

Christian-Albrechts-Universität zu Kiel

Essays on the Economics of Mitigating Climate Change

Inaugural-Dissertation

zur Erlangung des akademischen Grades eines Doktors
der Wirtschafts- und Sozialwissenschaften
der Wirtschafts- und Sozialwissenschaftlichen Fakultät
der Christian-Albrechts-Universität zu Kiel

vorgelegt von

Martin Christopher Hänsel, M.Sc.

aus Frankfurt

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1 Introduction to the Dissertation

Climate change is one of the greatest challenges that we face as a global society. Scientific evidence regarding the human influence on the global climate has accumulated during the last decades. The last report of the Intergovernmental Panel on Climate Change (IPCC 2014, p. 47) summarizes that it is “*extremely likely*” that the dominant cause of the observed global average surface temperature since the mid-20th century is the anthropogenic increase in greenhouse gas concentrations.

Since about the same time an increasing number of economists have been thinking about the climate change problem. At least since the publication of the Stern Review in 2006 that called climate change the “*greatest market failure the world has ever seen*” (Stern 2007, p. viii), the global community acknowledged that research on the economic characteristics of the climate problem is of prime importance. The simple reason is that the human influence on climate change through greenhouse gas emissions is still strongly linked to economic growth that is fueled by the combustion of fossil fuels which yet provide the lion’s share of the global energy supply.

In the recent paper *The Economics of the Climate* that was published in the *Journal of Economic Literature*, Heal (2017) reviews central aspects of the climate change problem that we as economists need to deal with. Those aspects include the discussion of an appropriate rate to discount future benefits of climate change mitigation, the effect of climate change on notions of sustainability as well as issues of uncertainty and geoengineering. With the first two chapters of my dissertation I seek to contribute to the first two aspects mentioned in Heal’s overview (*Discounting and Sustainability and Substitution*).

Climate change occurs on a very long timescale. Hence, while the costs of climate change mitigation have to be born by the current generation, the benefits are mostly felt in the more distant future. As a consequence the cost-benefit ratio of climate change mitigation policies is highly sensitive to the rate at which those future benefits are discounted. Moreover, deciding on an appropriated discount rate translates into distinct assumptions about how well-being shall be intertemporally distributed. During the last decades there has been a controversial debate on the appropriate discount rate (Nordhaus 2007, 2008; Stern 2007) leading to very different estimations

of the social cost of carbon, i.e. the societal cost of emitting an extra ton of carbon dioxide (CO_2) into the atmosphere. The social cost of carbon is an important figure that is widely used by governmental bodies to inform carbon pricing (e.g. by the US Interagency Working Group on Social Cost of Carbon (IWG 2016)).

In the co-authored first chapter of my dissertation (with Martin F. Quaas), entitled *Intertemporal Distribution, Sufficiency, and the Social Cost of Carbon*, we suggest to avoid explicit discounting choices but instead directly specify alternative intertemporal distributions of well being. The advantage of our approach is that it becomes very clear that the social cost of carbon is largely determined by normative conceptions of intergenerational distributive justice. Specifically we use the well-known Dynamic Integrated Climate Economy model (DICE) to find that the social cost of carbon increases over-proportional with the level of well-being that is reached when the global economy is in steady state. We call this constant steady state “*sufficiency*” level of well-being as it reflects the desire for long-run growth of the global economy. We propose that a controversial discussion on what might be a sufficient level of well being could be more transparent than deciding on an abstract rate with which to discount future well-being in the light of climate change.

I have contributed substantially to this paper at every stage of the research process, including the design of the research question, analytical and numerical modeling as well as writing and revising the paper. The paper has been published online in *Ecological Economics* (<https://doi.org/10.1016/j.ecolecon.2017.11.024>).

The debate on an appropriate discount rate to value future cost and benefits that was initiated by the Stern Review quickly also led to extensions of the standard discounting framework. Among others, considering changing relative prices of goods and services that are not traded on markets, like environmental goods that become successively scarcer due to climate change, has received attention (Gollier 2010, Hoel and Sterner 2007, Sterner and Persson 2008). Also Heal (2017) explicitly mentions changing relative prices of natural capital in his chapter on *sustainability and substitution* as an important issue to be dealt with in climate economics. The reason is that if non-market goods and services, like those provided by the natural environment, are important for economic welfare and climate change irreversibly damages

their available stock, than economic welfare can only be sustainable if the substitution possibilities between market-traded human made goods and non-market environmental goods is high enough. Until now, there exists no systematic study of how relative prices of non-market goods change in the presence of climate change. The purpose of the second co-authored chapter of my dissertation (with Moritz A. Drupp), entitled *Relative Prices and Climate Policy: How the Scarcity of Non-Market Goods Drives Policy Evaluation*, is to fill this gap.

It provides a comprehensive analysis of the change in the relative price of non-market goods in terms of market goods, its determinants and its impact on climate policy evaluation. We consider non-market goods and services at a highly aggregated level including those related to human health and to the natural environment that can range from clean water to aesthetic beauty. After the introduction of relative prices of non-market goods in a stylized model, we make use of the latest version of the integrated assessment model DICE to first replicate the results of an earlier study on changing relative prices (Stern and Persson 2008) and subsequently numerically illustrate how relative price changes should be interpreted. Here we show that the DICE model already implicitly contains changing relative prices, which can be described by a mild degree of complementarity of market and non-market goods.

Based on an extensive sensitivity analysis of the determinants of relative price changes as well as recent empirical evidence, we provide a plausible range and a central estimation for the change in the relative price and three climate policy measures until the end of this century. For our central calibration we find that neglecting relative price changes would lead to a considerable underestimation of the social cost of carbon of almost 50 percent for the current generation. Additionally we make a connection to the discounting debate and show that, when using the peak atmospheric temperature as a comparison metric, considering changing relative prices is equivalent to adjusting the rate of pure time preference by more than a half percentage point. Hence, we conclude that the changing relative price of non-market goods in terms of market goods is of considerable magnitude compared to established determinants of economic evaluation.

The paper has been presented at multiple international conferences and workshops and we are considering the submission to a general economic journal. I have contributed substantially to this paper at every stage of the research process, including the design of the research question, analytical and numerical modeling as well as writing and revising the paper.

An overarching topic in Heal's review is uncertainty with respect to the damage function of integrated assessment models. It maps changing atmospheric temperatures into economic losses and is thus, essential in bridging the dynamics of the climate with those of the economic system in order to quantify climate damage. However, the rise in atmospheric CO_2 does not only lead to increasing temperatures on the earth's surface, but also generates *the other CO_2 problem* that is not explicitly considered in damage functions. A considerable amount of atmospheric CO_2 is taken up by the oceans and although this CO_2 sink buffers the temperature increase on earth, it makes the ocean become more acidic. This phenomenon, termed as *ocean acidification*, is projected to negatively affect ecosystem services provided by the oceans, such as, among others, fisheries, biodiversity and tourism (Turley and Gattuso 2012, Hilmi et al. 2012, Gattuso et al. 2015, Rodrigues et al. 2015). Socioeconomic consequences could be considerable especially for small developing island nations that mostly depend on income generated from sectors that could be affected (Cooley et al. 2012). Thus, even if the impact of ocean acidification on the global damage function was negligible, because developed economies have enough sectors that are independent from damage of ocean acidification, it is important to develop policies that address the damage from ocean acidification in developing economies.

In the third chapter of my dissertation, entitled *Interacting Externalities of Ocean Acidification, Global Warming and Eutrophication: General Equilibrium Analysis for a Developing Country*, I change the focus from a global to a national analysis of the economically optimal mitigation of climate change. I describe a developing economy that depends on agriculture and fisheries to study optimal and second-best environmental policy in the face of interacting external effects of ocean acidification, global warming and eutrophication. Hence, I account for the recommendation given in recent ocean acidification research to study ocean acidification in a broader context of global

environmental change (Riebesell and Gattuso 2015). In particular on a regional basis, ocean acidification is often intensified by eutrophication caused by nutrient run-off from acidic fertilizers used in agricultural production.

The proposed general equilibrium model is designed to capture stylized facts of ocean acidification research in order to study optimal policy responses when externalities interact. I not only derive an analytic expression for the optimal tax on atmospheric carbon and nutrient run-off, but also for the second-best optimal tax on nutrient run-off for the case that the negative effects of global warming and ocean acidification are not fully internalized by the carbon tax. I show that the second-best tax on nutrient run-off will always be higher than its Pigouvian level, which is equal to the marginal social damage of nutrient run-off, to account for those damages not covered by the carbon tax. The last chapter of my dissertation reveals that although climate change is a global phenomenon and only a global solution can tackle it entirely, it can be vital to design national policy instruments that capture regional distinctiveness of environmental change under increasing CO_2 levels.

This last chapter is single-authored and has been presented at the 2017 World Congress of the Resource Modeling Association in Barcelona. I consider submitting it to a field journal in environmental and resource economics.

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2 Intertemporal Distribution, Sufficiency, and the Social Cost of Carbon

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Abstract: We explore how the intertemporal distribution of well-being affects the social cost of carbon. In contrast to the literature that studies parameters of a particular social welfare function, such as the discount rate, we shift the focus and directly assume a parametric form for the intertemporal distribution of well-being. This has the advantage of avoiding explicit discounting choices, which has initiated much debate. Specifically, we consider a set of intertemporal distributions that reach a pre-specified steady-state level of “sufficient” well-being, or equivalently, after a pre-specified “end-of-growth horizon”. We numerically illustrate our results in DICE and find that the social cost of carbon increases over-proportionally with the sufficiency level of well-being. While the social cost of carbon in 2015 is US\$ 7 if the sufficiency level is four-fold the present level, it is US\$ 30 if the sufficiency level is 15-fold and US\$ 100 if the sufficiency level is 26-fold the present level. This shows in a transparent way how conceptions of intergenerational distributive justice drive the social cost of carbon.

Keywords: Climate change, social cost of carbon, optimal tax, DICE, optimal growth, sustainability, social welfare function, discounting

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2.1 Introduction

A major challenge for humankind is avoiding dangerous climate change. Economic studies of optimal climate policy typically use integrated assessment models (IAMs) to determine an optimal path of emission abatement (Stern 2007, Nordhaus 2008, Golosov et al. 2014). Many of these studies adopt an intertemporal discounted utilitarian social welfare function (SWF) and arrive at remarkably different estimates for the optimal tax rate on carbon emissions into the atmosphere, i.e. the social cost of carbon (Table 3.1). These differences are largely attributable to the specific parametrization of the SWF in terms of the so called “ethical parameters”, namely the social time preference rate (ρ) and the intertemporal elasticity of substitution ($1/\eta$). The specification of parameter values for ρ and η translates into specific assumptions about how well-being² ought to be intertemporally distributed.

Table 2.1: Selected estimates of the optimal carbon tax, quoted after Golosov et al. (2014)

Study	Parameter	Optimal tax
Nordhaus (2008)	$\rho = 1.5\%$, $\eta = 2$	30 US\$/tC
Golosov et al. (2014)	$\rho = 1.5\%$, $\eta = 1$	60 US\$/tC
Stern (2007)	$\rho = 0.1\%$, $\eta = 1$	250 US\$/tC

Starting with Ramsey (1928), the long lasting economic and philosophical discussion on which intertemporal SWF should be applied mostly focuses on the “correct” parametrization of the SWF within the standard discounted utilitarian framework (Buchholz and Schymura 2011). Recently there is a growing literature developing alternative social welfare criteria (Asheim 2010, Zuber and Asheim 2012, Fleurbaey and Zuber 2015) although applications of these in well-known IAMs are still relatively rare (Botzen and van den Bergh 2014).

Instead of studying a particular SWF and restricting the analysis to specific ethical

²In the studies presented in table 3.1 the level of well-being reduces to an index of consumption equivalents (or inclusive consumption), which abstracts from the relative price effects of other components of well-being on the social cost of carbon, like environmental quality (Stern and Persson 2008). We acknowledge this shortcoming, but stick to using inclusive consumption as a proxy for well-being as defined in Nordhaus and Sztorc (2013) and Nordhaus (2014) for our analysis.

parameter values, one can also take a very different approach, which avoids explicit discounting choices: the intertemporal distribution of well-being can directly be specified in a parametric form. Recently this direct approach has been applied to study sustainable economic development in the light of anthropogenic climate change (Llavador et al. 2010, 2011, Roemer 2011). However, these studies do not systematically address the question how the intertemporal distribution of well-being is related to the social cost of carbon.

In this paper we parametrize intertemporal paths of well-being that allow us to study the trade-off between the intertemporal distribution of human-well being and the present social cost of carbon. We choose a specific set of intertemporal distributions that is driven by five underlying assumptions, which mainly reflect a schedule of smoothly decreasing growth rates leading to a steady state with a pre-specified constant, “sufficient” level of well-being, or, equivalently, after a pre-specified “end-of-growth” horizon, resulting in an “s-shaped” intertemporal distribution of well-being. Due to, among others, the last global economic crisis, climate change and biodiversity loss, the debate on limits to economic growth pioneered by Meadows et al. (1972) has recently been intensified (Turner 2008, Victor 2010, Antal and van den Bergh 2014). In a recent questionnaire on public opinions on economic growth and environmental sustainability Drews and van den Bergh (2016) find that two thirds of the respondents believe that growth in rich countries will stop at some future point in time. This is consistent with developing countries typically following an s-shaped course of economic development with high initial growth rates, which decrease in the course of time. Also the DICE model assumes that the growth rate will continuously decline down to zero.

Among the s-shaped set of development paths, we determine the one that minimizes the time until the pre-specified sufficient level of well-being is reached (i.e., the “end-of-growth horizon”). By varying the sufficiency level of well-being we can study how the desire for economic efficiency, growth and the resulting intertemporal distribution affects the social cost of carbon. We quantitatively illustrate our results with the 2013 version of DICE (Nordhaus and Sztorc 2013, Nordhaus 2014), which is the most widespread and well-known IAM. The minimization of the end-of-growth horizon requires a full-fledged dynamic optimization, as it affects patterns of investment in

human-made capital, as well as carbon emissions into the atmosphere, both of which have long-term consequences that fully have to be taken into account.

We believe that our approach to directly define intertemporal distributions of well-being has clear advantages over making specific discounting choices. For society and policy-makers it might be easier to agree on a certain intertemporal distribution of well-being than to argue on parameter values for a particular SWF. In a recent survey, Drupp et al. (2015) elicit expert opinion on the value of the long-term social discount rate. One of the responses to their open-ended question for comments was the following: *"Instead of imposing a SWF and calculate the corresponding optimum, it is 'better' to depict a set of feasible paths of consumption, production, temperature, income distribution, etc. and let the policy maker make a choice"* (Drupp et al. 2015, p.17). A similar metaphor has been proposed by Edenhofer and Minx (2014) who suggest economists to construct a feasible "map" of economic development that could be used by policy-makers to "navigate" among different policy options.

Such a "map" requires to parameterize a conceivable set of feasible paths of well-being. As discussed above, the set of s-shaped paths of intertemporal well-being is a particular sensible assumption. This is why we focus on this particular specification in this paper. For each efficient path the policy-maker will be able to obtain the associated social cost of carbon under optimal climate policy. For society our approach could lead to a better informed discussion on normative conceptions of intergenerational distributive justice, which crucially determine the social cost of carbon and are typically hidden in discounting choices within the standard discounted utilitarian model. It becomes very clear, for example, that the desire to attain a high level of well-being in the future, or equivalently to keep the global economy growing for a longer time horizon, substantially increases the social costs of carbon, because in the long-run growth of well-being requires to protect the future generations from adverse consequences of climate change.

The remainder of this paper is organized as follows: Section 2.2 first formally derives the condition prescribing the optimal intertemporal distribution of well-being when using a (discounted) utilitarian SWF, which is embodied in most IAMs like DICE. Second, we briefly sketch the relevant literature that uses this condition to

capture social preferences with respect to intertemporal distributions in IAMs. Section 2.3 characterizes our approach of directly considering a specific functional form for the intertemporal distribution of well-being. Section 2.4 presents the numerical results of the dynamic optimization, before section 2.5 discusses our results.

2.2 Intertemporal distributional objectives embodied in a social welfare function

The dominant approach to determine the social costs of carbon is to use a Social Welfare Function in a dynamic Integrated Assessment Model of climate and the economy (IAMs), such as DICE (Nordhaus 2014). In order to contrast our approach of directly specifying the intertemporal distribution of well-being with a functional form to this standard in the literature, we briefly describe the Social Welfare approach.

Most deterministic dynamic IAMs rank intertemporal paths of per capita consumption c_t , which they refer to as inclusive consumption capturing “well-being”, by means of the intertemporal social welfare function (SWF),

$$W_0(c_0, c_1, c_2, \dots) = \sum_{t=0}^T \frac{1}{(1+\rho)^t} L_t \frac{c_t^{1-\eta}}{1-\eta}, \quad (2.1)$$

which can be interpreted as the discounted Utilitarian objective function or as the utility function of a representative, infinitely-lived agent (ILA), weighted by population size L_t . We consider a discrete-time setting with $t = 0, 1, 2, \dots, T$. The parameters of the welfare function are the time preference rate, ρ , and the preference for consumption smoothing over time, η , with $1/\eta$ being the constant intertemporal elasticity of substitution of consumption.

Maximizing (3.6) subject to the economic and climate constraints of the DICE model (Nordhaus 2014) leads to the following condition (see Appendix 1 for a derivation),

$$(1+\rho) \left(1 + \frac{c_t - c_{t-1}}{c_{t-1}} \right)^\eta = 1 + Y_{K_t} - \delta^K, \quad (2.2)$$

where Y_{K_t} denotes the marginal productivity of capital and δ^K the proportional rate

of capital depreciation. Equation (2.2) is the discrete-time version of the well-known Ramsey rule (Dasgupta 2008) and characterizes the intertemporal distribution of well-being that is optimal according to (3.6).

Much of the recent economic debate on the social costs of carbon focuses on how a society should choose the values for the discounting parameters of a SWF, i.e. ρ and η . Interpreting the SWF (3.6) as the utility function of a representative ILA, these parameters can be derived from observed behavior on markets reflecting opportunity costs of capital (Arrow et al. 1996, Buchholz and Schymura 2011). In this vein, Nordhaus (2008) argues that short-term time preferences should be in line with historical consumption choices. He thus uses the Ramsey equation (2.2) to determine ρ and η from inferred values of real market interest rates and the consumption growth rate.

