital stocks and labor. All dynasties are aware of the externality caused by their own emissions and, therefore, mitigate. However, since all foreign emissions are exogenous to each dynasty, the larger the number of dynasties is, the smaller is the amount of the externality which is internalized. From the perspective of each dynasty, as $N \rightarrow \infty$, the social marginal cost of carbon emissions within the own dynasty goes down to zero and, thus, households effectively do not mitigate.

Although the economic intuition behind the business as usual scenario by Rezai (2011) is very plausible, for simplicity, I choose to solve the scenario as described above, where the economy has one representative agent who takes carbon emissions as fully exogenous. Both economies evolve along the same path. Yet, the business as usual scenario by Rezai is computationally not as stable, as the one stated above. When dynasties become very small, in order for mitigation to converge to zero, their gross income and consumption become very small, too. Combined with the discounting of future values, at some point the savings rate becomes arbitrary.

3.2. Endogenous growth and the DICE model

In the endogenous growth scenario, labor augmenting productivity, A_t , is explained within the model. The social planner has the additional option to invest into R&D, which fosters the development of new skills and technologies. To introduce endogenous growth to the DICE model, two alterations are necessary. First, it has to be clarified how the cost of

investments into R&D is deducted from the budget and, second, one needs to define a functional form of how R&D investments translate into growth. I base those modifications on the Schumpeterian growth model. In this model economic growth is driven by vertical innovations. The likelihood of an innovation increases in R&D investments. However, R&D investments are costly and reduce the social planners budget for investments into the capital stock and for consumption. The explicit trade-off between the marginal cost and the marginal benefit of R&D investments in this study is new to the literature and it opens up an additional channel through which climate change affects economic growth. First, climate damages reduce the budget, which is available for re-investment versus consumption, and, second, they reduce the return on investments.

Social planner problem In this scenario the social planner internalizes the entire climate externality. He has two instruments at hand. He can mitigate climate change through direct emission control or by shifting resources away from carbon-emitting capital and knowledge stocks. The transition equation of the capital stock is identical to that in the original DICE model in equation (4). In the endogenous growth model version, however, household income is now split between consumption, investments into the capital stock and R&D expenditures R :

$$I_t = Y_t (1 - \Omega(TATM_t) - \Lambda(MIU_t)) - C_t - L_t R_t \quad (14)$$

$$A_{t+1} = \left(1 + \lambda \left(\frac{R_t}{A_t}\right)^\gamma\right)^{T_\Delta} A_t, \quad 0 < \gamma < 1, \quad 0 < \lambda \quad (15)$$

The growth rate of labor augmenting productivity A_t is driven by per capita R&D expenditures. R&D expenditures are normalized by population size because a growing population size implies that research expenditures have to be spread across more firms and products. This assumption implies that there are no economies of scale. In addition, research expenditures are normalized by the current productivity level A_t , because resource costs for new innovations rise the further technology advances. In the Schumpeterian

growth literature, this is referred to as the curse of complexity. The exponent γ causes decreasing returns to research with respect to R&D investments and λ is a re-scaling factor. From a technical point of view, together the parameter values λ and γ determine how R&D translates into productivity growth. Therefore, they are treated as free parameter values used to calibrate the endogenous growth component to the original growth component of the DICE model.

Constrained optimal problem This scenario is equivalent to the constrained optimal scenario with exogenous growth. The only difference is that investments into the knowledge stock are endogenous. Again, the social planner is capable of fully internalizing the externality. However, he is constrained and unable to mitigate, such that $MIU_t = 0$.

Business as usual problem This scenario is equivalent to the business as usual scenario with exogenous growth. However, the knowledge stock grows at an endogenously determined rate. Households anticipate their future climate damages, but do not acknowledge that these are caused by their own carbon emissions. Therefore, households take climate change as a given obstacle and not as an externality to production, which may be internalized.

4. Calibration

The original version of the DICE model has a Ramsey-type economy at its core and economic growth is driven by the growth rate of total factor productivity. This productivity term follows an exogenously given path and its growth rate declines over time. For this reason, the growth rate of GDP declines over time. After some years, gross income follows an approximately linearly ascending path, which is visualized in figure 1 (a). This is in contrast to the endogenous growth component suggested in this paper, which follows an exponential growth path with a constant rate of growth once the steady state is reached. For this reason, it is not possible to achieve a perfect fit between the endogenous growth

component and the original growth component of the DICE model. This is why I construct not only a new version of DICE with an endogenous growth component, but also one with a Ramsey model, which essentially is identical to the original version except for its path of total factor productivity growth. Total factor productivity growth in the new Ramsey model is calibrated such that it produces the same path of output as the endogenous growth model.

For the calibration, I divide the original DICE model as well as the new exogenous and endogenous growth model versions of DICE into their growth and climate components. Ignoring the climate component for now, I first calibrate the endogenous growth component to the original growth component by minimizing the sum of squared errors between both models' gross output. In this calibration, the free parameters are those which determine how investments into R&D translate into the propensity to innovate. In equation (15) these are γ , the constant which causes decreasing returns to R&D, and the scaling factor λ . The resulting growth trajectory is plotted in figure 1 (a). In a second step, I calibrate the new and exogenous growth component with exponential growth towards the endogenous growth component. Again, I do this by minimizing the sum of the squared residuals between gross income in both growth models. This time, however, I use the level of total factor productivity in each time period as the parameters of calibration, such that I am able to generate a near-perfect match between gross income in both models (apart from a numerical error plotted in figure 1 (b)). In this way, gross output of the recalibrated growth model versions is in the ballpark of the original growth model in DICE. Since gross output of the recalibrated model versions is almost identical, I will be able to compare the climate impacts of the endogenous growth setting to its exogenous growth counterpart in DICE. The climate component of the DICE model remains unchanged.