Other studies interpret the intertemporal SWF (3.6) as the (discounted) Utilitarian objective. According to this point of view, ethical considerations regarding intergenerational trade-offs of well-being should guide the choice of ρ and η (Arrow et al. 1996, Aldy et al. 2010), often implying a more long-term focus on climate impacts (Stern 2007, Gerlagh and Liski 2017). Already Ramsey (1928) and Pigou (1932) argued for a zero rate of time preference on ethical grounds. In this approach, the rate at which future well-being is discounted falls considerably below the opportunity cost of capital and thus these studies arrive at much higher estimates for the social cost of carbon. In that vein, (Stern 2007) uses a very small value of $\rho = 0.001$, merely to reflect a positive probability that humankind may become extinct at some future date, and calculates an optimal carbon tax, which exceeds the one recommended by Nordhaus (2008) by almost one order of magnitude.

In addition, an increasing number of studies consider declining discount rates, e.g. due to uncertainty about future discount rates (Arrow et al. 2013, 2014, Cropper et al. 2014), or when aggregating heterogeneous individual discount rates (Heal and Millner 2013, Quaas et al. 2017). There are also several studies that consider Epstein-Zin (Epstein and Zin 1989) preferences to disentangle risk aversion and time preference in order to more appropriately capture observed preferences over the distribution of income over time (Ackerman et al. 2013). Finally, some studies use surveys to elicit expert opinion on the discounting parameters of a SWF (Weitzman 2001, Drupp et al.

2015, Howard and Sylvan 2015). The most recent expert survey from Drupp et al. (2015) finds that only a minority of experts recommends discounting parameters in line with the Ramsey equation (2.2).

The diversity in views on the correct values for the discounting parameters ρ and η is one of the main drivers in explaining the broad range of estimates for the social cost of carbon today. Many studies, however, do not make explicit which distributional assumptions are embodied in their choice of ρ and η . Indeed, small differences in the specification of ρ and η may lead to substantially different values for the social cost of carbon (van den Bijgaart et al. 2016). We believe that most policy-makers, and probably even many scholars, will have difficulties in making up their opinion on the correct values for these parameters accurately enough that they can trust the resulting value for the social cost of carbon. Possibly policy-makers will not be able to recognize what actually drives a certain estimate for the social cost of carbon, which may damage the applicability of such a quantitative estimate.

We thus propose to shift the focus away from discounting choices of a particular SWF, but instead directly assume a functional form for the intertemporal distribution of well-being. This enables us to simulate a set of intertemporal distributions and quantitatively estimate each resulting social cost of carbon by using the DICE model. In the next section 2.3 we explicitly introduce the suggested functional form for the intertemporal distribution of well-being.

2.3 A direct specification of the intertemporal distribution

The main aspects in our specification of the intertemporal distribution of well-being are that (a) the present level of well-being, c_0 , is kept fixed, and (b) that some steady-state level of well-being, c_{\max} , is obtained after a finite time of growth, i.e. after the “end-of-growth horizon”, τ . This means, we impose the following assumptions.

Assumption 1 (Given level of initial well-being). *The current generation’s well-being is kept fixed at the observed level c_0 .*

Assumption 2 (end-of-growth horizon/sufficiency). *Growth in well-being is maintained until $\tau > 0$ such that after finite time τ a steady-state with constant well-being $c_{\max} > c_0$ is reached.*

In addition, we have to specify the development of well-being between the present, $t = 0$, and $\tau > 0$. To this end, we define the notions of a preference for “early growth” and a preference for “smooth growth”, which we capture by ‘preference’ functions $h(\cdot)$ and $f(\cdot)$, respectively. Both apply to the period of growth only, as after τ the economy then is in a steady state by definition, such that notions of “early growth” or “smooth growth” are meaningless after τ .

In a sense, the notions of “early growth” and “smooth growth” capture the ideas of discounting and a preference for intertemporal consumption smoothing. The functional forms of $h(\cdot)$ and $f(\cdot)$ will then specify the preference for “early growth” and “smooth growth”. The difference between the setting considered here and the standard discounted utilitarian setting is that here we define the two separately, rather than having both aspects of intertemporal preferences built into one social welfare function.

Definition 1 (early growth). *If there are two feasible streams c_t and c'_t with the same aggregate level of well-being over $[0, T]$, $\int_0^T (c_t - c'_t) dt = 0$, c_t is said to exhibit ‘early growth’ relative to c'_t if*

$$\int_0^\tau h(t - \tau) c_t dt > \int_0^\tau h(t - \tau) c'_t dt, \quad (2.3)$$

with $h'(t - \tau) < 0$ (and without loss of generality $h(0) = 0$) capturing preference for early growth.

The function $h(\cdot)$ that is declining over time, similarly to a discount factor, gives a higher weight to well-being at early points in time compared to later points in time. The more strongly $h(\cdot)$ declines over time, the ‘stronger’ is the preference for early growth.³

The second assumption is that society tends to prefer “smooth growth”, i.e. a consumption path that avoids strong fluctuations, defined as follows:

³Below we specify the preference for early growth by a quadratic function $h(t - \tau) = (\tau - t)^2$.

Definition 2 (smooth growth). *If there are two feasible streams c_t and c'_t with the same aggregate level of well-being over $[0, T]$, $\int_0^T (c_t - c'_t) dt = 0$, c_t is said to have ‘smooth growth’ relative to c'_t if*

$$\int_0^T f(c_t) dt > \int_0^T f(c'_t) dt, \quad (2.4)$$

with $f''(c) < 0$ capturing preference for smooth growth.

The curvature properties of the concave function $f(\cdot)$ capture the preference for smoothing out consumption over time. The more concave the function $f(\cdot)$ is, the stronger is the preference for smooth growth.⁴ Based on these two definitions, we now state the assumptions on social preferences.

Assumption 3 (early growth). *Consider two feasible streams c_t and c'_t with the same aggregate level of well-being over $[0, T]$, and same ‘smoothness’, $\int_0^T (f(c_t) - f(c'_t)) dt = 0$. If c_t exhibits ‘early growth’ relative to c'_t , c_t is preferred over c'_t , $c_t \succ c'_t$.*

Assumption 4 (smooth growth). *Consider two feasible streams c_t and c'_t with the same aggregate consumption over $[0, T]$, and same ‘earliness’, $\int_0^T h(t-\tau) (c_t - c'_t) dt = 0$. If c_t exhibits ‘smooth growth’ relative to c'_t , c_t is preferred over c'_t , $c_t \succ c'_t$.*

To illustrate how these assumptions work, consider the function

$$c_t = \begin{cases} c_{\max}^{1-(1-\frac{t}{\theta})^2} \cdot c_0^{(1-\frac{t}{\theta})^2} & \text{for } t \leq \theta \\ c_{\max} & \text{for } t > \theta \end{cases}, \quad (2.5)$$

for c_t , which has the three parameters c_0 , c_{\max} and θ (we will discuss this function in further detail below). If both c_t and c'_t have such a functional form, in Assumption 3 two of the parameters are constrained by the conditions on identical aggregate well-being and identical ‘smoothness’, while the differences in the third one can give rise to differences in ‘earliness’. Similarly, in Assumption 4 two of the parameters are constrained by the conditions on identical aggregate well-being and identical ‘earliness’, while the differences in the third one can give rise to differences in ‘smoothness’.

⁴Below we specify the preference for smooth growth by the Shannon entropy measure, i.e. we specify $f(c) = -c \ln(c)$.

This is illustrated in Figure 2.1, panels (a) and (b), where we use $f(c) = -c \ln(c)$ to characterize the preference for smoothness and $h(t - \tau) = (\tau - t)^2$ to characterize the preference for earliness (see footnotes 3 and 4). In panel (a), the two paths c_t and c'_t have the same aggregate well-being (4914), and the same ‘smoothness’ (-6199), but the path c_t exhibits more early growth compared to c'_t (15.3 vs. 11.0 millions). In panel (b), the two paths c_t and c'_t have the same aggregate well-being (4914), and the same ‘earliness’ (15.3 millions), but the path c_t exhibits more smooth growth compared to c'_t (-6199 vs. -6584).

We will see below that when the function $h(\cdot)$ capturing the preference for early growth and the function $f(\cdot)$ capturing the preference for smooth growth are specified, and given assumptions 1 and 2, the intertemporal distribution of well-being is specified except for the values of τ and c_{\max} . These are fixed by imposing the following standard efficiency condition.

Assumption 5 (efficiency). *Consider two feasible streams c_t and c'_t with the same ‘smoothness’, $\int_0^\tau (f(c_t) - f(c'_t)) dt = 0$, and the same ‘earliness’, $\int_0^\tau h(t-\tau) (c_t - c'_t) dt = 0$. If c_t exhibits a higher aggregate level of well-being than c'_t , $\int_0^T (c_t - c'_t) dt > 0$, c_t is preferred over c'_t , $c_t \succ c'_t$.*

Given the above-made assumptions, the consumption path is characterized by the following theorem.

Theorem 1. *Under Assumptions 1–5, and for a pre-specified end-of-growth horizon τ , well-being c_t is monotonic in time from c_0 to $c_\tau = c_{\max}$ according to*

$$c_t = f'^{-1} \left(f'(c_{\max}) \left(1 + \frac{h(t-\tau)}{h(-\tau)} \left(\frac{f'(c_0)}{f'(c_{\max})} - 1 \right) \right) \right) \quad (2.6)$$

with

$$c_{\max} = \max \{ c_{\max} \in \mathbb{X} \mid c_t \text{ given by (2.6) for all } t < \tau \text{ and } c_t = c_{\max} \text{ for all } t \geq \tau \}. \quad (2.7)$$

where \mathbb{X} is the set of consumption paths that is feasible given the economic and climate constraints.

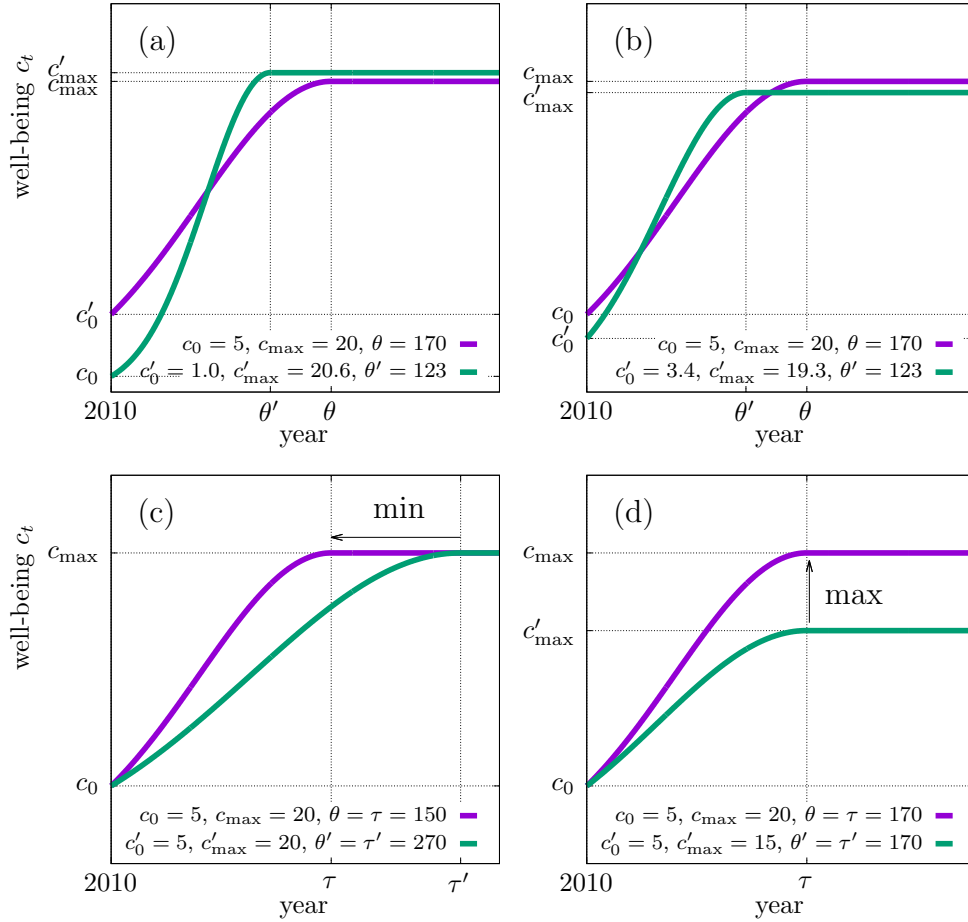


Figure 2.1: Panels (a) and (b) illustrate Assumptions 3 and 4. In panel (a), the two paths c_t and c'_t have the same aggregate well-being per capita and the same smoothness, but c_t exhibits more early growth compared to c'_t . In panel (b), the two paths c_t and c'_t have the same aggregate well-being and the same earliness, but c_t exhibits more smooth growth compared to c'_t . Panels (c) and (d) show well-being per capita c_t for varying end-of-growth horizon (panel c) and varying maximum well-being per capita (panel d). In both panels, the shift from the lower to the upper curve illustrates optimization towards the Pareto-efficient path of well-being. All paths are constructed with the functional form (2.5), parameter specifications are given in the figures.

The proof of theorem 1 can be found in Appendix 2. Smoothness and monotonic growth follow directly from assumptions 3 and 4. For a given end-of-growth-horizon τ , assumptions 1–4 specify the intertemporal distribution of well-being only up to the free parameter c_{\max} . Efficiency requires that this level is chosen at the maximum feasible level, as stated in (2.7).

The higher the sufficiency level of steady-state well-being or the more we shift τ into the future, the more evenly growth in well-being will be intertemporally distributed and thus, the more weight society puts on intergenerational distributive justice. Thus, changing c_{\max} or shifting τ back and fourth in time enables us to study a set of intertemporal distributions, which can incorporate different conceptions of intergenerational distributive justice. If τ is equal to zero, the result would be the maximin distribution (Solow 1974), i.e. an intertemporally constant well-being per capita level, which equals the level of the first, worst-off generation. By construction, however, maximin dismisses any investment into the well-being of future generations above the level of the present generation. Consequently, a strict application hinders economic growth leading to stagnation (Rawls 1971). Rawls (1971) proposed a two-stage model in order to assure distributive justice between generations. During a first accumulation phase generations would be required to adopt a positive net savings rate determined by a just savings principle resulting in positive growth rates of well-being. Once equal liberties and just institutions are implemented the net savings rate would fall to zero in the beginning of the second stage leading to a zero steady-state growth rate of well-being. Thus, Rawls' idea is that economic growth is not desirable per se, but rather because it brings about just institutions and equal liberties. Once these are established generations should leave as least as much as they received from the generation before. In terms of our model, the first phase takes until τ , while the second phase corresponds to a steady state at the sufficiency level of well-being c_{\max} .

Some growth in human well-being may be desirable for different reasons. For example parents may wish their children to have a higher quality of live compared to them or society wants to make an on-going development of humankind's achievements, like increasing average life expectancy, also possible in the far future (Llavador et al. 2011). In a series of recent papers Llavador, Roemer, and Silvestre (2010, 2011) and

Roemer (2011) study the implications of alternative distributions of intergenerational well-being on the first generations' well-being in a dynamic framework with an exogenous emissions scenario. By maximizing the initial level of well-being and maintaining a constant exogenous growth rate of well-being afterwards, they show that both intergenerational maximin (i.e. no growth) and a sustainable growth path are feasible and yield higher levels of well-being for the first generation than their reference value in 2000. Moreover, they find that in case of the sustainable growth path, the trade-off for the first generation in terms of consumption sacrifice is small compared to the prospect of sustained future growth in well-being.

We reflect these considerations by requiring efficiency, which means to maximize consumption subject to the technical and natural constraints. Here we consider these constraints as specified in the DICE model (Nordhaus 2014). Appendices 1 and 3 describe the details of the DICE model including functional forms.

The maximization problem in equation (2.7) states that the Pareto efficient path is obtained by choosing the path of well-being per capita and CO_2 emissions in a way that results in the maximal steady state level of well-being per capita for a particular end-of growth horizon. Straightforward calculations show that c_t , as given by (2.6) is monotonically increasing with c_{\max} and monotonically decreasing with τ . Thus, efficiency can be equivalently obtained by maximizing c_{\max} for a given end-of-growth horizon τ , or by minimizing τ for a given sufficiency level of well-being c_{\max} . In the following, we focus on the latter approach, and vary the pre-specified steady-state level of well-being per capita that could be interpreted as “sufficient” in the sense of Rawls (1971). We are particularly interested in the question how changes in c_{\max} affect the social cost of carbon (see section 2.4).

The exact functional forms of $h(\cdot)$ and $f(\cdot)$ determine the shape of the function that gives well-being as a function of time in the growth period $0 < t < \tau$. In order to apply our approach, we have to give the problem more structure and to specify the functional forms for $h(\cdot)$ and $f(\cdot)$. In the following corollary to Theorem 1 we propose specific functional forms that lead to a growth function that we find particularly appealing.

Corollary 1. *Under Assumptions 1–5, and with the specification $f(c) = -c \ln(c)$ and $h(t - \tau) = (t - \tau)^2$, the intertemporal distribution of well-being is given by (2.5) with $\theta = \tau$ and the objective is to choose, for given values of c_0 and τ , the maximal feasible c_{\max} given the economic and climate constraints.*

The results follows after few steps of calculations when using the functional forms for $h(\cdot)$ and $f(\cdot)$ in (2.6). Corollary 1 specifies a particular preference for early growth, as captured by the particular specification of the function $h(t - \tau) = (t - \tau)^2$, i.e. the squared difference of the present point in time from the end-of-growth horizon τ . It also specifies a particular preference for smooth growth, as captured by the particular specification of the function $f(\cdot) = -c \ln(c)$, which is the Shannon entropy of the consumption path – a “smoothness” measure commonly used in various applications.

As a result, we obtain the functional form for the intertemporal distribution of well-being results given in (2.5). At any point in time, well-being c_t is a weighted geometric average of initial well-being and the sufficient steady-state level of well-being c_{\max} , where the weight on c_{\max} increases over time, for $t < \tau$, according to $(1 - t/\tau)^2$. If c_{\max} is large compared to c_0 , a sigmoid time path of well-being results.

Using g_c to denote the initial growth rate of c_t , $g_c \equiv \dot{c}_0/c_0$, the functional form (2.5) can also be written as $c_t = c_{\max} \exp(-\frac{g_0}{2\tau}(t - \tau)^2)$ for all $t < \tau$. For the growth rate of well-being we obtain

$$\frac{\dot{c}_t}{c_t} = \max \{g_c (1 - t/\tau), 0\}. \quad (2.8)$$

Thus, we have growth, $\dot{c}_t > 0$, for all $t < \tau$ and $c_t = c_{\max}$ thereafter. The growth rate is linearly decreasing from g^c to zero within the time horizon τ , and remains zero after τ . This reflects the stylized fact that during the course of economic development growth rates are typically relatively high first and decline thereafter. The linear decrease is a particular simple description of this process.⁵

Panels (c) and (d) in Figure 2.1 illustrate the optimization problems to maximize c_{\max} for a given value of τ or to minimize τ for a given value of c_{\max} . Both problems are equivalent.

⁵If the growth rate of well-being does not linearly decrease, the dynamics of well-being per capita and the resulting social cost of carbon would depend on additional parameters that determine the curvature of the growth path. Imposing linearity here is a simplification, as it reduces the number of parameter values to be specified.

A path of well-being described by (2.8) is feasible only if g^c is sufficiently small. Indeed, the longer the time horizon τ , the smaller g^c must be to render the path (2.8) feasible given the economic and climate constraints imposed by the DICE model.

In order to connect our approach of directly specifying the intertemporal distribution of well-being to the standard setting that uses a discounted utilitarian SWF as in equation (3.6) we ask, for which time-varying intergenerational discount rates of well-being would the streams of well-being that correspond to the different specifications of c_{\max} turn out to be optimal if these discount rates were used in a SWF as given in equation (3.6)? The answer is that the path of well-being corresponding to a high value of c_{\max} is the optimal outcome if the discount rate is small, or, equivalently, the discount factor is high. Hence, we next derive the endogenous social discount rate of well-being. In other words, we determine the dual to the problem mainly considered in this paper, which would be to maximize the present value of consumption, applying the time path of social discount rates implied by the model considered here.

Using φ_t to denote the Lagrangian multiplier for the constraint

$$c_t \geq \bar{c}_t = c_{\max}^{1-(1-\frac{t}{\tau})^2} c_0^{(1-\frac{t}{\tau})^2} \quad (2.9)$$

derived from (2.5), everything else as in the derivation of efficient developments in Appendix A.1.1, we find that the first-order conditions for this dynamic optimization problem are formally identical to (A.3), except that (A.3a) is replaced by $\varphi_t = \lambda_t^K$ for all t .

Thus, we can interpret the expression $\Delta(t; \tau) \equiv \frac{\varphi_t}{\varphi_0}$ as an intergenerational discount factor of well-being, where we explicitly note the dependency on τ . The average yearly intergenerational discount rate \bar{r} to arrive at the intergenerational discount factor $\Delta(t; \tau)$ for a specific time period t can then be defined as $\bar{r} \equiv \Delta(t; \tau)^{-1/t} - 1$. Furthermore, we define the time-dependent yearly intergenerational discount rate as $r_t = \left(\frac{\Delta(t-1; \tau)}{\Delta(t; \tau)} \right) - 1$.

2.4 Quantitative results for the DICE model

Economic growth comes at a cost, since emitting one additional ton of CO_2 into the atmosphere causes future climate damage, which society *should* (in a normative sense) consider in form of the social cost of carbon. The social cost of carbon associated with a given intertemporal distribution of well-being at a particular point in time is measured by the shadow price of CO_2 divided by the shadow price of aggregate well-being at this time. Within the optimal DICE framework that we consider here, the social cost of carbon at this point in time must correspond to the societal cost of abating an additional ton of CO_2 at that time, for reasons of efficiency. Indeed Nordhaus (2014) uses the marginal abatement cost function to calculate the social cost of carbon (see Appendix 3 for the exact formula).

We are interested in how the social cost of carbon today varies with the sufficiency level of steady-state well-being c_{\max} and the corresponding intertemporal distribution of well-being. Hence, we exogenously change τ and evaluate the corresponding optimal social cost of carbon in 2015. The numerical dynamic optimization results presented in the following have been calculated using the Knitro solver (version 9.0.1) together with the AMPL optimization software. The programming code is provided in Appendix 4.

Figure 2.2 shows the time paths for well-being per capita for different sufficiency levels of well-being, measured in multiples of the 2010 level of well-being, c_0 , $c_{\max} \in \{2, 5, 10, 15, 18, 22, 26\} \times c_0$, under minimized end-of-growth horizons. The higher the maximal level of well-being per capita the more the end-of-growth horizon is shifted into the future for which c_{\max} can efficiently be reached. The sub-graph in figure 2.2 illustrates that future growth in well-being per capita can only be implemented at the expense of lower near term growth rates (2010-2030). The smaller the steady-state level of well-being, the higher are the initial levels of well-being per capita from 2010 to 2030.

Thus, figure 2.2 nicely summarizes the intergenerational trade-off that our global society faces today: Achieving larger prosperity for future generations requires that the current generation sacrifices part of its well-being. Vice versa the current generation can be made better-off when the societal objective is to stop growing earlier implying a lower future prosperity. However, the absolute sacrifice that the current generation needs to make to enable larger future prosperity is relatively small compared to the possible absolute future gain in well-being.

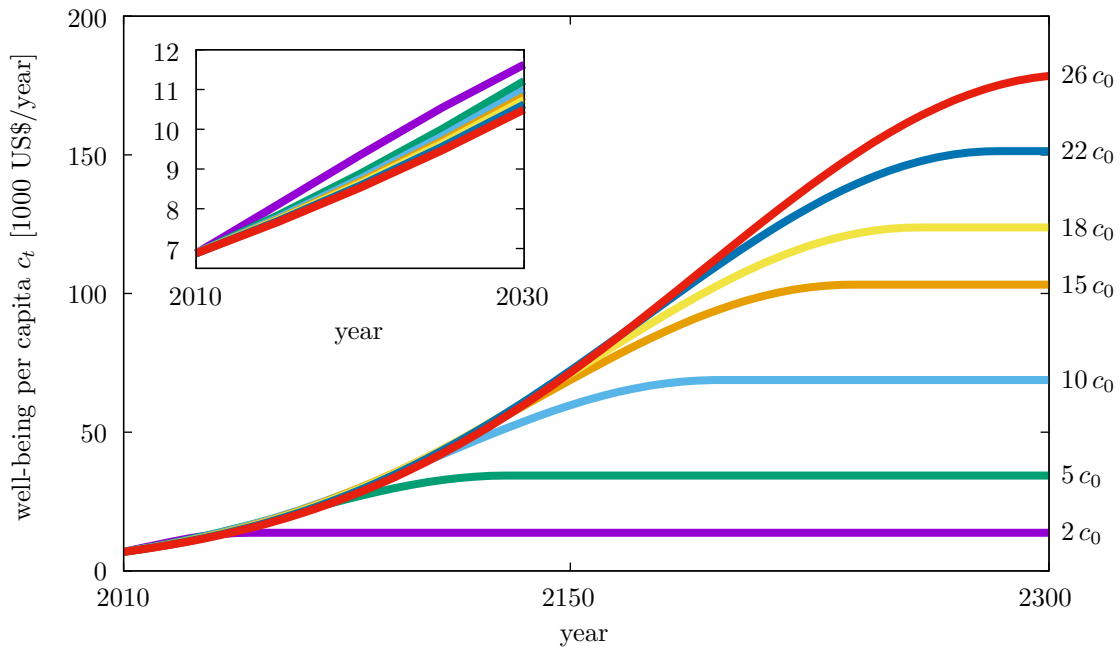


Figure 2.2: Time paths (2010-2300) of well-being per capita for varying sufficient steady-state levels of well-being c_{\max} , with optimized end-of-growth horizon τ .

We are interested in how the level of sufficient steady state well-being drives the social cost of carbon today. By varying the steady state level of well-being c_{\max} that society would consider “sufficient”, we are able to directly assess how the distribution of growth between generations determines today’s cost of emitting an additional ton of CO_2 into the atmosphere. Figure 2.3 shows the social cost of carbon in 2015 as a function of the sufficient steady-state levels of well-being c_{\max} . We find that the social cost of carbon in 2015 increases over-proportionally with the sufficiency level of well-being. While the social cost of carbon in 2015 is US\$ 7 if the sufficiency level is four-fold the present level, it is US\$ 30 if the sufficiency level is 15-fold and US\$ 100

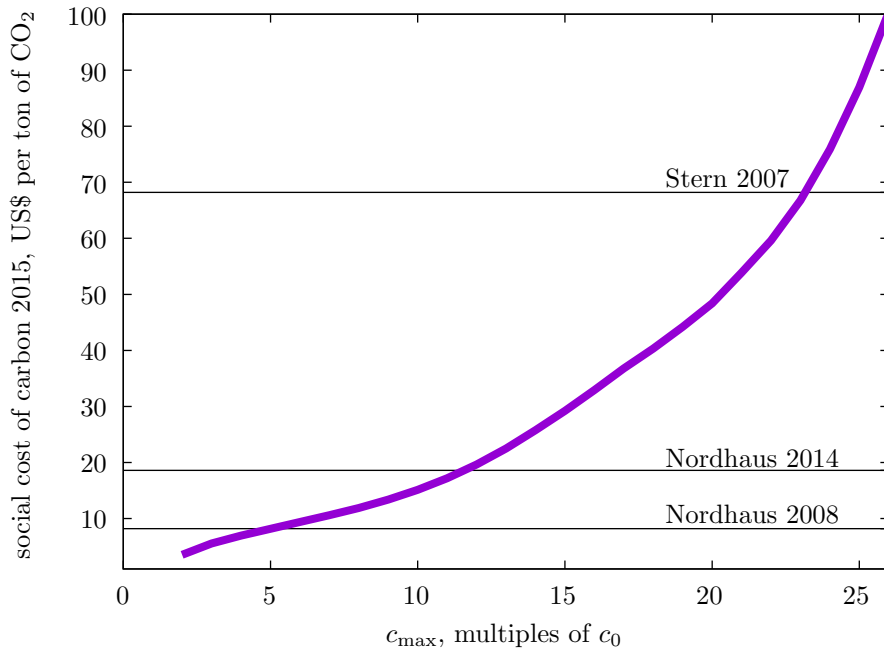


Figure 2.3: Social cost of carbon in 2015 as a function of the sufficient level of steady-state well-being c_{\max} , measured in multiples of the 2010 level c_0 .

if the sufficiency level is 26-fold the present level. The convex relationship between the sufficiency level of well-being and the social cost of carbon shows how strongly the social cost of carbon depends on the desired prospects for growth. When thinking of τ as measuring for how many generations a positive growth rate is maintained, the trade-off between future growth in well-being and the social cost of carbon becomes the more severe the larger the number of generations for which a society wants to keep on growing and thus, the more weight society puts on intergenerational distributive justice.

We can also compare the results of our approach with previous estimates of the social cost of carbon (cf. figure 2.3). The scenario of Nordhaus (2008), i.e. a social cost of carbon of US\$ 8.18 per ton of CO_2 in 2015, is roughly equivalent to a steady-state level of well-being five times larger than the 2010 level. Increasing the sufficiency level of well-being to 11.5 times the 2010 level matches the social cost of carbon in 2013 DICE model being 18.6 US\$ per ton of CO_2 (Nordhaus 2014). In turn, when growth ends at a level 23 times the 2010 level, the social cost of carbon in 2015 is US\$ 68.19, equivalent to the scenario of Stern (2007).

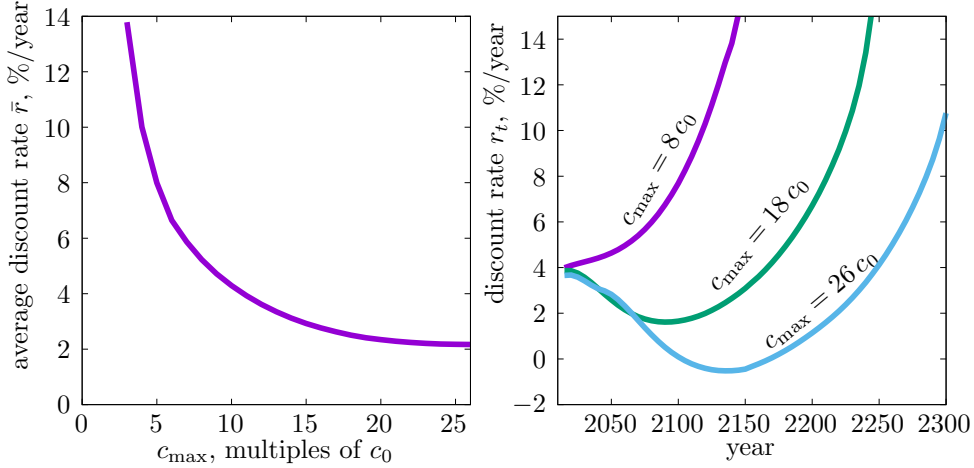


Figure 2.4: Left panel: Average endogenous intergenerational discount rate between 2010 and 2300 as a function of sufficient steady-state well-being c_{\max} . Right panel: Endogenous intergenerational discount rate over time for three different levels of sufficient steady-state well-being.

The left panel in figure 2.4 sheds some further light on how our approach of directly specifying the intertemporal distribution of well-being relates to the standard setting using a discounted utilitarian SWF: It depicts the average yearly intergenerational discount rate⁶ for well-being per capita $\bar{r}(t; c_{\max})$ as a function of c_{\max} , which would result in the respective discount factor in year 2100, i.e. $\Delta(2100; c_{\max})$. The function $\bar{r}(t; c_{\max})$ is a decreasing function of c_{\max} reflecting that a higher level of steady-state well-being is equivalent to a smaller intergenerational discount rate. The right panel in figure 2.4 shows the implied intergenerational discount rates as a function of time for three different steady-state levels of well-being. Clearly, these implied discount rates are non-constant over time. They first increase only slowly (for a low level of c_{\max}), or decrease (for higher levels of c_{\max}), and may temporarily imply negative values (for high levels of c_{\max}). Approaching the end-of-growth horizon τ , the implied intergenerational discount rates increase strongly, reaching high values shortly before the steady state is reached.

Comparing the results shown in Figures 2.3 and 2.4, we find that for the steady-state level of well-being $c_{\max} \approx 11.5$ that leads to a social cost of carbon similar to

⁶For the purpose of our analysis here we do not distinguish between different drivers of the intergenerational discount rate like the pure rate of time preference and the preference for intertemporal consumption smoothing. What matters in this paper is the possibility of choosing between different intertemporal distributions of well-being and acknowledging the implied social cost of carbon. The reason we make the link to discounting in figure 2.4, is to transparently show the way it is possible to switch from our approach back to the standard discounted utilitarian SWF setting.

the value from Nordhaus (2014), the corresponding average intergenerational discount rate is about 4.2% per year, which is in line with the Nordhaus model.

In short, our analysis makes the intergenerational trade-off in the light of anthropogenic climate change very transparent: Increasing τ and thereby letting g_t^c be more evenly intertemporally distributed, raises both the social cost of carbon in 2015 and the sacrifice in well-being for early generations.

2.5 Discussion and conclusions

Our paper explores how alternative social objectives on the intertemporal distribution of well-being affect the social cost of carbon. Specifically, it opens a new perspective for the lively debate on which parametrization of an intertemporal SWF should be applied in climate economics, by shifting the focus directly on alternative specifications of the intertemporal distribution of well-being, instead of alternative specifications of an abstract welfare function.

Determining the time path of well-being that efficiently reaches a pre-specified constant steady-state level of well-being after a finite “end-of-growth” time horizon by means of dynamic optimization, we find that the social cost of carbon in 2015 is a convex function of this sufficiency level of steady-state well-being. The convex effect of the sufficiency level of well-being on the social cost of carbon is bounded above by the availability of a backstop technology. Nordhaus and Sztorc (2013) and Nordhaus (2014) assume that the initial backstop price is 344 US\$ for 100% CO_2 removal in 2010 and then exponentially declines over time. Hence, the societal price of achieving a just intertemporal distribution in a carbon dependent economy also depends on the availability of mitigation technologies.

The level of well-being that is desired in steady state is related to the weight society puts on the well-being of future generations. In this respect, we find that a higher emphasis on long-run growth of well-being strongly raises the social cost of carbon today and increases the sacrifice in well-being for early generations. Consequently the earlier the point of zero growth is reached, implying a more uneven distribution of growth in well-being over time, the higher are the initial levels of per capita well-being from 2010 to 2030.

We acknowledge that for a policy-maker the specification of the steady-state level of well-being may be of similar complexity as the choice of the social discount rate within the standard approach of using a SWF. We believe, however, that a policy-maker could find it easier to choose a target steady-state level of well-being c_{\max} and understand the respective implications for intergenerational justice as opposed to understand the effect of the social discount rate being hidden in the SWF construct. Hence, although the policy-maker can be thought of as indirectly deciding on intergenerational discounting when choosing c_{\max} , the direct choice of an intertemporal distribution of well-being increases transparency for policy-makers and society.

By making the intergenerational trade-off in the light of anthropogenic climate change more transparent, the results show that normative conceptions of intergenerational distributive justice crucially determine the social cost of carbon. Therefore the knowledge of the overall societal goal in terms of the intertemporal distribution of well-being should be the starting point of the integrated assessment of climate change. Policy-makers then choose among different feasible paths of well-being as opposed to discussing the “correct” parameters of the respective intertemporal SWF.

For the given modeling horizon of 300 years in DICE and an infinite end-of-growth horizon, the intertemporal distribution of well-being would be determined by the maximal growth rate of well-being per capita that can be sustained for every period leading to almost the maximal possible social cost of carbon of 344 US\$ in 2015. But what about the effect of extending the modeling horizon? Being an IAM, the DICE model is designed to estimate optimal carbon prices for a finite time horizon. Nevertheless, given that we are not aware of an appropriate time horizon to be considered in climate change analysis, it is important to understand that the average optimized growth rate of well-being per capita will decrease with increasing time-horizon. Moreover, as time approaches infinity, the economy will have paid for both climate damages and abatement costs. Thus, only the underlying one-sector growth model will be relevant from which it is well-known that the per capita growth rate equals the growth rate of total factor productivity, which equals zero as time approaches infinity.⁷ In short, an infinite

⁷Let \bar{g} be the average growth rate of well-being per capita. Then we have $\lim_{t \rightarrow \infty} g_0^A e^{-5t\delta^A} = \lim_{t \rightarrow \infty} \bar{g} = 0$. See Appendix A.1.3 for detailed equations of the DICE model.

end-of-growth horizon τ would be feasible within the DICE modeling horizon of 300 years, but not in general as growth will be zero in the limit, which makes sense for the DICE-economy, were growth is not decoupled from carbon-intensive production.