The transition between growth models I calibrate the exogenous growth model with exponential growth towards the endogenous growth model, such that gross income in both models is a near-perfect match. I use the path of total factor productivity, A_t , as free

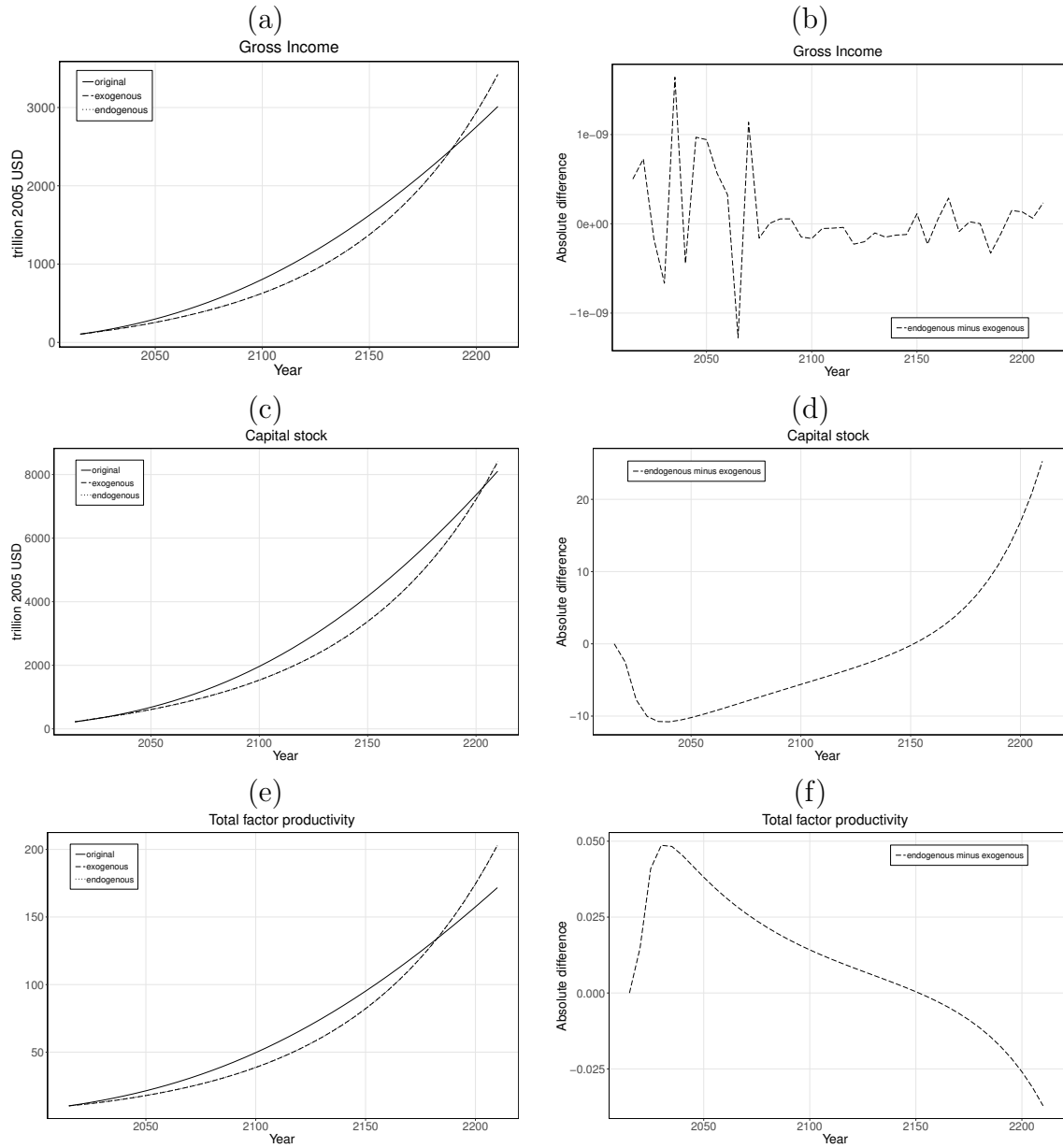


Figure 1: Left panels: Comparison of the original Ramsey model to an endogenous growth model and its new exogenous counterpart. The lines for the endogenous and the new exogenous growth model are on top of each other, since they are calibrated to one another. Right panels: Absolute differences between the endogenous growth model and its exogenous counterpart.

parameters of calibration. Population sizes remain unchanged. Looking at the production function in equation (3), it is clear that for every path of A_t there exists only one path for

the capital stock, K_t , which leads to a match of gross income, Y_t , in both models. Since the transition of K_t is uniquely determined by the social planner's optimization of social welfare over the savings rate, the adjustment of the exogenous to the endogenous growth model is a convex problem and there is only one combination of A_t and K_t which minimizes the difference in gross income between both models.

The reader should keep in mind that in the endogenous growth model, a certain share of household income is spend on R&D investments. In the exogenous growth model, households spend this same fraction of income on consumption or investments into the capital stock.

To better understand the transition from the endogenous to the exogenous growth model, think of the following thought experiment. What happens if I insert the same path of A_t from the endogenous growth model into the exogenous growth model? From the production function in equation (3) follows that in this case K_t would also have to be the same in both models in order to match gross income. But it wont be, because in this case all expenditures on R&D in the endogenous growth model would have to be added to consumption in the exogenous growth model. This, however, would change the marginal utility in consumption over time and, thus, the same path of K_t from the endogenous growth model is not necessarily welfare optimal in the exogenous growth model.

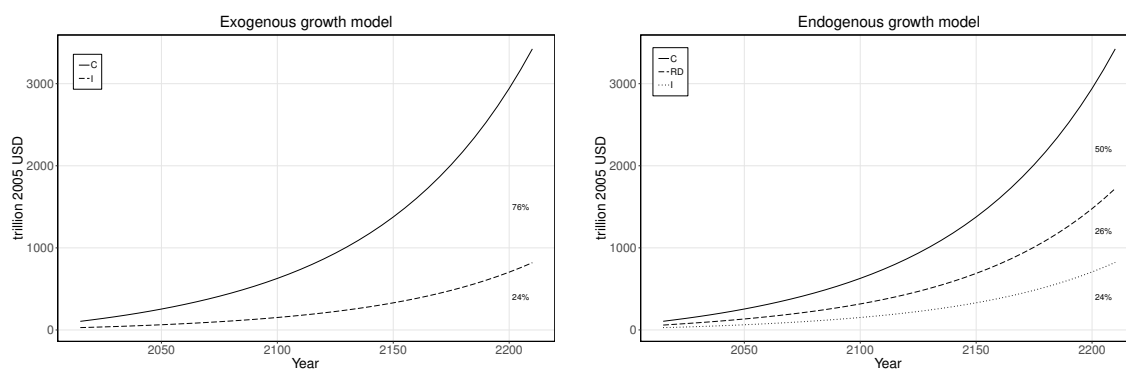


Figure 2: Stacked distribution of income

Ex-ante, it is not possible to say what the welfare optimal path for K_t in the exogenous model would be. Since households have an incentive to smooth their consumption over time, this will depend on the relative allocation of the additional units of consumption, which were freed from R&D investments. Therefore, I solve the exogenous growth model with the same path of A_t from the endogenous growth model⁴. I find that this leads to a higher welfare optimizing capital stock in early time periods than what would be necessary to match gross income. Apparently, households postpone some of their consumption into the future. However, since R&D investments in the endogenous growth model are very evenly distributed over time (see figure 2), this effect is rather small. The capital stock in the exogenous model differs by less than 3 % from the capital stock in the endogenous growth model.