Naturally the analysis in the paper is subject to limitations. Obviously, as we use the DICE model, our quantitative results are subject to limitations build into the DICE model. This includes that we ignore uncertainty, endogenous population and directed technical change. To include, for example, uncertainty on the growth rate of well-being, would be a difficult task since the whole approach we propose in this paper relies on choosing among pathways of well-being per capita that are known with certainty. Nevertheless, this could be an interesting future research project. Incorporating uncertainty on climate variables in turn, would not change the reasoning behind our results, we conjecture. Moreover, well-being is solely determined by an index of inclusive consumption per capita and hence, abstracts from relative price effects of other determinants of well-being. Sterner and Persson (2008) show that incorporating the relative price of environmental quality in the measurement of well-being can increase optimal emission abatement in DICE. Hence, besides using a lower intergenerational discount rate, relative prices can be an additional argument for more stringent climate policies. We suspect, however, that considering relative prices would not change the qualitative insights of this paper as the relation between the intertemporal distribution of well-being and the social cost of carbon is independent from the way well-being is actually measured.

Furthermore, the set of pathways obtained by directly specifying our functional form for the intertemporal distribution of well-being with different growth horizons τ is limited by its underlying assumptions. Although we believe that these assumptions are plausible and helpful to model the trade-off between the intergenerational distribution of well-being and the social cost of carbon, they are entirely normative and thus, subject to debate.

A.1 Appendix to Chapter 2

A.1.1 Efficient development of the climate-economy system

In the following we sketch the generic framework of the integrated climate-economy model according to the discrete-time DICE structure (Nordhaus and Sztorc 2013, Nordhaus 2014). Functional forms and parameter specifications can be found in Appendix 2.

We use K_t to denote the economy's capital stock in period t , and $Y(L_t, K_t, E_t, T_t^{AT}, t)$ to denote the production function. Output depends positively on labor L_t , which changes over time due to population growth, the capital stock K_t , and carbon emissions E_t . Output decreases with the global mean atmospheric temperature, T_t^{AT} , which determines climate damages. Productivity increases over time due to exogenous technical progress. Aggregate inclusive consumption⁸ in period t is $C_t = L_t c_t$, where L_t is population size and c_t is per capita consumption. Using δ^K to denote the proportional rate of capital depreciation, the national accounting equation reads

$$K_{t+1} = (1 - \delta^K) K_t + Y(L_t, K_t, E_t, T_t^{AT}, t) - L_t c_t \quad \text{accounting} \quad (\text{A.1a})$$

The atmospheric temperature develops according to

$$T_{t+1}^{AT} = T_t^{AT} + \chi^1 [F_{t+1} - \chi^2 T_t^{AT} - \chi^3 (T_t^{AT} - T_t^{LO})] \quad \text{atmospheric temperature} \quad (\text{A.1b})$$

where

$$F_{t+1} = \kappa \left[\frac{\log(M_{t+1}^{AT}/M_{EQ}^{AT})}{\log 2} \right] + F_{t+1}^{EX} \quad (\text{A.1c})$$

⁸Referred to as “consumption” from here on.

is radiative forcing, which depends on the atmospheric stock of Carbon, M_t^{AT} . Atmospheric temperature also reacts to the lower ocean temperature, which, in turn, develops according to

$$T_{t+1}^{LO} = T_t^{LO} + \chi^4 (T_t^{AT} - T_t^{LO}) \quad \text{lower ocean temperature} \quad (\text{A.1d})$$

The carbon cycle is modeled by the following three-box model which stocks of carbon in the atmosphere, M_t^{AT} , the upper ocean, M_t^{UP} , and the lower ocean, M_t^{LO} . Carbon emissions enter into the atmosphere. The entire carbon cycle is described by

$$M_{t+1}^{AT} = E_{t+1} + \phi^{11} M_t^{AT} + \phi^{21} M_t^{UP} \quad \text{atmospheric carbon stock} \quad (\text{A.1e})$$

$$M_{t+1}^{UP} = \phi^{12} M_t^{AT} + \phi^{22} M_t^{UP} + \phi^{32} M_t^{LO} \quad \text{upper ocean carbon stock} \quad (\text{A.1f})$$

$$M_{t+1}^{LO} = \phi^{23} M_t^{UP} + \phi^{33} M_t^{LO} \quad \text{lower ocean carbon stock} \quad (\text{A.1g})$$

Given the initial states of capital, K_0 , resource, S_0 , carbon stocks, M_0^{AT} , M_0^{UP} , M_0^{LO} , and temperatures, T_0^{AT} and T_0^{LO} , and given population and technology developments, the set of equations (A.1) define all feasible consumption/emission paths. The question is which among all feasible paths should be chosen. The answer to this question determines the social cost of carbon, i.e. the shadow price of carbon emissions into the atmosphere.

One natural restriction would be to choose only among the dynamically efficient consumption/emissions paths. Assuming that well-being depends only on consumption, a feasible path $c_t = (c_0, c_1, \dots)$ is dynamically efficient if no other feasible path $c'_t = (c'_0, c'_1, \dots)$ exists with $c'_t \geq c_t$ for all t and $c'_t > c_t$ for at least one period t . The dynamically efficient investment/emission path is found by maximizing per capita consumption c_{t_m} at one period in time t_m , keeping consumption at all other points in time at some pre-specified feasible minimum levels, $c_t \geq \bar{c}_t$ for all $t \neq t_m$.

Defining $\pi_{t_m} = 1$ and $\bar{c}_{t_m} = 0$, the Lagrangian for this optimization problem can be compactly written as

$$\begin{aligned}
L = & \sum_{t=0}^{\infty} \pi_t L_t (c_t - \bar{c}_t) + \lambda_t^K \left((1 - \delta^K) K_t + Y(L_t, K_t, E_t, T_t^{AT}, t) - L_t c_t - K_{t+1} \right) \\
& + \lambda_t^{TAT} \left(T_t^{AT} + \chi^1 \left[\kappa \left[\frac{\log(M_{t+1}^{AT}/M_{EQ}^{AT})}{\log 2} \right] + F_{t+1}^{EX} - \chi^2 T_t^{AT} - \chi^3 (T_t^{AT} - T_t^{LO}) \right] - T_{t+1}^{AT} \right) \\
& \quad + \lambda_t^{TLO} (T_t^{LO} + \chi^4 (T_t^{AT} - T_t^{LO}) - T_{t+1}^{LO}) \\
& \quad + \lambda_t^{MAT} (E_{t+1} + \phi^{11} M_t^{AT} + \phi^{21} M_t^{UP} - M_{t+1}^{AT}) \\
& \quad + \lambda_t^{MUP} (\phi^{12} M_t^{AT} + \phi^{22} M_t^{UP} + \phi^{32} M_t^{LO} - M_{t+1}^{UP}) \\
& \quad \quad + \lambda_t^{MLO} (\phi^{23} M_t^{UP} + \phi^{33} M_t^{LO} - M_{t+1}^{LO}), \quad (\text{A.2})
\end{aligned}$$

where π_t is the Lagrangian multiplier for the constraint $c_t \geq \bar{c}_t$; λ_t^K for the capital accumulation constraint (4.7); λ_t^{TAT} for atmospheric temperature (A.1b); λ_t^{TLO} for the temperature of the lower ocean (A.1d); and λ_t^{MAT} , λ_t^{MUP} , and λ_t^{MLO} for the carbon stocks in the atmosphere, upper and lower ocean, respectively.

The first-order conditions describing an efficient development of the climate-economy system can be written as follows. The conditions for the dynamically efficient consumption and emission levels are

$$\frac{\partial L}{\partial C_t} = 0 \quad \Leftrightarrow \quad \pi_t = \lambda_t^K \quad (\text{A.3a})$$

$$\frac{\partial L}{\partial E_t} = 0 \quad \Leftrightarrow \quad \lambda_t^K Y_{E_t} = -\lambda_{t-1}^{MAT} \quad (\text{A.3b})$$

and the condition for the efficient intertemporal allocation of capital is

$$\frac{\partial L}{\partial K_t} = 0 \quad \Leftrightarrow \quad \lambda_t^K (1 - \delta^K + Y_{K_t}) = \lambda_{t-1}^K \quad (\text{A.3c})$$

The conditions for the efficient temperature dynamics capture the coupled dynamics of the two temperature boxes, as well as damage caused by the atmospheric temperature on production output.

$$\frac{\partial L}{\partial T_t^{AT}} = 0 \quad \Leftrightarrow \quad \lambda_{t-1}^{TAT} = \lambda_t^{TAT} (1 - \chi^1 (\chi^2 + \chi^3)) + \lambda_t^{TLO} \chi^4 + \lambda_t^K Y_{T_t^{AT}} \quad (\text{A.3d})$$

$$\frac{\partial L}{\partial T_t^{LO}} = 0 \quad \Leftrightarrow \quad \lambda_{t-1}^{TLO} = \lambda_t^{TAT} \chi^1 \chi^3 + \lambda_t^{TLO} (1 - \chi^4). \quad (\text{A.3e})$$

Finally, the efficient dynamics of the carbon cycle are characterized by

$$\frac{\partial L}{\partial M_t^{AT}} = 0 \quad \Leftrightarrow \quad \lambda_{t-1}^{MAT} = \lambda_t^{MAT} \phi^{11} + \lambda_t^{MUP} \phi^{12} + \lambda_{t-1}^{TAT} \frac{\chi^1 \kappa}{\log 2} \frac{1}{M_t^{AT}} \quad (\text{A.3f})$$

$$\frac{\partial L}{\partial M_t^{UP}} = 0 \quad \Leftrightarrow \quad \lambda_{t-1}^{MUP} = \lambda_t^{MAT} \phi^{21} + \lambda_t^{MUP} \phi^{22} + \lambda_t^{MLO} \phi^{23} \quad (\text{A.3g})$$

$$\frac{\partial L}{\partial M_t^{LO}} = 0 \quad \Leftrightarrow \quad \lambda_{t-1}^{MLO} = \lambda_t^{MUP} \phi^{32} + \lambda_t^{MLO} \phi^{33}, \quad (\text{A.3h})$$

capturing the dynamics of carbon flows between the three boxes and the effect of atmospheric carbon on the atmospheric temperature. Conditions (A.3) together with (A.1) characterize any Pareto-efficient dynamic path. The initial social cost of carbon, measured in units of consumption, along the Pareto-efficient path are given by the ratio of the Lagrangian multiplier of atmospheric carbon, λ_0^{MAT} , and of consumption at $t = 0$, λ_0^K . Clearly, the pre-specified consumption levels \bar{c}_t will have a major influence on the social cost of carbon. Thus, a central question is how to distribute per-capita consumption over time, i.e. which among the many Pareto-efficient paths to choose.

Maximizing (3.6) subject to (A.1) leads to conditions (A.3), but with (A.3a) replaced by

$$(1 + \rho)^{-t} c_t^{-\eta} = \lambda_t^K \stackrel{(\text{A.3c})}{\Leftrightarrow} (1 + \rho) \left(1 + \frac{c_t - c_{t-1}}{c_{t-1}} \right)^\eta = 1 + Y_{K_t} - \delta^K, \quad (\text{A.4})$$

which is the discrete-time version of the well-known Ramsey rule (Dasgupta 2008). This condition characterizes the intertemporal distribution of consumption that is optimal according to (3.6).

A.1.2 Proof of Theorem 1

In general there are trade-offs between Assumptions 3, 4, and 5, i.e. the preferences for early growth, smooth growth, and efficiency. An intertemporal distribution of well-being c_t , $t \in 0, T$ with some finite $T > \tau$ that is compatible with all three Assumptions 3–5 is obtained by maximizing one of these three objectives while keeping the other two at some minimum levels. Additionally imposing 1 and 2, a path of well-being that is compatible with Assumptions 1–5 is characterized by the solution of the following optimization problem.

$$\max_{\{c_t\}_0^\tau: c_{\max} \in \mathbb{X}} \int_0^T c_t dt \quad \text{subject to} \quad (\text{A.5})$$

$$\int_0^\tau f(c_t) dt \geq \sigma \quad (\text{Lagrangian multiplier } \lambda) \quad (\text{A.6})$$

$$\int_0^\tau h(t - \tau) c_t dt \geq \epsilon \quad (\text{Lagrangian multiplier } \mu) \quad (\text{A.7})$$

$$c_t = c_{\max} \quad \text{for all } t \geq \tau \quad (\text{Lagrangian multiplier } \nu_t), \quad (\text{A.8})$$

and c_0 given, and where σ and ϵ are levels of ‘smoothness’ and ‘earliness’ fixed at feasible levels. In this formulation, the maximization (A.5) captures assumption 5 of efficiency, i.e. to maximize aggregate well-being over time while not reducing smoothness or earliness of growth below the respective given levels: constraint (A.6) captures the preference for smooth growth (assumption 4), constraint (A.7) captures the preference for early growth (assumption 3), constraint (A.8) the assumption that a sufficient level of well-being is maintained after the end-of-growth horizon τ (assumption 2), and finally the initial condition captures assumption 1.

The Lagrangian for the optimization problem is $L = \int_0^T c_t dt + \lambda (\sigma - \int_0^\tau f(c_t) dt) + \mu (\epsilon - \int_0^\tau h(t - \tau) c_t dt)$ and the first-order conditions for choosing c_t efficiently for all $t < \tau$ read

$$1 - \mu h(t - \tau) - \lambda f'(c_t) = 0. \quad (\text{A.9})$$

Note that μ and λ are time-invariant. Their values depend on the reference values σ for smooth growth and ϵ for early growth. Rearranging we obtain

$$\Leftrightarrow c_t = f'^{-1} \left(\frac{1 - \mu h(t - \tau)}{\lambda} \right). \quad (\text{A.10})$$

Using the boundary condition $c_\tau = c_{\max}$ we obtain

$$c_{\max} = f'^{-1} \left(\frac{1}{\lambda} \right) \Leftrightarrow \lambda = \frac{1}{f'(c_{\max})} \quad (\text{A.11})$$

The initial condition yields

$$c_0 = f'^{-1} \left(\frac{1 - \mu h(-\tau)}{\lambda} \right) \Leftrightarrow \mu = \frac{1}{h(-\tau)} \left(1 - \frac{f'(c_0)}{f'(c_{\max})} \right), \quad (\text{A.12})$$

where we have used the expression for λ derived above. Using (A.11) and (A.12) in (A.10) we obtain (2.6). For $t \geq \tau$, the first-order condition for the efficient level of c_t is $1 = \nu_t$. The derivative of the Lagrangian with respect to c_{\max} is equal to $\nu_t = 1 > 0$. Thus, c_{\max} is to be chosen at the maximum feasible level as specified in the theorem. Note that the given assumptions characterize the preferred paths of well-being in a rather restrictive way. Given c_0 and τ (Assumptions 1 and 2), and choosing c_{\max} at the maximum feasible level (Assumption 5) fully determines the ‘earliness’ and ‘smoothness’ of the path – there are no further degrees of freedom. Alternatively one could choose earliness or smoothness at the maximum feasible levels, but then the other of the two as well as aggregate consumption would be fixed.

As the last step of the proof, we verify that the path of well-being characterized by (2.6) is monotonic in time. This is the case, as $f'^{-1}(\cdot)$ is a decreasing function (due to the assumed concavity of $f(\cdot)$) and as

$$\begin{aligned} \frac{d}{dt} \left(f'(c_{\max}) \left(1 + \frac{h(t - \tau)}{h(-\tau)} \left(\frac{f'(c_0)}{f'(c_{\max})} - 1 \right) \right) \right) = \\ \frac{h'(t - \tau)}{h(-\tau)} (f'(c_0) - f'(c_{\max})) \lesseqgtr 0 \text{ if } c_0 \lesseqgtr c_{\max}. \end{aligned}$$

A.1.3 DICE-2013R model

Table 2.2: DICE 2013R, Data (1)

Parameter	Unity	Equation
Preferences		
Time preference rate / year	-	$\rho = 0.015$
Elasticity of marginal utility of consumption	-	$\eta = 1.45$
Population and technology		
Capital elasticity	-	$\gamma = 0.3$
Initial world population	Millions	$L_0 = 6838$
Population growth rate	-	$g^L = 0.134$
Depreciation rate of capital / year	-	$\delta^K = 0.1$
Initial world gross output	Trillions 2005 US\$	$Y_0^{Gross} = 63.69$
Initial capital	Trillion 2005 US\$	$K_0 = 135$
Initial level of total factor productivity (TFP)	-	$A_0 = 3.8$
Initial growth rate of TFP / period	-	$g_0^A = 0.079$
Decline rate of TFP / period	-	$\delta^A = 0.006$

Table 2.3: DICE 2013R, Data (2)

Parameter	Unity	Equation
Emissions		
Initial industrial emissions	Gigatons CO ₂	$E_0^{Ind} = 33.61$
Initial emissions control rate	-	$\mu_0 = 0.039$
Emissions control rate 2010-2150	-	$\mu = [0, 1]$
Emissions control rate 2150-2310	-	$\mu = [0, 1.2]$
Initial land emissions	Gigatons CO ₂	$E_0^{Land} = 3.3$
Initial cumulative emissions	Gigatons CO ₂	$E_0^{Cum} = 90$
Initial carbon intensity	Kilograms CO ₂	$\sigma_0 = \frac{E_0^{Ind}}{Y^{Gross}(1-\mu_0)}$
Initial growth of carbon intensity	-	$g_0^{sigma} = -0.01$
Decline rate of carbon intensity / period	-	$\delta^\sigma = -0.001$
Carbon cycle		
Initial concentration atmosphere	Gigatons carbon	$M_0^{AT} = 830.4$
Initial concentration upper oceans	Gigatons carbon	$M_0^{UP} = 1527$
Initial concentration deep oceans	Gigatons carbon	$M_0^{LO} = 10010$
Equilibrium concentration atmosphere	Gigatons carbon	$M_{EQ}^{AT} = 588$
Equilibrium concentration upper oceans	Gigatons carbon	$M_{EQ}^{UP} = 1350$
Equilibrium concentration deep oceans	Gigatons carbon	$M_{EQ}^{UP} = 10000$
Flow atmosphere to atmosphere	-	$\phi_{11} = 1 - \phi_{12}$
Flow upper oceans to atmosphere	-	$\phi_{21} = \phi_{12} \frac{M_{EQ}^{AT}}{M_{EQ}^{UP}}$
Flow atmosphere to upper oceans	-	$\phi_{12} = 0.088$
Flow upper oceans to upper oceans	-	$\phi_{22} = 1 - \phi_{21} - \phi_{23}$
Flow deep oceans to upper oceans	-	$\phi_{32} = \phi_{23} \frac{M_{EQ}^{UP}}{M_{EQ}^{LO}}$
Flow upper oceans to deep oceans	-	$\phi_{23} = 0.0025$
Flow deep oceans to deep oceans	-	$\phi_{11} = 1 - \phi_{12}$

Table 2.4: DICE 2013R, Data (3)

Parameter	Unity	Equation
Climate model		
Equilibrium climate sensitivity	°C increase /doubling of CO ₂	$\nu = 2.9$
Forcing due to equilibrium CO ₂ doubling	Watts / square meter	$\kappa = 3.8$
2010 forcing of non-CO ₂ GHG	Watts / square meter	$F_0^{EX} = 0.25$
2100 forcing of non-CO ₂ GHG	Watts / square meter	$F_{18}^{EX} = 0.7$
Initial atmospheric temperature change	°C from 1750	$T_0^{AT} = 0.8$
Initial deep oceans temperature change	°C from 1750	$T_0^{LO} = 0.0068$
Speed of adjustment atmospheric temperature	-	$\chi_1 = 0.098$
Equilibrium forcing /doubling of CO ₂	-	$\chi_2 = \kappa/\nu$
Heat loss from atmosphere to deep oceans	-	$\chi_3 = 0.088$
Heat gain of deep oceans	-	$\chi_4 = 0.025$
Climate change abatement costs		
Damage quadratic term	-	$\psi = 0.00267$
Initial abatement costs	Trillions 2005 US\$	$\Lambda_0 = 0$
Exponent of abatement cost function	-	$\Theta = 2.8$
Initial backstop price	2005 US\$	$p_0^{Back} = 344$
Decline rate of backstop price / period	-	g^{Back}

Table 2.5: DICE 2013R, Exogenous equations

Parameter	Unity	Equation
Total population	Millions	$L_t = L_{t-1} \left(\frac{10500}{L_{t-1}} \right)^{g^L}$
Total factor productivity (TFP)	-	$A_t = \frac{A_{t-1}}{1-g_{t-1}^A}$
Growth rate TFP per period	-	$g_t^A = g_0^A e^{-5t\delta^A}$
Total factor productivity (TFP)	-	$A_t = \frac{A_{t-1}}{1-g_{t-1}^A}$
Carbon intensity	Kilograms CO ₂ / output	$\sigma_t = \sigma_{t-1} e^{-5g_{t-1}^\sigma}$
Growth rate of carbon intensity / period	-	$g_t^\sigma = \frac{g_{t-1}^\sigma}{(1+\delta^\sigma)^5}$
External forcing	Watts / square meter	$F_t^{EX} = F_0^{EX} + \frac{1}{18} (F_{18}^{EX} - F_0^{EX}) (t + 2)$
Backstop price	2005 US\$ / ton of CO ₂	$p_t^{Back} = p_{t-1}^{Back} (1 - g^{Back})$
Adjusted cost factor for backstop	2005 US\$ / ton of CO ₂	$\hat{p}_t^{Back} = \frac{p_t^{Back} \sigma_t}{1000 \theta}$

Table 2.6: DICE 2013R, Endogenous equations

Parameter	Unity	Equation
Welfare under Nordhaus	-	$W_0(c_0, c_1, c_2, \dots) = \sum_{t=0}^{60} \frac{1}{(1+\rho)^{5t}} L_t \frac{c_t^{1-\eta}}{1-\eta}$
Total emissions	Gigatons CO ₂	$E_t = E_t^{Ind} + E_t^{Land}$
Carbon concentration atmosphere	Gigatons carbon	$M_t^{AT} = \frac{5}{3.666} E_t + \phi^{11} M_{t-1}^{AT} + \phi^{21} M_{t-1}^{UP}$
Carbon concentration upper oceans	Gigatons carbon	$M_t^{UP} = \phi^{12} M_{t-1}^{AT} + \phi^{22} M_{t-1}^{UP} + \phi^{32} M_{t-1}^{LO}$
Carbon concentration lower oceans	Gigatons carbon	$M_t^{LO} = \phi^{23} M_{t-1}^{UP} + \phi^{33} M_{t-1}^{LO}$
Total radiative forcing	Watts / square meter	$F_t = \kappa \left[\frac{\log(M_t^{AT}/M_{EQ}^{AT})}{\log 2} \right] + F_t^{EX}$
Atmospheric temperature change	°C from 1750	$T_t^{AT} = T_{t-1}^{AT} + \chi [F_t - \chi^2 T_{t-1}^{AT} - \chi^3 (T_{t-1}^{AT} - T_{t-1}^{LO})]$
Upper ocean temperature change	°C from 1750	$T_t^{LO} = T_{t-1}^{LO} + \chi^4 (T_{t-1}^{AT} - T_{t-1}^{LO})$
Capital	Trillions 2005 US\$	$K_t = (1 - \delta^K)^5 K_{t-1} + 5I_{t-1}$
Gross output	Trillions 2005 US\$	$Y^{Gross} = A_t \left(\frac{L_t}{1000} \right)^{1-\gamma} K_t^\gamma$
Industrial emissions	Gigatons CO ₂	$E_t^{Ind} = \sigma_t (1 - \mu_t) Y^{Gross}$
Cumulative emissions	Gigatons carbon	$E_t^{Cum} = E_{t-1}^{Cum} + \frac{5}{3.666} E_{t-1}^{Ind} \leq 6000$
Abatement costs	Trillions 2005 US\$	$\Lambda_t = Y_t^{Gross} \hat{p}_t^{Back} \mu_t^\Theta$
Damage fraction	-	$\Omega_t = \Psi (T_t^{AT})^2$
Net output	Trillions 2005 US\$	$Y_t = [Y_t^{Gross} (1 - \Omega_t)] - \Lambda_t$
Consumption	Trillions 2005 US\$	$C_t = Y_t - I_t$
Consumption per capita	Thousands 2005 US\$	$c_t = \frac{1000 C_t}{L_t}$
Social cost of carbon	2005 US\$ / ton of carbon	$p_t^c = p_t^{Back} \mu_t^{\Theta-1}$

A.1.4 AMPL programming code

```
# PARAMETERS

# modeling horizon
param T:=60;

# population and technology
param gamma:=0.3; # capital elasticity in production function
param L0:=6838; # initial world population (millions)
param gL:=0.134; # initial growth rate of world population per period
such that popasymt=10500

param L {t in 0..T}>=0;
let L[0]:=L0;
let {t in 1..T} L[t]:=L[t-1]*((10500/L[t-1])^gL);

param deltaK:=0.1; #depreciation rate on capital per year
param Qgross0:=63.69; #initial world gross output (trillions 2005 USD)
param K0:=135; #initial capital value (trillions 2005 USD)
param A0:=3.8; #initial level of total factor productivity (TFP)
param gA0:=0.079; #initial growth rate for TFP per period
param deltaA:=0.006; #decline rate of TFP per period

param gA {t in 0..T}>=0; # growth rate for TFP per period
let {t in 0..T} gA[t]:=gA0*exp(-deltaA*5*(t));

param A {t in 0..T}>=0; # TFP
let A[0]:=A0;
let {t in 1..T} A[t]:=A[t-1]/(1-gA[t-1]);
```

```

# emission parameters
param gsigma0:=-0.01; #initial growth rate of sigma (coninuous per year)
param deltasigma:=-0.001; #decline rate of decarbonization per period
param ELand0:=3.3; # initial land emissions(GtCO2)
param deltaLand:=0.2; #decline rate of land emissions per period
param EInd0:=33.61; # initial industrial emissions(GtCO2)
param Ecum0:=90; #initial cumulative emissions (GtC)
param mu0:=0.039; # initial emissions control rate
param Lambda0:=0; # initial abatement costs(trillions 2005 USD)
param sigma0:=EInd0/(Qgross0*(1-mu0)); #initial carbon intensity(kgCO2 per output)

param gsigma {t in 0..T}; # growth rate of carbon intensity per period
let gsigma[0]:=gsigma0;
let {t in 1..T} gsigma[t]:=gsigma[t-1]*((1+deltasigma)^5);

param sigma {t in 0..T}>=0; # carbon intensity(kgCO2 per output of 2005 USD)
let sigma[0]:=sigma0;
let {t in 1..T} sigma[t]:=sigma[t-1]*exp(gsigma[t-1]*5);

param ELand {t in 0..T}>=0; # land emissions per period (GtCO2)
let ELand[0]:=ELand0;
let {t in 1..T} ELand[t]:=ELand [t-1]*(1-deltaLand);

# carbon cycle
param MAT0=830.4; # initial concentration in atmosphere(GtC)
param MUP0:=1527; # initial concentration in upper ocean/biosphere(GtC)
param ML00:=10010; # initial concentration in deep oceans(GtC)
param MATEQ:=588; # equilibrium concentration in atmosphere
(preindustrial atmospheric carbon) (GtC)
param MUPEQ:=1350; # equilibrium concentration in upper ocean/biosphere (GtC)
param MLOEQ:=10000; # equilibrium concentration in deep oceans(GtC)

```

```

# flow parameters (carbon cycle transition matrix)
param phi12:=0.088;
param phi23:=0.00250;
param phi11=1-phi12;
param phi21=phi12*MATEQ/MUPEQ;
param phi22=1-phi21-phi23;
param phi32=phi23*MUPEQ/MLOEQ;
param phi33=1-phi32;

# climate model parameters
param nu:=2.9; # equilibrium climate sensitivity (°C per doubling CO2)
param kappa:=3.8; # forcing of equilibrium CO2 doubling (Wm-2)
param Fex0:=0.25; # 2010 forcing of non-CO2 GHG (Wm-2)
param Fex18:=0.70; # 2100 forcing of non-CO2 GHG (Wm-2)
param Fex {t in 0..T}=Fex0+1/18*(Fex18-Fex0)*(2+t); # external forcing (Wm-2)
param TL00:=0.0068; # initial temperature change of upper ocean/biosphere
(°C from 1750)
param TAT0:=0.80; # initial atmospheric temperature change (°C from 1750)
param xi1:=0.098; # speed of adjustment parameter for atmospheric temperature
param xi2=kappa/nu; # climate model parameter
param xi3:=0.088; # coefficient of heat loss from atmosphere
to upper oceans/biosphere
param xi4:=0.025; # coefficient of heat gain by deep oceans

# climate damage parameters
param Psi:=0.00267; # damage quadratic term

# abatement cost
param Theta:=2.8; # exponent of abatement cost function
param pback0:=344; # initial backstop price(2005 USD per tCO2)

```

```

param gback:=0.025; # decline rate of backstop price per period

param pback {t in 0..T}>=0; # backstop price(2005 USD per tCO2)
let pback[0]:=pback0;
let {t in 1..T} pback[t]:=pback[t-1]*(1-gback);

param phead {t in 0..T}=pback[t]*sigma[t]/Theta/1000;
# adjusted cost factor for backstop

# VARIABLES # Upper and lower bounds for stability according to Nordhaus (2013)

# capital(trillions 2005 USD)
var K {t in 0..T}>=1;

# Gross output(trillions 2005 USD)
var Qgross {t in 0..T}=A[t]*((L[t]/1000)^(1-gamma))*(K[t]^gamma);

# carbon atmosphere (GtC)
var MAT {t in 0..T}>=10;

# carbon upper ocean (GtC)
var MUP {t in 0..T}>=100;

# carbon lower ocean (GtC)
var MLO {t in 0..T}>=1000;

# total radiative forcing (Wm-2)
var F {t in 0..T}=kappa*((log(MAT[t]/MATEQ))/log(2))+Fex[t];

# atmospheric temperature change (°C from 1750)
var TAT {t in 0..T}>=0,<=40;

```

```

# ocean temperature change (°C from 1750)
var TLO {t in 0..T}>=-1, <=20;

# damage fraction
var Omega {t in 0..T}=Psi*(TAT[t])^2;

# damages(trillions 2005 USD)
var damage {t in 0..T}=Omega[t]*Qgross[t];

# emission control rate
var mu {t in 0..T}>=0;

# abatement costs as fraction of output(trillions 2005 USD)
var Lambda {t in 0..T}=Qgross[t]*phead[t]*(mu[t]^Theta);

# industrial emissions (GtCO2)
var EInd {t in 0..T}=sigma[t]*Qgross[t]*(1-mu[t]);

# total emissions (GtCO2)
var E {t in 0..T}=EInd[t]+ELand[t];

# maximum cumulative extraction fossil fuels (GtC)
var Ecum {t in 0..T}<=6000;

# Marginal cost of abatement (social cost of carbon)(2005 USD per tCO2)
var cprice {t in 0..T}=pback[t]*mu[t]^(Theta-1);

# output net of damages and abatement(trillions 2005 USD)
var Q {t in 0..T}=(Qgross[t]*(1-Omega[t]))-Lambda[t];

```

```

# per capita consumption (1000s 2005 USD)
param cmax default 178.88;
param c0 default 6.88;
var tau >=0;
var c {t in 0..T} = cmax^(1-(1-t/tau)^2)*c0^((1-t/tau)^2);

# aggregate consumption (trillions 2005 USD)
var C {t in 0..T} = L[t]*c[t]/1000;

# Investment(trillions 2005 USD)
var I {t in 0..T}>=0;

# OBJECTIVE FUNCTION

minimize objective_function: tau;

subject to constr_accounting {t in 0..T}: c[t]=1000*(Q[t]-I[t])/L[t];
subject to constr_capital_dynamics {t in 1..T}: K[t]=(1-deltaK)^5*K[t-1]+5*I[t-1];
subject to constr_cumulativeemissions {t in 1..T}:
Ecum[t]=Ecum[t-1]+(EInd[t-1]*5/3.666);
subject to constr_atmosphere {t in 1..T}:
MAT[t]=E[t]*(5/3.666)+phi11*MAT[t-1]+phi21*MUP[t-1];
subject to constr_upper_ocean {t in 1..T}:
MUP[t]=phi12*MAT[t-1]+phi22*MUP[t-1]+phi32*MLO[t-1];
subject to constr_lower_ocean {t in 1..T}:
MLO[t]=phi23*MUP[t-1]+phi33*MLO[t-1];
subject to constr_atmospheric_temp {t in 1..T}:
TAT[t]=TAT[t-1]+xi1*((F[t]-xi2*TAT[t-1])-(xi3*(TAT[t-1]-TLO[t-1])));
subject to constr_ocean_temp {t in 1..T}:
TLO[t]=TLO[t-1]+xi4*(TAT[t-1]-TLO[t-1]);

```

```
# Initial conditions
subject to initial_capital: K[0] = K0;
subject to initial_Ecum: Ecum[0]=Ecum0;
subject to initial_MAT: MAT[0]=MAT0;
subject to initial_MUP: MUP[0]=MUPO;
subject to initial_MLO: MLO[0]=MLO0;
subject to initial_TLO: TLO[0]=TLO0;
subject to initial_TAT: TAT[0]=TAT0;
subject to control1 {t in 1..28}: mu[t]<=1;
subject to control2 {t in 29..T}: mu[t]<=1.2;
```


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3 Relative Prices and Climate Policy

How the Scarcity of Non-Market Goods Drives Policy Evaluation

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Abstract: This paper provides a comprehensive analysis of the relative price of non-market vis-à-vis market goods and its impact on climate policy evaluation. As non-market goods are projected to become scarcer compared to market goods, it is increasingly important to consider changing relative prices when evaluating long-term policies. Based on the climate-economy model DICE and recent empirical evidence, we propose a plausible range for relative price changes. For our central calibration, the relative price change amounts to 4.4 percent in 2020 and 2 percent in 2100. Neglecting relative prices leads to an underestimation of the social cost of carbon of more than 40 percent in 2020. We furthermore show that accounting for relative price changes is equivalent to a sizable decrease in the rate of pure time preference by more than a half percentage point. Our findings offer guidance for project appraisal and for the evaluation of climate policy.

Keywords: Climate change economics, discounting, non-market goods, social cost of carbon, substitutability, sustainability

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3.1 Introduction

Relative prices are central to economics and their changes inherent in the structural transformation of economies over time. While we can easily infer relative prices from market data for most goods, estimating them for non-marketed goods poses a special challenge. In light of the continuous growth of the global economy and a loss of non-market goods, such as environmental goods (MEA 2005; IPCC 2014), at the same time, accounting for changes in the relative price of non-market goods vis-à-vis market goods is crucial for evaluating long-term policies like climate change mitigation.²

This paper provides a comprehensive analysis of the change in the relative price of non-market goods in terms of market goods, its determinants and its impact on climate policy evaluation. This is closely connected to the discussion on discounting the future, as the difference in good-specific discount rates amounts to the change in relative prices over time. The debate on how to value future costs and benefits that ensued after the publication of the Stern Review initially focused on the contentious rate of pure time preference (Nordhaus 2007, 2008; Stern 2007), but it quickly shifted to examining extensions to the standard discounting framework. Besides issues of risk and uncertainty, considering relative prices has been one of the extensions receiving wide-spread attention.³ Yet until today, there exists no systematic study of relative prices changes of non-market goods. The purpose of this paper is to fill this gap. In particular we study different drivers of relative price changes and quantify implications for the integrated assessment of climate change policy.

²Relative price changes are determined by the difference in growth rates and the degree of substitutability between goods. Suppose that the relative price of, say, biodiversity increases by 2 percent per year, such as when market goods grow at 2 percent, biodiversity remains constant and there is Cobb-Douglas substitutability. Within 100 years, the value of a unit of biodiversity in terms of a market good unit would increase by 617 percent. Hence, it is crucial to take relative price changes into account.

³See, for example, Arrow et al. (2013), Dasgupta (2008), Gollier (2012), Gollier and Hammitt (2014), Sterner and Persson (2008), and Weitzman (2007, 2009). In his recent review on *The Economics of the Climate*, Heal (2017) discusses concerns about limited substitutability after discounting and before uncertainty. Furthermore, environmental scarcity and associated relative price changes has been among the most-mentioned issues missing in discounting guidance in a recent expert survey (Drupp et al. 2015).