The result of this thought experiment is also reflected in the calibration of the exogenous growth model to the endogenous growth model. I assume that the initial capital stocks in both models are the same. In figure 1 (d), the welfare optimizing capital stock is initially slightly higher in the exogenous model and it is offset by an initially smaller total factor productivity which is depicted in figure 1 (f). As a result, gross-income in both models in figure 1(b) is a near-perfect match. Both differ only by a numerical error⁵.

To conclude, since the paths for K_t and A_t in both growth models are very close, nearly all resources, which are freed from investments in the endogenous growth model, are used for consumption in the exogenous growth model as shown in figure 2.

⁴I set the initial capital stock in the exogenous growth model to the same value as in the endogenous growth model.

⁵To see whether the small differences in K_t and A_t in figures 1 (d) and (f) are driven by the end-point conditions of both models, I have also run the calibration of both growth models with 90 instead of 60 time steps. However, the curvature of both graphs for K_t and A_t remain. The results start to differ slightly after 35 time periods. Since I evaluate only the first 20 time periods of the DICE model, which correspond to 100 years, I conclude that my end-point conditions do not drive these results.

5. Results

After having calibrated the exogenous and the endogenous growth models with no climate externality towards each other and towards the original growth component of the DICE model, they are now put back together with the climate cycle from the original DICE model. For each, the exogenous as well as the endogenous growth model version of DICE, there exist three different scenarios, the *social planner optimum* (OPT), the *constrained optimum* (COPT) and the *business as usual* (BAU) problem. All scenarios were already described in section 3.

The current section will focus on the impact that climate change has on economic growth in an exogenously versus an endogenously growing economy. The effects crucially depend on two economic mechanisms. First, they depend on how the social planner and households allocate their savings versus consumption over time and, second, on how they distribute their savings across investments into physical capital versus knowledge stocks. In addition, in the OPT scenario this impact also depends on the size of investments into direct mitigation efforts.

To disentangle all growth effects which occur due to the climate externality, the endogenization of the growth component and the three different scenarios, the following discussion is subdivided into paragraphs each targeted at a distinct model comparison.

Comparison of the exogenous OPT, COPT and BAU scenarios In this paragraph, I lean on Rezai (2011) to describe the differences between the OPT, COPT and BAU scenarios in the exogenous growth setting. These are best understood when looking at the return on capital. Figure 3 depicts the return on capital in all six versions of the DICE model in different metrics. The absolute return on capital in the OPT scenario based on exogenous growth is depicted in sub-plot (a). This plot serves as a reference point to the other sub-plots. Sub-plot (b) depicts the returns on capital in the exogenous COPT and BAU scenarios plotted against the OPT scenario.

In the COPT scenario, the absence of a mitigation instrument increases carbon emissions

and climate damages relative to each unit of capital investments compared to the OPT scenario and, therefore, lowers the return on capital. For this reason, in figure 3 (b), in the first time period the return on capital sets out at a lower level in the COPT compared to the OPT scenario. Because the only way to internalize the climate externality in the COPT scenario, is to avoid investments into carbon-emitting physical capital, the capital stock in figure 4 (b) remains at a lower level. In a world with decreasing returns to capital, this increases the marginal return to capital relative to the OPT scenario. Therefore, after only a few years, the return on capital in the COPT scenario is slightly above the one in the OPT scenario (figure 3 (b)). In the long run, as climate damages kick in, the return on capital goes down way below the optimal scenario.

In the BAU scenario, the private return on capital does not reflect the social cost of the productive assets. It neglects the negative climate externality and, therefore, in early time periods, it exceeds by far the socially optimal return in the OPT scenario. Hence, economic agents over-invest. Eventually, climate damages dominate all other effects and the return on investment under BAU adjusts to the return under COPT. This is also reflected in the behavior of the capital stock in figure 4 (b). While the capital stock under BAU is above the capital stock in the OPT scenario for a century, eventually, climate damages become so big, that it falls below the OPT benchmark. Gross income in figure 8 (b) in the appendix follows a similar behavior as the capital stock and consumption per capita in figure 6 (b) goes down whenever investments go up and vice versa. In the exogenous growth scenarios, total factor productivity is exogenously given. Thus, their pathways are identical, as figure 5 (b) shows.

The endogenization of growth To understand the endogenization of growth in DICE, I will first revisit the endogenization of growth in general. In the literature, it is often overlooked that the effects of a transition from an exogenous to an endogenous growth model remain, when we add a climate externality to the model. Although, they are accompanied by effects which are specifically brought about by the climate externality. Figures 3 (c) to 7 (c) depict the relative differences between all three scenarios, when moving from the

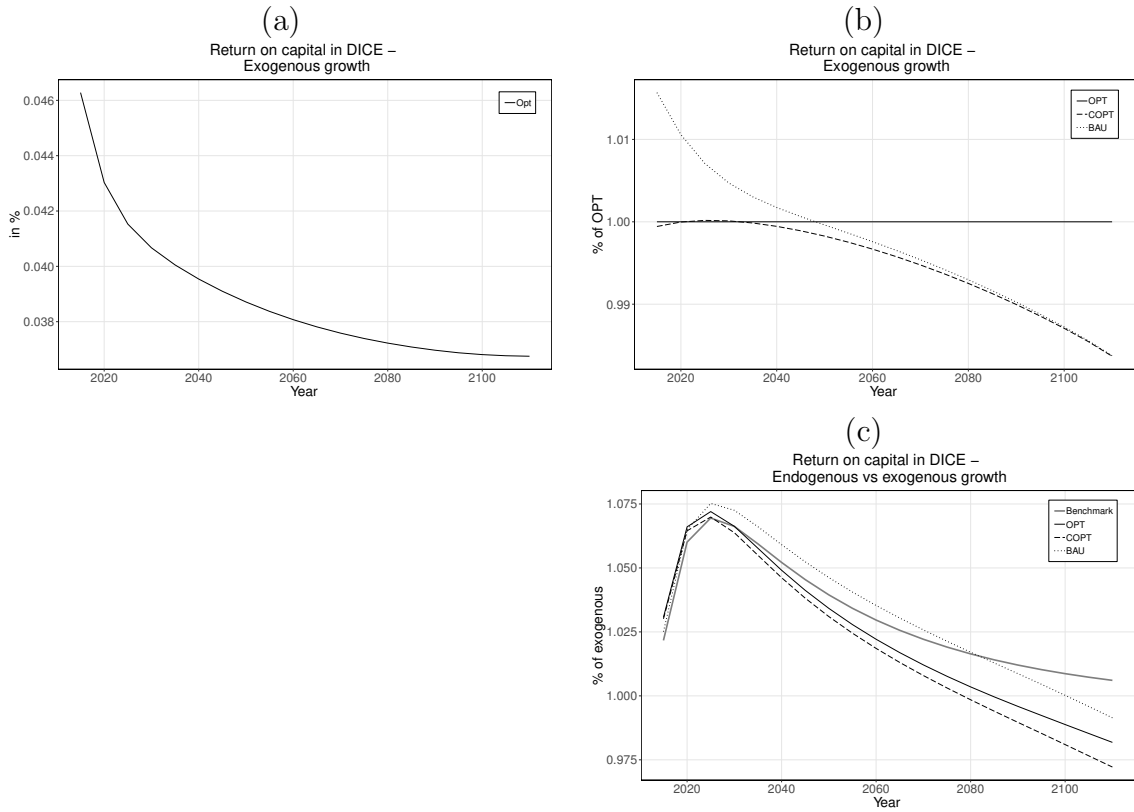


Figure 3: Comparison of DICE model versions: Return on capital

exogenous to the endogenous model version. The benchmark line illustrates the relative difference between the exogenous and the endogenous growth model component without a climate externality. Hence, it depicts those changes which are purely due to the transition between growth models.

Gross output is calibrated to be the same in both model versions (see the strictly horizontal benchmark line in figure 8 (c)). Additional investments into the knowledge stock in early time periods are, to a very small degree, compensated for by a reduction of investments into physical capital. This is in accordance to the thought experiment, which I have discussed in section 4. In figure 4 (c) the benchmark line depicts a reduction in the capital stock in the first decade, which does not fully recover within the upcoming century. As a result, the marginal benefit of capital investments increases and, thus, the benchmark for the return on capital in figure 3 (c) goes up. The labor force in both model versions

is the same. Therefore, as the physical capital stock goes down, it is offset by a slightly higher knowledge stock, respectively total factor productivity, as depicted in figure 5 (c). Since the additional expenditures on R&D are paid for by a reduction in consumption, the benchmark for consumption per capita in figure 6 (c) is significantly lower than one.

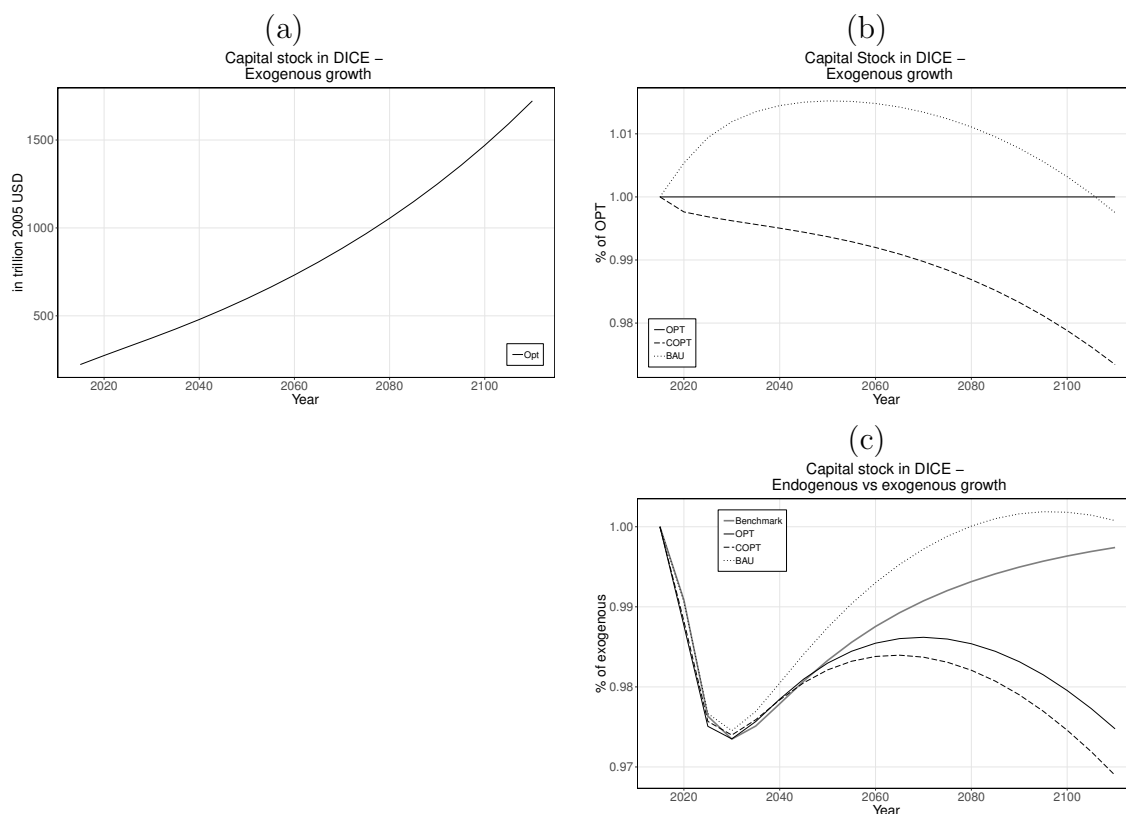


Figure 4: Comparison of DICE model versions: Capital stock

Transitioning from a pure growth model to DICE Transitioning from a growth model without a climate externality to a growth model which entails a climate externality, due to climate damages, the savings effect and the capital accumulation effect kick in. In section 1, I argued that both effects are negative. First, the capital accumulation effect is negative, because climate damages lower the budget that is available for investments. Second, the savings effect is negative, because, due to climate damages, the return on investment decreases and, therefore, the economic agent has an incentive to shift some of his consumption towards earlier time periods. Using the DICE model, Fankhauser and

Tol (2005) show in a numerical example that this incentive is stronger than the one of consumption smoothing, where households have an incentive to save more in earlier time periods in order to make up for future losses. In the endogenous growth model version of DICE, through the capital accumulation and savings effect the climate externality has an additional and negative impact on the size of investments into the knowledge stock. Therefore, the relative total factor productivity in figure 5 (c) in all three scenarios of the DICE model eventually falls below the benchmark. This means that the endogenization of growth in all three scenarios of DICE has a relative impact on total factor productivity which is negative compared to the endogenization of a pure growth model. This is also true for the BAU scenario after approximately one century has passed.