The literature has developed two approaches to dealing with relative price changes.⁴ The first approach uses ‘dual discount rates’ and discounts consumption streams for market and non-market goods separately.⁵ The second approach computes comprehensive consumption equivalents for each period, by appropriately valuing non-market goods using relative prices, and discounts this aggregated bundle with a single consumption-equivalent discount rate. The relative price of non-market goods is given by the marginal rate of substitution between consuming a further unit of non-market goods relative to market goods. What has been termed the ‘relative price effect’ in the literature (Hoel and Sterner 2007) is the change of the relative price of non-market goods over time. It is determined by the degree of substitutability between market and non-market goods as well as the difference in their (weighted) growth rates.

Relying on constant, exogenous growth rates for environmental goods at the global level and on substitutability estimates derived from non-market valuation studies, Baumgärtner et al. (2015) and Drupp (2016) estimate that the yearly relative price change for environmental goods amounts to around 1 percent. These estimates encouraged the Netherlands to consider relative price changes in policy guidance for cost-benefit analysis and to recommend discounting the consumption of environmental goods at a lower rate than for market goods (Hepburn and Groom 2017; Koetse et al. 2017; MFN 2015). Yet, in general, the growth rate of non-market goods is non-constant and endogenous to how we manage climate change, for instance. Our analysis therefore builds on an integrated assessment model following Sterner and Persson (2008), who first highlighted the importance of considering relative prices for climate policy. They assumed that non-market goods are complementary to consumption goods and argued that optimal climate policy—when introducing relative prices—should be more stringent than as advocated in the Stern Review, even when using the considerably higher rate of pure time preference of Nordhaus (2007). As changes in relative prices play a crucial role for the appraisal of long-term public projects, it is imperative to scrutinize the potential quantitative magnitude of the relative price effect, its determinants as

⁴See, among others, Baumgärtner et al. (2015), Drupp (2016), Gollier (2010), Gueant et al. (2012), Guesnerie (2004), Hoel and Sterner (2007), Traeger (2011), Weikard and Zhu (2005).

⁵This is the only viable approach if non-market goods and consumption goods are perfect complements (Weikard and Zhu 2005). Otherwise, the two approaches are equivalent and, at each point in time, the difference in the good-specific discount rates corresponds to the change in relative prices.

well as its implications for climate policy evaluation more closely.

We perform our analysis of relative prices in the latest version of the integrated assessment model DICE (Nordhaus 2017).⁶ We proceed as follows. Section 3.2 defines the relative price effect of non-market goods in a stylized model and subsequently presents how the DICE model can be adapted to explicitly consider relative prices. In line with previous work, we consider non-market goods at a highly aggregate level, encompassing goods related to human health as well as environmental goods, which range from clean water to aesthetic beauty. As many readers will be familiar with the study by Sterner and Persson (2008) as a natural benchmark, we initially draw on all their components for introducing relative prices into the most recent DICE version in Section 3.3. Following from this replication, we clarify how relative price changes should be interpreted and show that the standard DICE model already—implicitly—contains a sizable relative price effect, which has so far not been observed in the literature. Thus, explicitly introducing relative prices into the integrated assessment of climate change can lead to more but also less stringent optimal climate policy as compared to Nordhaus (2017). It also follows from this analysis that if non-market goods are as complementary to market goods as assumed by Sterner and Persson (2008), the impact of considering relative prices may be even more pronounced than suggested previously.

Section 3.4 scrutinizes the impact of the different determinants of relative price changes in both the short and the long run. These determinants include the degree of substitutability between market and non-market goods, the magnitude of non-market climate damages and a potential subsistence requirement in terms of non-market goods. We also study how the rate of pure time preference, the elasticity of marginal utility of consumption and technological progress affect relative price changes through the endogenous growth rate of market goods. The degree of substitutability turns out to be the key driver of relative price changes. While the elasticity of marginal utility of consumption and pure time preference matter considerably in the short-run,

⁶Integrated assessment models (IAM), such as DICE, are subject to substantial critique (Pindyck 2017). Our aim is to systematically explore the relative effect sizes of different drivers of climate policy evaluation. Although closed-form analytic climate models start to emerge (van den Bijgaart et al. 2016; Rezai and van der Ploeg 2016; Traeger 2015), IAMs still represent a useful tool for such purposes.

technological progress exerts its influence on relative price changes only in the longer run.

In Section 3.5, we combine the two previous steps of the analysis. Based on our systematic study of the individual determinants of the relative price effect, we construct plausible ranges for each of the drivers and perform a Monte Carlo analysis to determine the range of values for the relative price effect and three climate policy measures. When combining the plausible ranges of all six drivers, the resulting 95 percent interval for the relative price effect ranges from 1.3 to 9.6 percent in 2020 and from 0.8 to 3.6 percent in 2100. In our central calibration, the relative price effect amounts to 4.4 percent in the year 2020 and decreases to 2.0 percent in the year 2100. In terms of climate policy evaluation, we find that neglecting relative prices would lead to an underestimation of the social cost of carbon of around 43 (68) percent in the year 2020 (2100), and to a stabilization of temperature change that is 0.5°C higher. Using peak temperature as a comparison metric, we show that considering relative prices is equivalent to reducing the rate of pure time preference by more than 0.5 percentage points.

While there are inevitably a number of limitations of our analysis, which we discuss in Section 3.6, we overall conclude that changes in relative prices are of considerable magnitude compared to conventional considerations in the economic evaluation of climate change policy. Section 3.7 closes by drawing implications for governmental project appraisal and climate policy.

3.2 Modeling relative prices

3.2.1 A simple model of relative price changes

The well-being of a representative agent is determined by the consumption of two goods – a market-traded private consumption good C , with c as consumption per-capita, and a non-market good E . Both goods may be interpreted as composites with continuously scalable amounts. The agent may require an amount \bar{E} of the non-market good to satisfy her subsistence needs (Baumgärtner et al. 2017; Heal 2009).⁷

The agent’s preferences are represented by a utility function

$$U(E, c) = \begin{cases} U_l(E) & \text{for } E \leq \bar{E} \\ U_h(E, c) & \text{else.} \end{cases} \quad (3.1)$$

If the subsistence requirement is met ($E > \bar{E}$), which we assume throughout the remainder of this paper, utility is given by:

$$U_h(E, c) = \left[\alpha (E - \bar{E})^\theta + (1 - \alpha) c^\theta \right]^{1/\theta} \quad \text{with } -\infty < \theta \leq +1, \theta \neq 0; 0 < \alpha < 1, \quad (3.2)$$

where θ is the substitutability parameter, and α is a share parameter for the weight of the environmental good in utility.⁸ In the standard constant elasticity of substitution (CES) case without a subsistence requirement ($\bar{E} = 0$), which forms the workhorse of previous research on relative prices, the elasticity of substitution σ is solely determined by the exogenous substitutability parameter θ , with $\sigma = \frac{1}{1 - \theta}$.⁹ In the presence of a subsistence requirement, this direct relationship breaks down and the elasticity of substitution depends also on other determinants besides θ (Baumgärtner et al. 2017).

For the intertemporal setting, we build on Baumgärtner et al. (2015), Drupp (2016), Gueant et al. (2012), Hoel and Sterner (2007), Traeger (2011) and Weikard and Zhu (2005): A social planner has perfect knowledge about the future and maximizes a

⁷Examples may include food, water and air necessary for survival, or cultural goods such as sacred sites that the agent would not be willing to trade-off. In terms of environmental goods, this may also be thought of as a preference-based measure of a ‘planetary boundary’ (Rockström et al. 2009).

⁸ The extension of $U_h(E, c)$ for $\theta \rightarrow 0$ is a special Cobb-Douglas-Stone-Geory case: $(E - \bar{E})^\alpha c^{(1-\alpha)}$.

⁹ Important special cases of the elasticity of substitution are perfect substitutes ($\theta = 1$; $\sigma = \infty$), Cobb-Douglas ($\theta = 0$; $\sigma = 1$) and perfect complements ($\theta \rightarrow -\infty$; $\sigma = 0$).

constant intertemporal elasticity of substitution (CIES) social welfare function based on the instantaneous utility function U_h (Equation 3.2). Welfare is given by

$$W(E_t, c_t, L_t) = \sum_{t=0}^T L_t \frac{1}{(1+\delta)^t} \frac{1}{1-\eta} [\alpha(E_t - \bar{E})^\theta + (1-\alpha)c_t^\theta]^{\frac{1-\eta}{\theta}}, \quad (3.3)$$

where L_t is period t 's population size, δ is the rate of pure time preference and η is the inverse of the CIES with respect to the within-period aggregate consumption bundle $\tilde{c}(\theta, \bar{E}) = [\alpha(E_t - \bar{E})^\theta + (1-\alpha)(c_t)^\theta]^{\frac{1}{\theta}}$. This is often referred to as the elasticity of the marginal utility of consumption (equivalents).

We now turn to the focus of our analysis: the ‘relative price effect of non-market goods’ (hereafter denoted as RPE). The value of non-market goods measured in terms of the market good numeraire is U_E/U_c , which is the implicit ‘price’ of environmental goods.¹⁰ This tells us by how much the consumption of market goods would need to increase for a marginal decrease in non-market goods to hold utility constant. The RPE measures the change in this valuation of non-market goods, and thus their relative scarcity over time (Hoel and Sterner 2007, Eq. 7):

$$RPE_t = \frac{\frac{d}{dt} \left(\frac{U_E}{U_c} \right)}{\left(\frac{U_E}{U_c} \right)}. \quad (3.4)$$

For the utility function with a non-market subsistence requirement (Equation 3.2), the relative price effect RPE at time t reads (see Appendix B.1.1 for a derivation):

$$RPE_t = (1-\theta) \left[g_{c_t} - \frac{E_t}{E_t - \bar{E}} g_{E_t} \right].^{11} \quad (3.5)$$

The RPE depends on the degree of substitutability θ between market and non-market goods, their growth rates g_{c_t} and g_{E_t} as well as on the consumption of non-market goods over and above the subsistence requirement $\frac{E_t}{E_t - \bar{E}}$.

¹⁰This assumes that the two goods are imperfect complements ($\theta > -\infty$).

¹¹The ‘relative price effect of non-market goods’ is the same as the difference in the two good specific discount rates for market and non-market goods. This was first demonstrated by Weikard and Zhu (2005); See Drupp (2016) for a derivation of Equation 3.5 with subsistence consumption.

3.2.2 Relative prices in integrated assessment

Integrated assessment models (IAM) are a widespread tool for quantitatively analyzing climate-economy feedbacks and thus useful for studying the dynamic impacts of considering the relative price changes. We use the most recent version of the global Dynamic Integrated Climate-Economy (DICE-2016R) model by Nordhaus (1992 - 2017). It combines a Ramsey-Economy with a simple climate module through a negative feedback loop of the atmospheric temperature on economic output. A representative agent maximizes her population-weighted and discounted value of the utility of per capita consumption within a finite time horizon of 100 periods each encompassing 5 years.

To explicitly incorporate relative prices in the spirit of Sterner and Persson (2008) into DICE-2016R, we need to modify the social welfare function and the damage function from climate change. First we present how Nordhaus (2017) models social welfare and damages and, second, report the changes necessary to explicitly include relative prices. The social welfare function in Nordhaus (2017) is given by:

$$W_0(c_0, c_1, c_2, \dots) = \sum_{t=0}^{100} L_t \frac{1}{(1 + \delta)^t} \frac{\tilde{c}_t^{1-\eta}}{1 - \eta}. \quad (3.6)$$

Comprehensive consumption per-capita \tilde{c}_t is defined as an index of generalized consumption (Nordhaus and Szork 2013), which is meant to also include non-market damages but no subsistence requirement (i.e. $\bar{E} = 0$). Total climate damages D_ϕ are expressed as a percentage of the global economy's aggregate output and depend on the squared change in atmospheric temperature T compared to pre-industrial levels:

$$D_\phi = \phi T_t^2 \quad (3.7)$$

Nordhaus (2017) calibrates the aggregate scaling parameter for the damages on all generalized consumption goods via production-damages, ϕ (Equation 3.7), such that market plus non-market damages are equal to 2.12 percent of global output for a temperature increase of 3°C. These total damages include 25 percent non-market damages

additional to market damages, which amount to 1.63 percent of global output.¹² Thus, there is perfect substitutability between market and non-market damages. From this one might infer that there is also perfect substitutability between market and non-market goods in DICE (e.g. Neumayer 1999; Sterner and Persson 2008). Yet, this is not the case: Since overall damages—which include non-market damages—enter multiplicatively into what is a Cobb-Douglas production function of labor and capital at its core, the DICE model implicitly includes a relative price effect of non-market goods.¹³ Thus, while there is perfect substitutability in damages in the standard DICE, there is limited substitutability in terms of goods.

To explicitly consider relative prices in DICE, we extend the model such that utility depends not only on market but also on non-market goods. To replicate the results of Sterner and Persson (2008) within DICE-2016R, we follow their approach in extending the DICE framework to a two-good setting. Specifically we use the welfare function defined in (3.3), with $T = 100$ periods of 5 years each. First, we assume that the initial level of the aggregate non-market good E_0 is equal to the initial level of consumption of market goods ($C_0 = c_0 \times L_0$). Second, we assume that the evolution of the non-market good depends (inversely) on the square of the change in atmospheric temperature T compared to pre-industrial levels and the damage parameter ψ :

$$E_t = \frac{E_0}{[1 + \psi T_t^2]}. \quad (3.8)$$

Third, we follow Sterner and Persson’s (2008) assumption that non-market damages double the loss in consumption of marketed goods to re-calibrate ϕ . Thus, we include an additional 100 percent non-market damages on top of market damages. Hence, for

¹²Nordhaus (2017) builds on 36 studies that estimate climate damages and adds 25 percent to each damage estimate to incorporate non-market damages. These estimates are treated as data drawn from an underlying damage function and ϕ is calibrated by equating it with the coefficient of the impact of squared temperature change on climate damage estimates from an median, quadratic, weighted regression (see Nordhaus and Moffat (2017) for more details).

¹³It is not straightforward to back out the degree of substitutability already contained in the DICE model. First, non-market damages only indirectly affect market consumption goods through production. Second, the production function is not just Cobb-Douglas between labor and capital (and total factor productivity), among others due to abatement. Third, the DICE model does not directly consider exhaustible and polluting resources as production inputs (see Riekhof and Bröcker (2017) for such an extension to DICE). Our computations in Section 3.3 recover the Nordhaus comparison path in an explicit relative prices model for a mild degree of complementarity.

the baseline Nordhaus (2017) model we assume that market plus non-market damages are equal to 3.26 percent of global output for a temperature increase of 3°C. These total climate damages have to be disentangled into damages on market and non-market goods. Two new damage parameters ψ [κ] now scale up the magnitude of non-market [market] damages. Based on Nordhaus and Moffat (2017), we re-calibrate damages on market-good consumption D_κ . The damage function for market goods becomes:

$$D_\kappa = \kappa T_t^2. \quad (3.9)$$

To account for the 100 percent non-market damages on top of market damages, we follow the approach of Sterner and Persson (2008) to calibrate the non-market climate damage parameter ψ by comparing two different model specifications:¹⁴ First, a model in which non-market damages D_ϕ for a given temperature increase are perfectly substitutable for damages on market goods and are included in consumption directly. Second, a model in which damages are attributed to market goods D_κ and non-market goods D_ψ . The parameter ψ is calibrated as a residual, with $C_0 = E_0$ and $\bar{E} = 0$ (see Appendix B.1.2), and depends in particular on the non-market damage costs.

With the evolution of the non-market good (Equation 3.8) and the calibrated non-market good climate damage coefficient ψ , the *RPE* in DICE is given by:¹⁵

$$RPE_t^{DICE} = (1 - \theta) \left[g_{c_t}(\delta, \eta, \dots) + \frac{2\psi T_t^2 g_{T_t}}{(1 + \psi T_t^2)} \left(\frac{E_0}{E_0 - \bar{E}(1 + \psi T_t^2)} \right) \right]. \quad (3.10)$$

Accordingly the *RPE* in DICE depends on three components: First the growth rate of the market good g_{c_t} , which is optimally determined by the Ramsey Rule in DICE and thus depends on a number of key variables and parameters.¹⁶ It is in

¹⁴See Barrage (2016) for an alternative approach to calibrating non-market damages.

¹⁵The growth rate of non-market goods in continuous time is given by $g_{E_t} = \frac{\dot{E}_t}{E_t} = -\frac{2\psi T_t \dot{T}_t}{(1 + \psi T_t^2)}$. In discrete time, we have $g_{E_t} = \frac{E_t - E_{t-1}}{E_{t-1}} = -\frac{\psi(T_t^2 - T_{t-1}^2)}{(1 + \psi T_t^2)}$. With $T_t^2 - T_{t-1}^2 = \dot{T}_t^2 = 2T_t \dot{T}_t = T_t^2 g_{T_t}$ this is equivalent to the continuous time version.

¹⁶The growth rate of the market good is determined by $g_{c_t} = \left[\left(\frac{1}{1 + \delta} \right) (1 + Y_{K_t} - \xi) \right]^{\frac{1}{\eta}} - 1$, where ξ is the proportional rate of capital depreciation and Y_{K_t} is the marginal productivity of capital, which depends on labor L_t , capital C_t , climate damages $D_\phi(T_t)$ and is in particular driven by total factor productivity $A_t = \frac{A_{t-1}}{1 - g_{t-1}^A}$. Total factor productivity A_t grows exogenously at a decreasing rate, with

particular driven by the rate of technological progress as well as the distributional parameters of the social welfare function: the rate of pure time preference, δ , and the elasticity of the marginal utility of consumption, η . Second, the *RPE* depends on the growth rate of the non-market good g_{E_t} , which is a function of non-market damages for a particular temperature increase, summarized in the damage parameter ψ , and the growth rate of atmospheric temperature g_{T_t} , and is scaled by the size of the subsistence requirement \bar{E} . Finally, the difference in the two (weighted) good-specific growth driver categories are scaled by the degree of substitutability θ between both goods.

3.3 Relative prices and climate policy evaluation

3.3.1 The relative price effect and climate policy outcomes

In order to evaluate the impact of the relative price effect of non-market goods (*RPE*) on optimal climate policy, we consider three measures: Yearly industrial emissions, atmospheric temperature change above pre-industrial levels and the social cost of carbon (SCC).¹⁷ Industrial emissions and atmospheric temperature change are climate policy measures often referred to in science and policy circles, while the SCC is widely used by governmental bodies to inform carbon pricing.