A lower level of total factor productivity causes a lower growth rate of gross income, which also falls below its benchmark in all three scenarios in figure 8 (c). This, in turn, leads to an additional negative capital accumulation effect. If gross income is smaller, the budget which is available for investment is also smaller. Consequently, in the long run, the relative capital stocks in all three scenarios are eventually below the benchmark line in figure 4 (c)⁶. In accordance to this, after some decades, in the endogenous growth model version relative consumption in figure 6 (c) is lower than the benchmark. The relative return on capital in all three scenarios in figure 3 (c) falls below its benchmark, because its marginal product depends on the size of the knowledge stock.

Comparing the endogenization of OPT, COPT and BAU When comparing the endogenization of the OPT, COPT and BAU scenarios with each other, it is striking that the same effects that were observed for the exogenous growth model scenarios are now magnified when growth is endogenized. In the COPT scenario with endogenous growth, where there is no instrument of direct mitigation available, the return on investment for both stocks falls below the return on investment in the OPT scenario with endogenous growth. This means that the knowledge stock also grows at a slower rate than in the OPT scenario with endogenous growth and, thus, gross income growth and the accumulation of

⁶Even the relative capital stock in the BAU scenario falls below the benchmark shortly after year 2100.

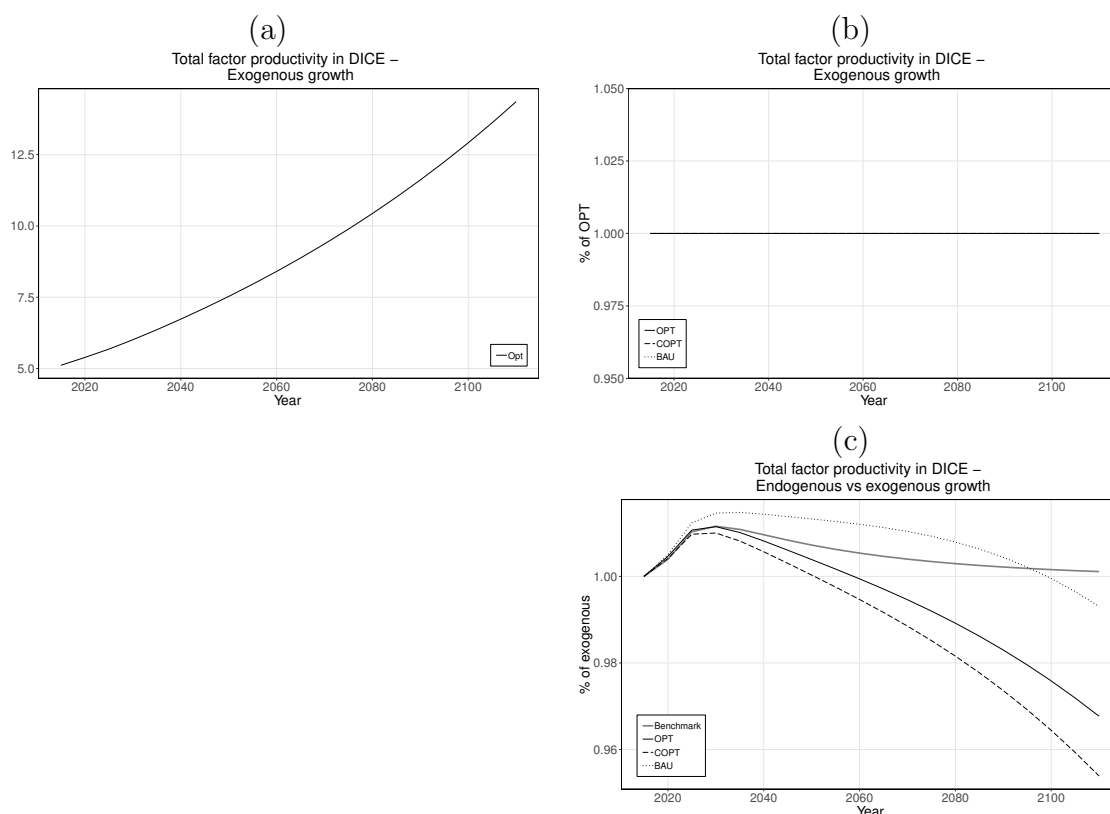


Figure 5: Comparison of DICE model versions: Total factor productivity

physical capital are slower. Consequently, when the COPT scenario is endogenized, gross income and the capital stock in relative terms in figures 8 (c) (in the appendix) and 4 (c) are lower compared to when the OPT scenario is endogenized. In addition, households shift their spending towards consumption (see figure 6 (c)). To sum up, when growth is endogenized the climate externality has a stronger, negative impact on economic growth in the COPT scenario than in the OPT scenario.

The same line of argument with opposite signs holds for the BAU scenario. In this scenario, the climate externality is perceived as exogenous and, therefore, the private return on investment exceeds the social return. This increases the rate at which the knowledge stock grows in the BAU scenario with endogenous growth compared to the OPT scenario with endogenous growth. Initially, this raises the pace at which gross income grows. As a result, the physical capital stock also grows at a higher pace, due to the accumulation effect.

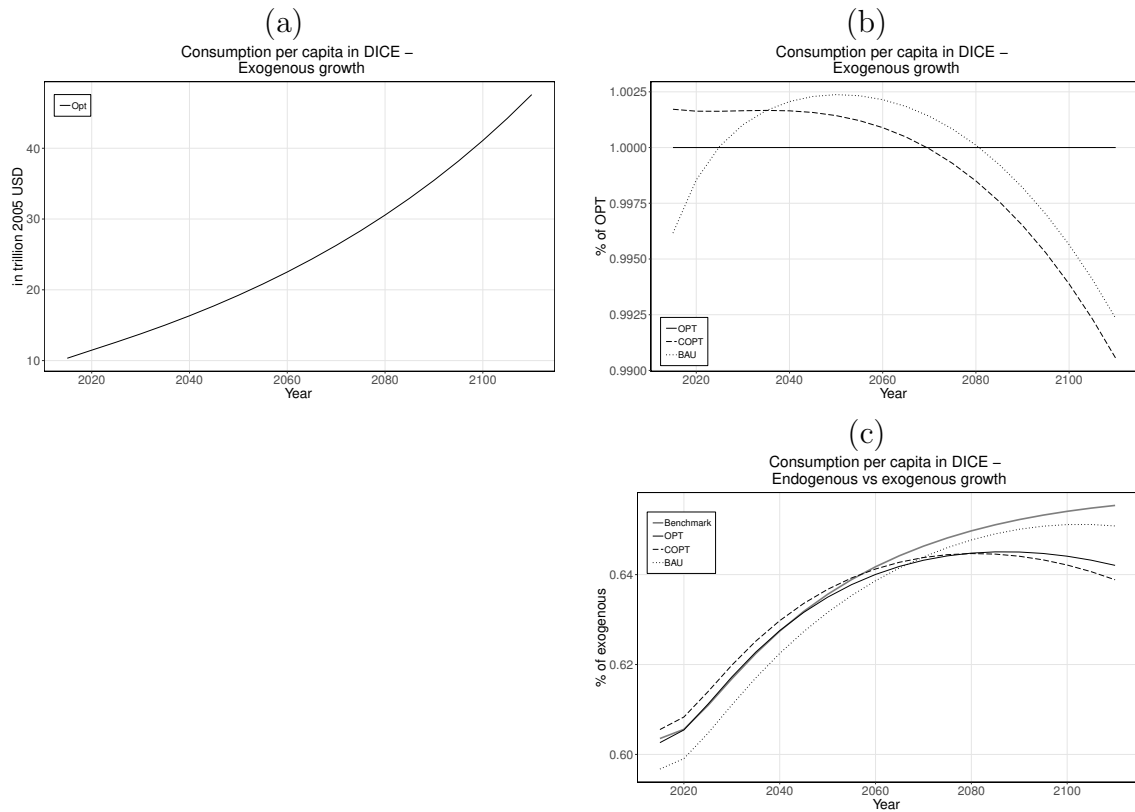


Figure 6: Comparison of DICE model versions: Consumption per capita

Therefore, when the BAU scenario is endogenized, gross income and the capital stock in relative terms are initially higher compared to when the OPT scenario is endogenized (see figure 8 (c) in the appendix and figure 4 (c)). To finance the over-investment into capital, consumption in figure 6 (c) is reduced. However, since a higher gross output causes stronger climate damages, this initially positive growth effect compared to the OPT scenario is eventually reversed around year 2200.

The temperature increase of the atmosphere In the OPT scenario with exogenous growth, the temperature increase in 2100 relative to pre-industrial times amounts to roughly 3.5°C (see figure 7). In figure (b), the temperature increase in the COPT and BAU scenarios with exogenous growth, compared to the OPT scenario with exogenous growth is even higher, because in these scenarios the agents do not have an instrument of direct mitigation at hand. The temperature increase in the BAU scenario is slightly higher

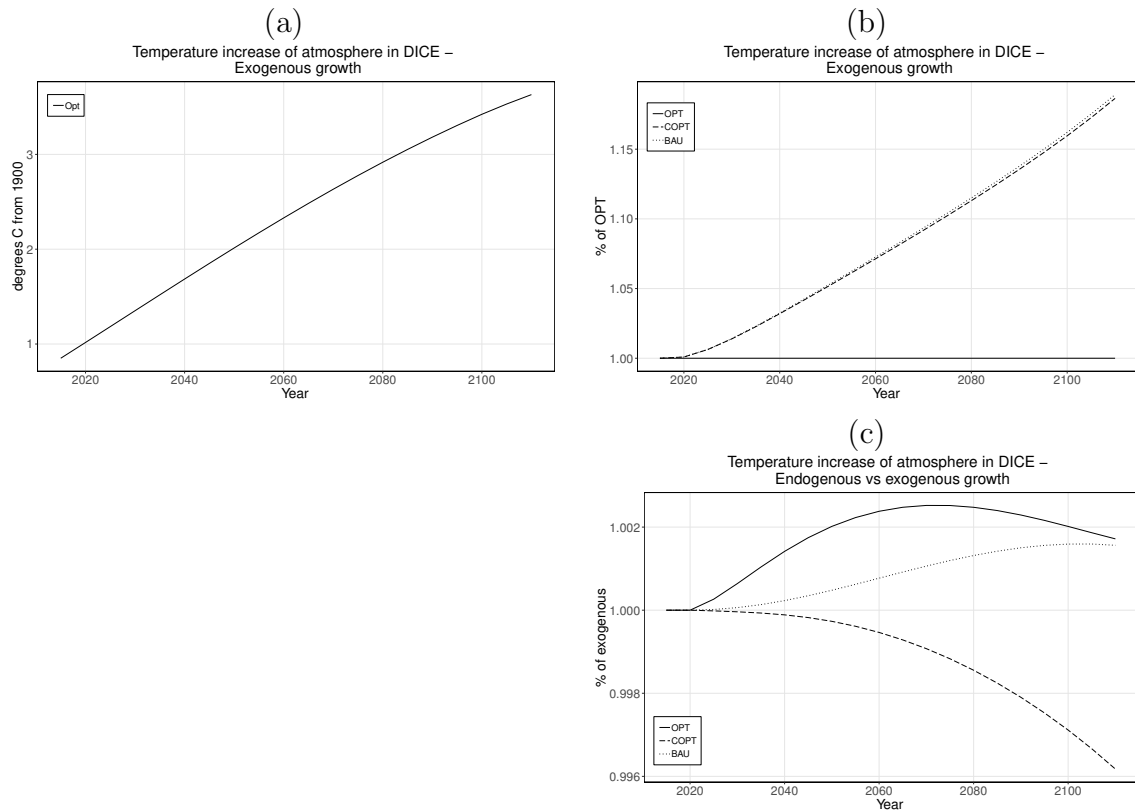


Figure 7: Comparison of DICE model versions: Temperature increase of atmosphere

than in the COPT scenario, as gross-income under BAU is higher than under COPT and consequently the economy emits more carbon into the atmosphere. When growth is endogenized in sub-figure (c), temperatures increase even further in the BAU scenario, because in this scenario gross income is higher than in the BAU scenario with exogenous growth. Vice versa, in the COPT scenario with endogenous growth the temperature increase is smaller, because gross income in this scenario is smaller than in the COPT scenario with exogenous growth. In the OPT scenario, the endogenization leads to a smaller gross income compared to the exogenous growth version of this scenario. Therefore, the social planner's resources for climate mitigation shrink and thus the social planner reduces its mitigation efforts. This effect even over-compensates the fact that a lower gross income also leads to less carbon emissions. Therefore, the temperature increase in the OPT scenario with endogenous growth is higher than in the OPT scenario with exogenous growth. Yet, figure 7 (c)

shows that these effects are rather small. The differences in the atmospheric temperature increase between the scenarios are brought about by similar pathways of carbon emissions (see figure 9 in the appendix) and they lead to equivalent damages as a fraction of gross income (see figure 10 in the appendix).

6. Conclusions

Empirical findings on the interdependent nature of climate change and economic growth have sparked a discussion of how the interaction between the two should be modeled in the theoretical literature as well as in the integrated assessment modelling literature. For the DICE model, prominent ideas are, to have climate damages not only reduce gross income levels, but also physical capital or even knowledge stocks. These models predict by far more severe reductions of economic growth and a higher social cost of carbon, than the original DICE model does. However, these results are strongly driven by their underlying model assumptions.