We draw all parameter inputs from Nordhaus’s (2017) DICE-2016R, except for those that concern the explicit introduction of the non-market good—the preference share parameter α , the degree of substitutability θ as well as the magnitude of non-market damages—which are based on Sterner and Persson (2008, abbreviated as S&P). Table 3.1 provides an overview of the parameter specifications used in the S&P-*RPE* case. Figure 3.1 depicts how the S&P-*RPE* evolves over time from the year of 2020 to 2100, and how it impacts industrial CO_2 emissions, temperature change and the SCC.¹⁸

$g_t^A = g_0^A e^{-5t\tau^A}$, where τ^A can be interpreted as the exogenous decline rate of technological progress.

¹⁷ In contrast to Nordhaus (2017), we compute the SCC without accounting for a backstop technology.

¹⁸The computations consider the full planning horizon of DICE. Appendix B.1.3 depicts the overview figure for a longer time horizon, from 2020 to 2300. The numerical dynamic optimization results presented in the following are calculated using the Knitro solver (version 10.2) together

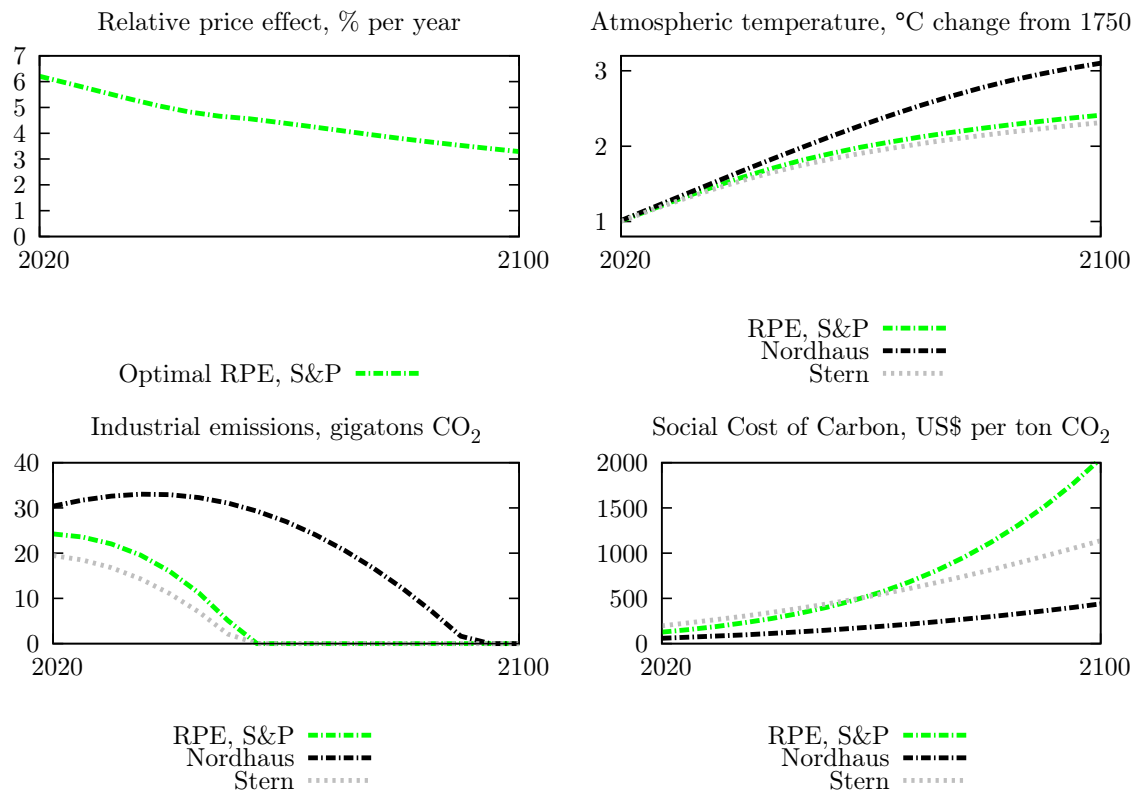


Figure 3.1: Relative price effect (RPE) and comparison of climate policy paths. The green line shows the Sterner and Persson (2008) case. The black line depicts the ‘Nordhaus’ comparison case (with comparable and thus higher damages as in DICE-2016R). The dotted grey line features another comparison case, yet with the lower rate of pure time preference, δ , of Stern.

Table 3.1: Parameter values for replicating Sterner and Persson (2008) in DICE-2016R

Parameter	δ	η	MD**	NMD***	α	θ	\bar{E}
Baseline	1.5%	1.45	1.81%	1.81%	0.1	-1	0
Source*	N	N	N	S&P	S&P	S&P	N, S&P

* N denotes values taken from Nordhaus (2017), while S&P denotes Sterner and Persson (2008).

** MD denote market damages under 3°C warming, with $\kappa = 0.0181$.

*** NMD denote non-market damages under 3°C warming, corresponding to $\psi = 0.01604$, which is calibrated endogenously according to Equation A.9.

The time path of the S&P- RPE depicted in the upper-left corner of Figure 3.1 shows that under optimal climate policy in DICE the S&P- RPE amounts to more than 6 percent in 2020 and decreases over time to about 3 percent in 2100. As the growth rate of non-market goods is negative but close to zero due to the optimal management of climate change, this decrease in the S&P- RPE is primarily driven by the declining growth rate of market consumption goods.

with the AMPL optimization software. The programming code is provided in Appendix B.1.4.

Hence, although non-market goods become continuously scarcer in absolute terms until peak temperature is reached (cf. Equation 3.8), and in relative terms as compared to market goods throughout the planning horizon, the change in relative scarcity, as measured by the relative price change, falls over time.

Moreover, Figure 3.1 compares this S&P-*RPE* to two cases that do not change the DICE-2016R approach of (only implicitly) dealing with relative prices but that differ in their assumptions about a key discounting parameter—the rate of pure time preference, δ . First, we compare the S&P-*RPE* case to the optimal climate policy trajectories in the ‘Nordhaus’ case.¹⁹ According to Sterner and Persson (2008), this provides the direct comparison case to judge the impact of introducing relative prices. To capture the findings of Sterner and Persson (2008) within the DICE-2016R modeling framework and to get an idea of how substantial the impact of the S&P-*RPE* is, we also consider another case with Stern’s (2007) lower rate of pure time preference of $\delta = 0.1$ percent.

The lower-left panel of Figure 3.1 depicts the time path for industrial emissions, which corresponds to the results figure in Sterner and Persson (2008, p. 70). In DICE-2016R, and with the comparable assumption regarding non-market climate damages based on Sterner and Persson (2008), emissions peak in 2035, while they did not peak but continuously increased until 2100 in the older DICE version Sterner and Persson (2008) refer to.²⁰ When considering the S&P-*RPE*, industrial emissions decrease immediately and become almost zero in 2055. Full decarbonization of the global economy is achieved as fast as when using the rate of pure time preference advocated by Stern (2007). Yet, cumulative emissions are higher when considering the S&P-*RPE* as compared to the optimization using Stern’s lower rate of pure time preference. The upper-right panel of Figure 3.1 shows the development of atmospheric temperature

¹⁹Recall that climate damages are higher in the ‘Nordhaus’ run than in Nordhaus (2017) for comparability with Sterner and Persson (2008).

²⁰We follow Nordhaus (2017) in depicting industrial emissions in terms of CO_2 , not carbon. Note that there are a number of changes between the DICE version that Sterner and Persson (2008) refer to (DICE-2006) and the most recent version of DICE that we use (DICE-2016R), such as a lowering of the rate of pure time preference and the inclusion of the possibility negative emissions. These determine the difference of the dynamics of industrial emissions in Figure 3.1 to those depicted in the key results figure in Sterner and Persson (2008, p. 70). With respect to pure time preference, a higher δ for the baseline S&P-*RPE* and for the ‘Nordhaus’ case would result in more emissions in both runs. Also, as we will show in Section 3.4, a higher δ implies a lower S&P-*RPE*. Thus, that the S&P-*RPE* and ‘Stern’ case emission paths is not due to the change in δ .

change. We find that it stabilizes around 2.63°C with the S&P-*RPE* but increases until 3.44°C in the ‘Nordhaus’ case. For comparison, using the rate of pure time preference of 0.1 percent (‘Stern’) leads to a peak atmospheric temperature of 2.52°C .

These emission and temperature developments translate into substantial differences between the time paths of the SCC (see the lower-right corner of Figure 3.1). Comparing the S&P-*RPE* to the ‘Nordhaus’ case, we find that the SCC is 112 (365) percent higher in 2020 (2100) in the S&P-*RPE* case. Comparing the ‘Nordhaus’ and ‘Stern’ runs, we find that the latter leads to an SCC that is 229 (159) percent higher in 2020 (2100) as compared to the former. Overall, Figure 3.1 underscores the need to distinguish between standard discounting and relative price changes as related but distinct drivers of climate policy evaluation.

3.3.2 Stern or Sterner? Clarifying the influence of relative prices on the stringency of climate policy

The discussion of Figure 3.1 naturally leads to the question how we can meaningfully compare the stringency of climate policy across different optimization runs in order to make statements such as ‘introducing relative prices yields an “even Sterner” review’ (Sterner and Persson 2008)? Such comparisons depend on how the following questions are answered: First, what is the comparison metric? Second, what is the comparison variable? Third, what is the baseline specification against which to compare the influence of introducing relative prices?

First, Sterner and Persson (2008) base their finding of an an “even Sterner” report on an examination of yearly carbon emissions. In their comparison within the 2006 DICE version, yearly emissions in the S&P-*RPE* simulation were initially in-between the ‘Nordhaus’ and ‘Stern’ comparison cases, yet the S&P-*RPE* path of optimal emissions led to an earlier decarbonization as compared to the ‘Stern’ case. In the most recent DICE version (DICE-2016R) this is no longer the case: Initial emissions are still in-between the ‘Nordhaus’ and ‘Stern’ comparison cases but the S&P-*RPE* path does not lead to earlier decarbonization as compared to the ‘Stern’ case. Irrespective of these differences due to changes in the DICE model over time, using yearly emissions is not a clear-cut comparison metric because emission paths can potentially cross.

With crossing of emission paths it may be that even if a model run leads to earlier decarbonization, it can entail higher cumulative emissions or a higher peak temperature. Unambiguous comparison metrics would thus be peak atmospheric carbon concentration or peak temperature achieved under a given model parameterization. If we use peak temperature change relative to pre-industrial levels as the comparison metric to examine the relative impact of introducing the S&P-*RPE* with changes in the highly disputed rate of pure time preference, we find the following: Considering relative prices in the specification of Sterner and Persson (2008) is equivalent to reducing the pure time preference from Nordhaus's (2017) value of 1.5 percent by 1.2 percentage points, i.e. a model run with a δ of 0.3 percent yields the same peak temperature as we obtain when introducing the S&P-*RPE*. Although this shows that explicitly considering relative prices does not yield 'an even Sterner review', as the reduction is lower than 1.4 percentage points, which would be comparable to using Stern's rate of pure time preference or a lower value, it still represents a very substantial influence on optimal climate policy.

Second, what is the appropriate comparison variable? How meaningful is the direct comparison of the S&P-*RPE* versus the 'Nordhaus' and 'Stern' cases given that explicitly introducing relative prices entails a number of changes to the DICE framework, which already implicitly contains relative prices? The cleanest comparison between a model with relative prices and models that only differ in their rate of pure time preference would be within a model that includes the *RPE* to a case with perfect substitutability ($\theta = 1$), as the *RPE* vanishes in this case (cf. Equations 3.5 and 3.10). We therefore now examine more closely the effect of changing the degree of substitutability only, and compare its impact on optimal climate policy to the rate of pure time preference, which is perhaps the most vividly discussed parameter in climate economics. As climate policy comparison measure we use the peak temperature change relative to 1750 that is reached in any given optimization run, as this yields a unique maximum.

Figure 3.2 depicts the optimal atmospheric peak temperature obtained over the whole planning horizon as a function of the rate of pure time preference, δ , for different degrees of substitutability, θ . The bold black line shows the comparison case of

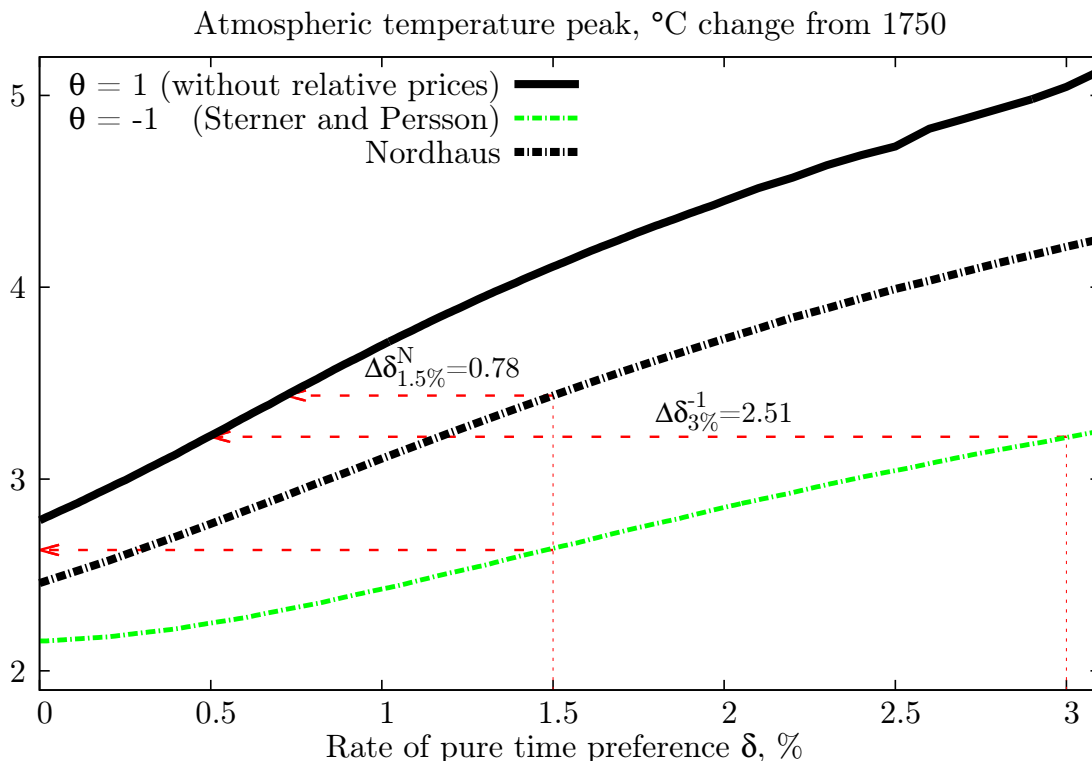


Figure 3.2: The comparative influence of introducing relative prices on peak temperature. The Figure depicts peak temperature as a function of the rate of pure time preference, δ , for different degrees of substitutability, θ . The solid black line shows the comparison case of perfect substitutability and thus without relative prices. The dashed green (black) line depicts the substitutability assumption of Sterner and Persson with $\theta = -1$ ('Nordhaus'). A model run with relative prices can then be compared to a run without them but with a higher δ such that peak temperature is the same across both runs. For example, the implicit degree of limited substitutability contained in the 'Nordhaus' case is equivalent to a model without relative prices if we decrease δ by $\Delta\delta_{1.5\%}^N = 0.78$ percentage points.

perfect substitutability and thus without relative prices.²¹ In contrast, the dashed lines depict runs with different degrees of limited substitutability and thus with *RPEs*. The dashed green line shows the complementarity assumption of the S&P-*RPE* ($\theta = -1$), while the dashed black line depicts the 'Nordhaus' case with its implicit degree of limited substitutability and relative prices. A model run with relative prices can now be compared to a run without relative prices ($\theta = 1$) but with a higher δ such that the resulting optimal peak temperature is the same across both runs. This yields the equivalent change in the pure rate of time preference, $\Delta\delta_{sub}^{sup}$, of introducing relative prices into climate policy evaluation, where the *subscript* denotes the baseline δ and the *superscript* the degree of substitutability, θ , of the considered *RPE*. For example, introducing relative prices with Cobb-Douglas substitutability ($\theta = 0$) at a baseline of $\delta = 1.5$ is equivalent to decreasing δ by $\Delta\delta_{1.5\%}^0 = 0.6$ percentage points in terms

²¹When market and non-market goods are perfect substitutes, optimal peak temperature reaches 2.9°C (4.1°C) for a rate of pure time preference of 0.1 (1.5) percent.

of optimal peak temperature. This analysis reveals that the implicit degree of limited substitutability and thus of relative prices contained in the ‘Nordhaus’ case is equivalent to a model without relative prices if we decrease δ by $\Delta\delta_{1.5\%}^N = 0.78$ percentage points.²² This also means that if substitution possibilities are, for example, Cobb-Douglas, explicitly introducing an *RPE* into DICE would lead to less stringent optimal climate policy as compared to the ‘Nordhaus’ case.

Figure 3.2 also allows us to re-examine whether introducing relative prices yields an “even Sterner” review. Starting from the baseline value of pure time preference of 1.5 percent and the complementarity assumption of Sterner and Persson (2008), the lowest red subsidiary line shows the equivalent decrease in the rate of pure time preference as we increase the degree of substitutability (from right to left). Comparing the S&P-*RPE* to the ‘Nordhaus’ case reveals that an equivalent decrease in pure time preference would amount to 1.20 percentage points. Thus, again, this comparison would not yield an “even Sterner” report. Yet, as this subsidiary line does not intersect the black line comparison case of perfect substitutability, we find that there is no positive rate of pure time preference that would allow for an equivalent reduction in peak temperature as introducing the S&P-*RPE*, that is $\Delta\delta_{1.5\%}^{-1} = \text{undefined}$. Already a degree of substitutability of $\theta = -0.66$ would be equivalent to reducing pure time preference from the value employed by Nordhaus to that of Stern, that is $\Delta\delta_{1.5\%}^{-0.66} = 1.4$ percentage points. Introducing relative prices with the complementarity assumption of Sterner and Persson (2008) may thus be considered as “even Sterner” than suggested previously.