In this paper, I focus on the effects of climate change expectations on economic growth. By endogenizing economic growth in the DICE model, I am able to differentiate between the accumulation of capital and knowledge stocks. The dynamics of the investment based channel turn out to have a substantial negative and, in particular, lasting impact on economic growth.

Using a re-calibrated version of the DICE model with endogenous growth, I find that in the optimal scenario, where the climate externality is fully internalized, the exogenous growth model version of DICE over-estimates gross income by 2.3 % in 2100 and by 6.8 % in 2150. In the very long run, this gap grows even larger.

This result is driven by two mechanisms: First, climate damages reduce the budget which is available for investments into the knowledge stock and, second, the social planner chooses to invest less into labor-augmenting productivity as a measure to reduce carbon emissions. The DICE model includes only one dirty technology. Therefore, it is optimal for the social planner to endogenously reduce the rate of growth of the economy. However, in reality

we would rather invest into a clean technology in order to realize higher future rates of economic growth. But even if the DICE model included directed technical change a la Acemoglu et al. (2012), especially in early time periods, the avoidance of investments into dirty growth would persist. As a measure to reduce carbon emissions it would be mixed with investments into the green technology. Only over time, as the economy transitions towards a green technology, would the intentional reduction of investments into economic growth cease. A limitation of investments into dirty growth is rational, until new and clean technologies allow for higher rates of economic growth again.

A. The DICE model in detail

The growth model The population size, L_t , evolves exogenously according to:

$$L_1 = 7403 \quad (\text{million people}) \quad (16)$$

$$L_{t+1} = \frac{L_t \left(\frac{11500}{L_t} \right)^{0.134}}{1000} \quad (17)$$

The initial value of the capital stock, K_1 , is:

$$K_1 = 223 \quad (\text{in trillion 2010 USD}) \quad (18)$$

Total factor productivity, al_t , evolves exogenously according to:

$$al_1 = 5.115 \quad (19)$$

$$al_{t+1} = \frac{al_t}{1 - ga_t} \quad (20)$$

with ga_t representing productivity growth:

$$ga_t = 0.076e^{-0.005\Delta T(t-1)} \quad (21)$$

The return on investment, r_t , is derived from the Keynes-Ramsey rule. ρ denotes the rate of time preference, ϵ the elasticity of marginal utility from consumption and C_t denotes consumption in absolute terms:

$$r_t = (1 + \rho) \left(\frac{C_{t+1} * 1000}{L_{t+1}} \frac{L_t}{C_t * 1000} \right)^{\frac{\epsilon}{T\Delta}} - 1 \quad (22)$$

The climate model The adjusted backstop price φ_t is:

$$\varphi_t = 0.212 * 0.975^{(t-1)} * \sigma_t \quad (23)$$

with an emissions output ratio σ_t of:

$$\begin{aligned} \sigma_1 &= 0.35 \\ \sigma_{t+1} &= \sigma_t e^{g_{sig} * T_{\Delta}} \end{aligned} \quad (24)$$

The change in σ_t , named g_{sig} , equals the cumulative improvement of the energy efficiency:

$$\begin{aligned} g_{sig_1} &= -0.0152 \\ g_{sig_{t+1}} &= g_{sig_t} * 0.999^{T_{\Delta}} \end{aligned} \quad (25)$$

Emissions from deforestation, E_{Landt} , amount to:

$$E_{Landt} = 2.6 * 0.885^{(t-1)} \quad (26)$$

Exogenous forcing of other greenhouse gases is denoted by $FORC_{EXt}$:

$$FORC_{EXt} = 0.5 + \frac{0.5}{17} * (t - 1) \quad \text{for } t \leq 17 \quad (27)$$

$$FORC_{EXt} = 1 \quad \text{for } t \geq 18 \quad (28)$$

B. Graphs

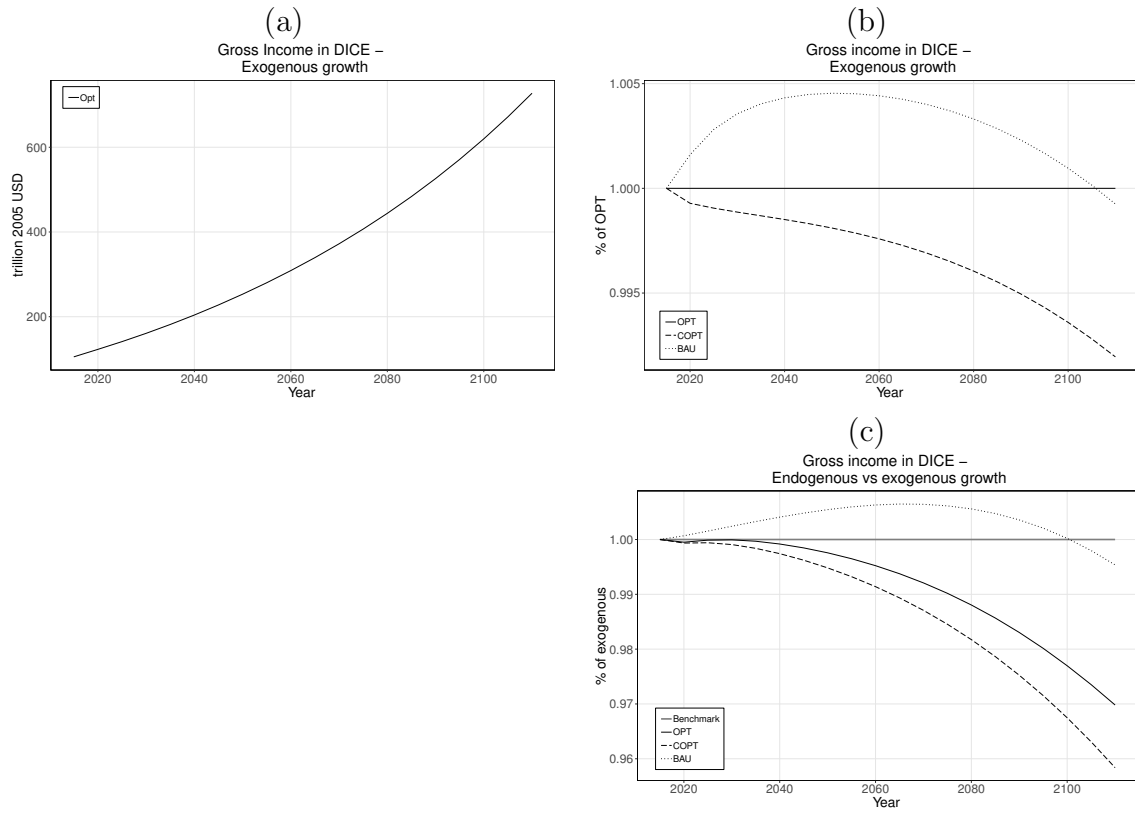


Figure 8: Comparison of DICE model versions: Gross income

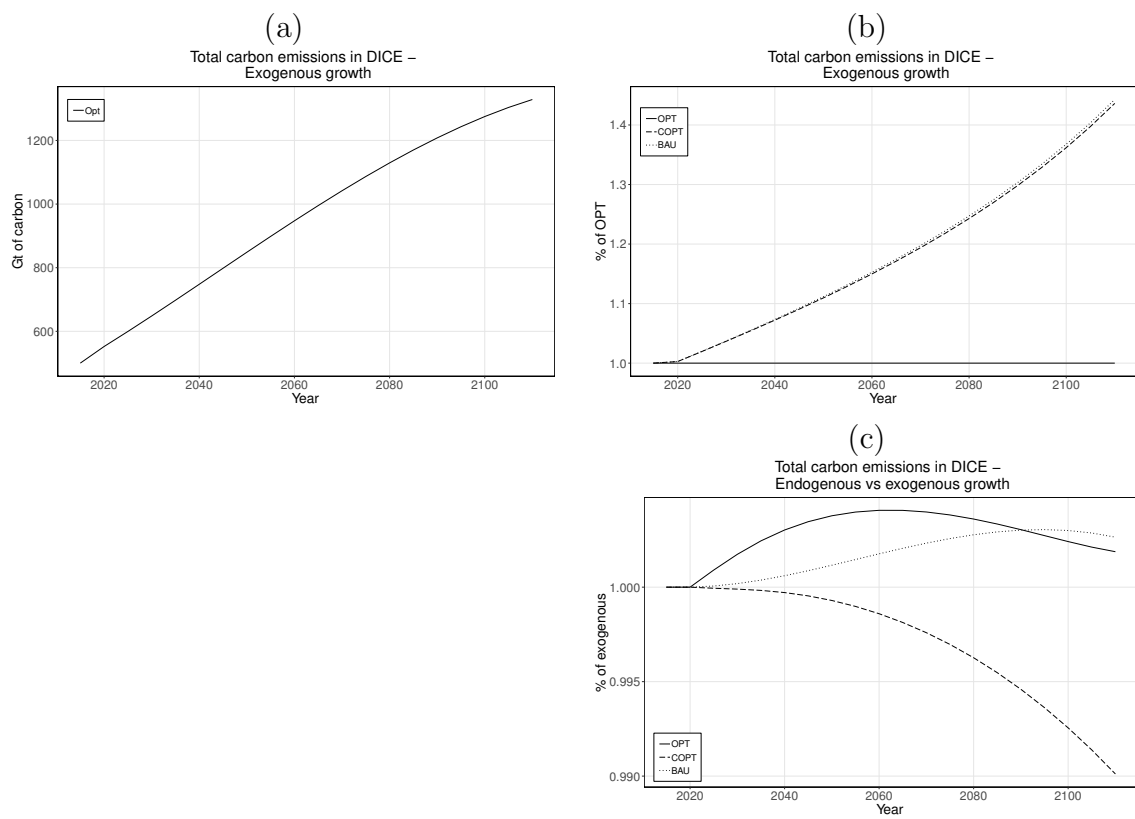


Figure 9: Comparison of DICE model versions: Total carbon emissions

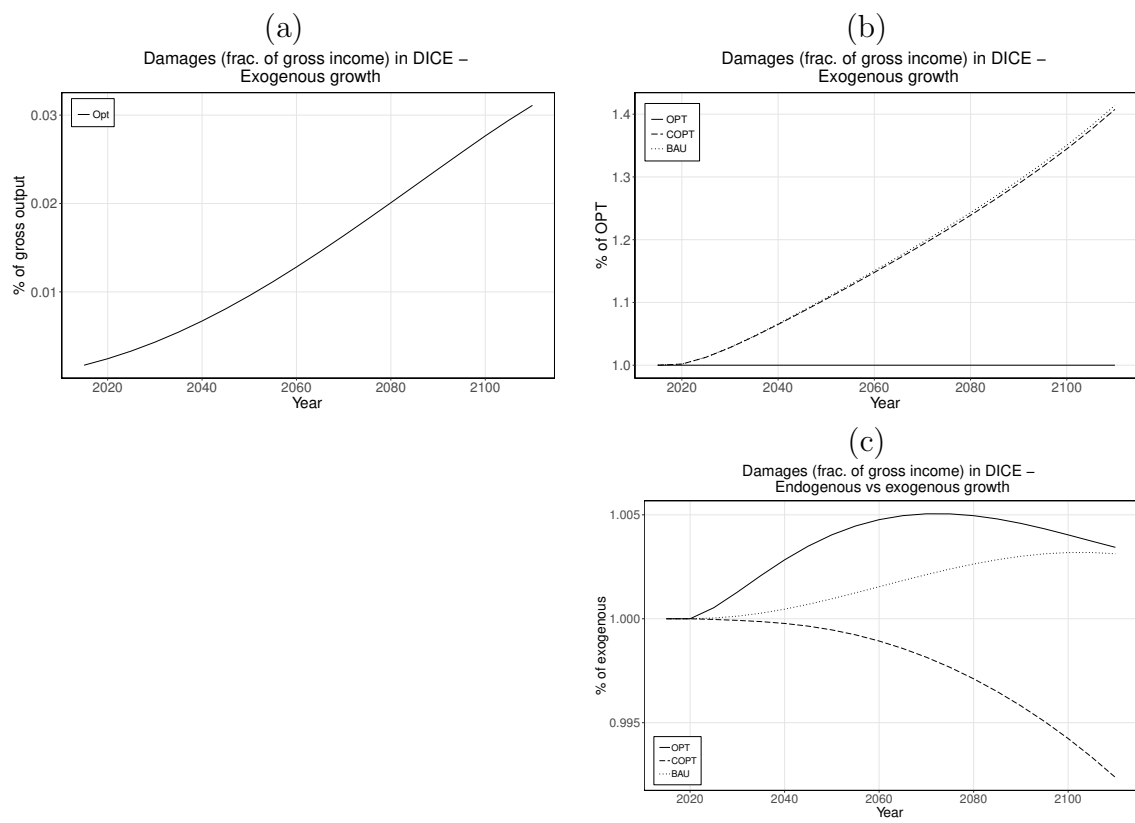


Figure 10: Comparison of DICE model versions: Damages as fraction of income

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