Third, we address the question of what is the appropriate baseline specification? The analysis depicted in Figures 3.1 and 3.2 is based on the baseline specification of the most recent DICE version from Nordhaus (2017), with the exception of higher damages introduced to allow for a better conceptual comparability with Sterner and Persson (2008). Yet, which baseline parameters we choose—for example regarding the welfare parameters δ and η —matters for the effect sizes we obtain when making comparison across model runs. If, for example, we use the higher (initial) rate of pure

²²We find that the implicit degree of substitutability contained in the ‘Nordhaus’ case is non-constant. We estimate the implicit θ for 2020 and 2100 to be -0.09 and -0.17 , respectively. The $\Delta\delta_{1.5\%}^{-0.13}$ for the mean of these two degrees of substitutability would be 0.77 percentage points.

time preference of 3 percent that was, for example, used in earlier DICE versions, we would find that introducing relative prices with the complementarity assumption of Sterner and Persson (2008) is equivalent in terms of peak temperature as reducing the rate of pure time preference from 3 percent by $\Delta\delta_{3\%}^{-1} = 2.5$ percentage points. Overall, it is therefore crucial to be specific about the baseline model specification. This makes it particularly important to systematically examine how different potential determinants affect the *RPE* and its influence on climate policy evaluation.

3.4 What drives the relative price effect (*RPE*)?

This section scrutinizes how the *RPE* depends on its main potential drivers. For this sensitivity analysis, we consider two points in time: the year 2020 as the next ‘short-run’ planning step as well as the year 2100 for a ‘longer-run’ picture. First, we consider (i) the degree of substitutability between market and non-market goods. Next, we consider (ii) the magnitude of non-market damages and (iii) the size of the subsistence requirement for non-market goods. Finally, we analyze the main drivers of the growth rate of human-made goods: (iv) the rate of pure time preference, (v) the elasticity of the marginal utility of consumption and (vi) the rate of technological progress.

Substitutability

A key driver of the *RPE* is the degree of substitutability between market and non-market goods. The upper panel of Figure 3.3 depicts the effects of varying the substitution parameter θ along a range of -2 to 1. This corresponds to a range of the elasticity of substitution, σ , of one-third to infinity. The range encompasses all benchmark values assumed in the literature on relative prices and ecological discounting, such as the Cobb-Douglas assumption of $\theta = 0$ (Gollier 2012), as well as different degrees of complementarity, e.g. $\theta = -0.333$ (Kopp et al. 2012) and $\theta = -1$ (Sterner and Persson 2008). Furthermore, it includes indirect empirical estimates of substitutability (Baumgärtner et al. 2015; Drupp 2016). These make use of the relationship between the degree of substitutability and the income elasticity of willingness-to-pay for public goods to estimate the elasticity of substitution from non-market valuation studies. Drupp (2016) gathers indirect evidence on the substitutability parameter for

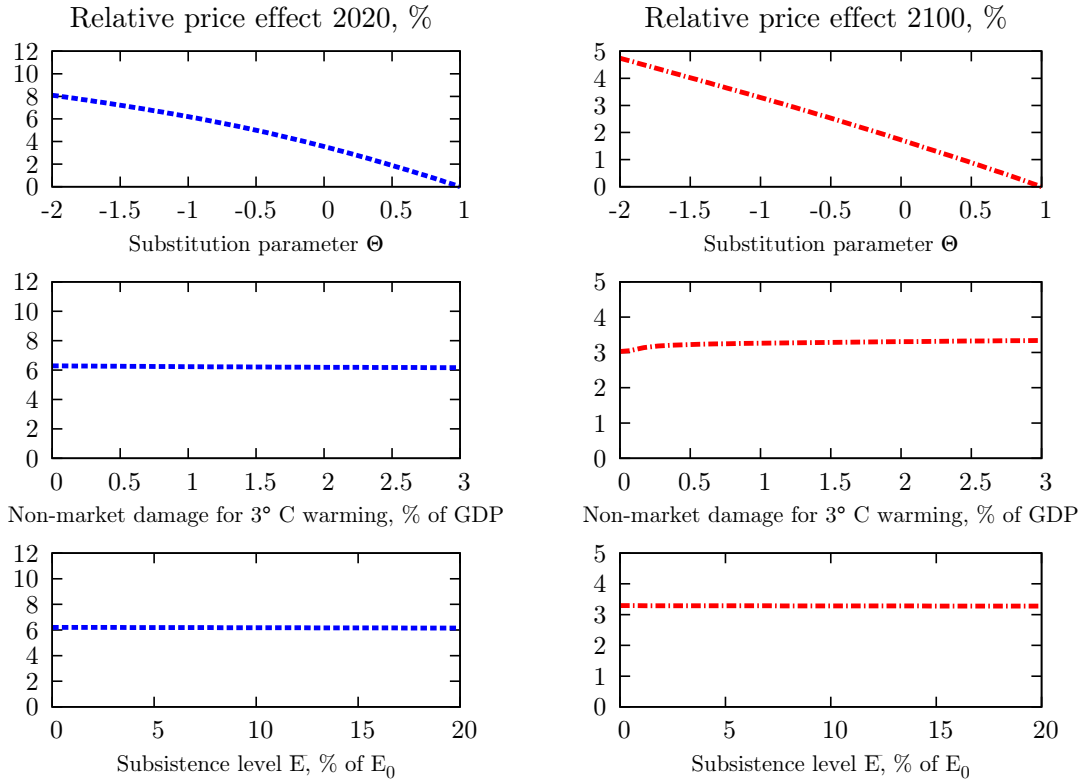


Figure 3.3: Drivers of the relative price effect (*RPE*) of non-market goods (I). Top to bottom: substitutability, non-market damages and subsistence consumption—and their impact on the *RPE* in 2020 (left panel) and in 2100 (right panel).

environmental goods from 18 non-market valuation studies and finds a mean estimate [range] for the income elasticity of 0.43 [0.14, 0.72] and thus a substitutability parameter θ of 0.57 [0.28 to 0.86].²³ Figure 3.3 confirms that the degree of substitutability is an important driver of the *RPE* in both the ‘short-run’ (2020) and ‘longer-run’ (2100). Assuming perfect substitutes eliminates the *RPE*, while the *RPE* in 2020 increases to 6.20 percent for the baseline of $\theta = -1$ (Stern and Persson 2008), and to 8.10 percent for $\theta = -2$. The respective values of the *RPE* in 2100 are 3.29 (4.74) percent for $\theta = -1$ ($\theta = -2$) and the *RPE* reduces to 1.73 (0.77) percent for a value of θ of 0 (0.57).

²³Since the composite non-market good in the DICE model also includes non-environmental goods, such as relating to health, it is important to know whether these elasticities are also adequate for other non-market goods. Within the health domain, there is a growing body of literature estimating income elasticities of the value of a statistical life. These studies typically find mean income elasticities in the range of 0.2 to 1 (Hammit and Robinson 2011; Hoffmann et al. 2017; Viscusi and Masterman 2017), thus corresponding closely to income elasticities obtained from environmental valuation studies.

The magnitude of non-market damages

In our model the magnitude of non-market damages refers to the hypothetical monetary damages from a climate change induced temperature increase to 3°C on the non-market good measured in percent of GDP. The baseline specification depicted in Figure 3.1 assumes, following Sterner and Persson (2008), that non-market damages account for an additional damage component that doubles overall climate damages. This amounts to 1.63 percent of GDP under 3°C warming. In contrast, Nordhaus (2017) considers non-market damages as an additional damage component, amounting to 0.49 percent of GDP under 3°C warming. Since the climate damages share on non-market goods is inherently uncertain, the only source of evidence we may draw on are expert surveys. Nordhaus (1994) surveyed 19 experts on the economic impacts of climate change. These experts forecast that 38 percent of damages should be attributed to non-market goods (for a 3°C warming until 2090). More recently, Howard and Sylvain (2015) extended upon this study and surveyed a larger number of experts on their “best guess of the percentage of total impacts (market plus non-market) that will be borne by the market sector?”. The best guess of 213 respondents is that 50 percent of damages accrue to non-market goods. This would be in line with the doubling of market-damages as assumed by Sterner and Persson (2008). A sizable standard deviation of 28 percent reveals substantial heterogeneity in responses. Figure 3.3 therefore depicts the effect of non-market damages on the *RPE* for a large range of non-market damages under 3°C warming in the year 2020, spanning from 0 to 3 percent of GDP. In absolute terms the *RPE* remains almost flat at 6 percent, ranging from 6.29 to 6.16 percent. In the year 2100 we find that the *RPE* ranges from 3.02 to 3.40. Thus, while the *RPE* falls slightly with higher non-market damages in 2020, it increases with higher non-market damages in 2100. Why is it—perhaps surprisingly—the case that the non-market damages scaling parameter has such a negligible effect on the *RPE*? In Equation 3.10 the magnitude of non-market damages scales the effect of temperature change to determine the growth rate of non-market goods.

Due to the optimal management, the decline of the non-market good through temperature change is dampened, such that the growth rate of the non-market good is close to zero. As a consequence higher non-market damages only marginally change the *RPE*.

Subsistence consumption

The subsistence requirement for the consumption of non-market goods refers to a distinct amount that the representative agent is not willing to substitute by the consumption of material goods. In our case the subsistence need basically reflects a boundary for the atmospheric temperature, which is the only driving force of the evolution of non-market goods. Figure 3.3 shows that the *RPE* is not sensitive to changes in the stringency of the subsistence level \bar{E} due to the optimal management that ensures that the non-market good is provided at a level well above the subsistence requirement. Specifically the *RPE* falls from 6.20 to only 6.15 percent when increasing the subsistence level from 0 to 20 percent of the initial non-market good E_0 . When increasing the stringency of the subsistence requirement, the difference between the two good-specific growth rates declines and thus lowers the *RPE*.²⁴ In the year 2100 we find qualitatively the same as for 2020: the *RPE* declines from 3.29 to 3.28 by increasing the subsistence requirement.

Rate of pure time preference

The rate of pure time preference δ , measures how the utility of the representative agent at different points should be weighted in relative terms. A positive rate implies that the utility of future agents is discounted just because they live in the future. There is considerable disagreement on what constitute plausible and justifiable values for the rate of pure time preference. Figure 3.4 depicts the effects of the rate of pure time preference on the *RPE* over an interval of 0 to 8 percent.²⁵ This range is taken from an expert survey on the determinants of the social discount rate by Drupp et al. (2015). Not surprisingly the *RPE* in 2020 falls with the rate of pure time preference from 7.17 percent for $\delta = 0$ percent to 1.76 percent for $\delta = 8$ percent per year.

²⁴Additionally, \bar{E} slightly impacts the *RPE* also indirectly via the calibration of the non-market good climate damage coefficient ψ (Equation A.8), with $\partial\psi/\partial\bar{E} \leq 0$ for $\theta \leq 1$.

²⁵Note that for computational reasons we approximate 0 with 0.000001 percent.

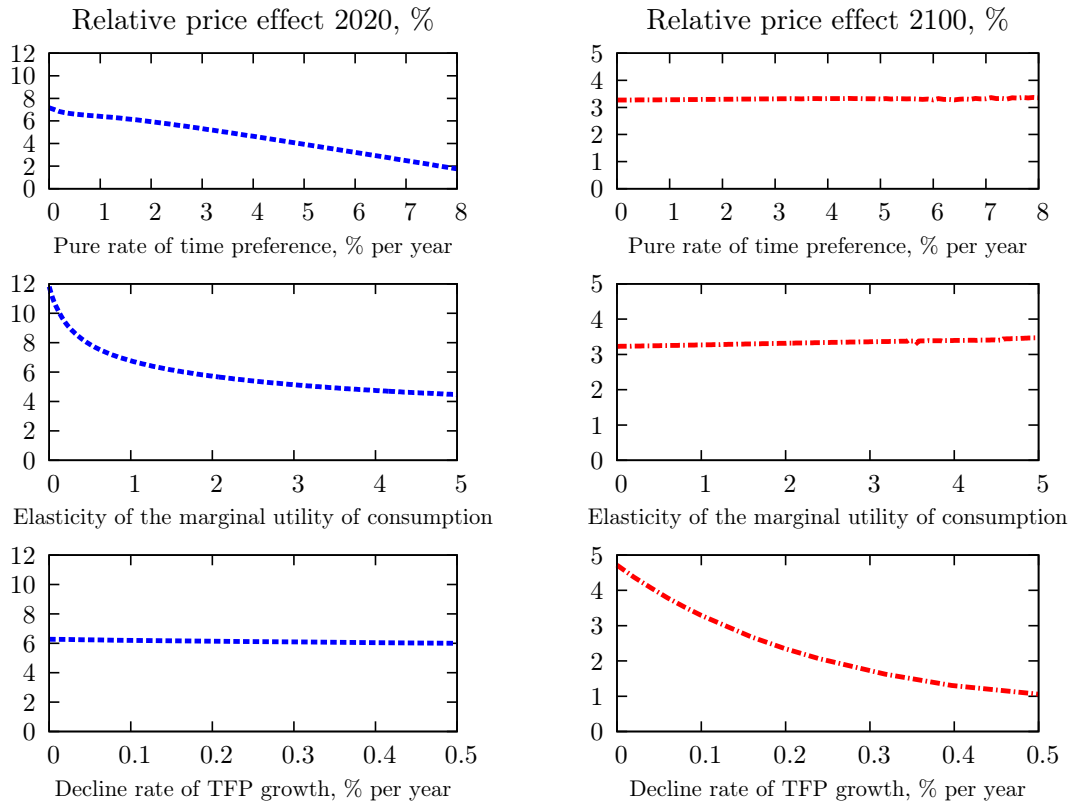


Figure 3.4: Drivers of the relative price effect (*RPE*) of non-market goods (II). The Figure depicts the key determinants of the growth rate of consumption goods. Top to bottom: rate of pure time preference, elasticity of the marginal utility of consumption, and decline rate of total factor productivity growth—and their impact on the *RPE* in 2020 (left panel) and in 2100 (right panel).

Nordhaus’s (2017) assumption of $\delta = 0.015$ corresponds to a *RPE* of 6.20 percent. In the year 2100, the rate of pure time preference has almost no effect on the *RPE*: the corresponding *RPE* range is only 3.27 to 3.37 percent, i.e. the sensitivity is negligible but qualitatively the influence of the rate of pure time preference on the *RPE* reverses.

Elasticity of the marginal utility of consumption

The elasticity of the marginal utility of consumption, η , is a measure of inequality aversion with respect to the intertemporal distribution of inclusive consumption \tilde{c} . Its range considered in Figure 3.4, from 0 to 5, includes all recommendations by respondents to the expert survey by Drupp et al. (2015). It encompasses values used in the prominent literature, such as unity (Stern 2007) and 1.45 as used in DICE (Nordhaus 2017). We find that the *RPE* decreases with η over this range of parameter values from 11.81 to 4.46 percent in 2020. In 2100, the *RPE* increases with η from 3.23 to 3.48 percent. The reversed pattern is thus the same as for the rate of pure time preference, but overall the *RPE* is more sensitive to changes in the elasticity of the marginal utility of consumption.

Decline rate of total factor productivity

The growth rate of material consumption is in particular driven by total factor productivity (TFP), $A_t = \frac{A_{t-1}}{1-g_t^A}$, which grows exogenously at a decreasing rate, with $g_t^A = g_0^A e^{-5t\tau^A}$ where τ^A can be interpreted as the decline rate of TFP. It represents the key exogenous parameter determining the dynamics of productivity growth in DICE. For our sensitivity analysis, we vary this parameter while we do not change the shape of the time profile of technological progress imposed by Nordhaus (2017).²⁶ We find that the *RPE* in 2020 (2100) decreases from 6.28 (4.72) percent for $\tau^A = 0$ percent to 6.00 (1.02) percent for $\tau^A = 0.5$ percent. The baseline case of Nordhaus (2017) implies a decline rate of TFP growth of around 0.1 percent per year corresponding to a *RPE* in 2020 (2100) of 6.20 (3.29) percent. A lower decline rate of TFP growth τ^A makes non-market goods scarcer relative to human-made consumption goods as global GDP is scaled up by higher exogenous growth in TFP. However, due to the logistic shape of the dynamics of TFP, the effect on relative prices is more pronounced in 2100: Here the *RPE* decreases more than linearly in the decline rate of TFP growth per year.

3.5 A plausible range for relative price changes and its influence on climate policy

Based on our systematic study of the individual determinants of the relative price effect, this section examines what might be a plausible range and a best-guess central calibration for each determinant of the *RPE*. To compare simulations and thus the effect of the *RPE* on climate policy evaluation, we focus on peak temperature as the comparison metric and make comparisons against the case of perfect substitutes.

In contrast to the analysis in Section 3.3, we specify a central calibration as a new baseline and perform a Monte Carlo analysis with 1000 draws to construct plausible ranges. For the lower and upper bounds, we consider a 95 percentile range around the mean. We make the following assumptions regarding the distribution of the individual determinants: For the degree of substitutability, we assume a Normal distribution

²⁶Alternatively, one could vary the initial level g_0^A or compute an average productivity measure over the whole planning horizon. The latter would, however, imply to change the time profile of TFP including higher initial growth rates, which thereby artificially increases the *RPE* in 2020.

for which the values used in Sterner and Persson (2008), $\theta = -1$, and the mean empirical estimate from Drupp (2016), here taken as $\theta = 0.6$, encompass the 95 percent confidence interval, with a mean of $\theta = -0.2$. For non-market damages, we draw on the expert responses from the survey by Howard and Sylvain (2015) and assume a Normal distribution with mean and standard deviation taken from their expert data.²⁷ For the subsistence requirement, we also consider a Normal distribution, with an assumed mean value that amounts to 10 percent of the initial non-market good. The 95 percent confidence interval is calculated such that it borders a zero subsistence requirement. For δ and η we use the mean expert recommendations from the survey of Drupp et al. (2015) for the central calibration. To construct plausible range we randomly draw 1000 times from the sample of expert recommendations and use this data for the 1000 Monte Carlo model runs. Finally, for the decline rate of TFP, τ^A , we assume a Normal distribution with the mean given by the value of Nordhaus (2017). The 95 percent confidence interval is calculated such that it is bounded from below by a zero decline rate.

Overall, while some parameter values contained in the plausible ranges may seem objectionable, they are chosen such that a non-negligible fraction of experts may advocate employing them.²⁸ Table 3.2 lists all the parameter choices for the optimization of the plausible ranges and of the central calibration. Figure 3.5 depicts the central calibration run (blue dashed line), the comparison run with perfect substitutability and thus without an *RPE* (black dashed line), and the plausible range of the *RPE* (blue-shaded area). Furthermore, it displays the impact of relative price changes on climate policy outcomes for the time between year 2020 and 2100.

Figure 3.5 shows that the 95 percentil plausible range for relative price changes is substantial: The *RPE* ranges between 9.6 and 1.3 percent in 2020 and between 3.6 to 0.8 percent in 2100. Peak atmospheric temperature ranges from 2.2°C to 5.1°C. The SCC increase from 9 to around 76 US\$ per ton of CO_2 in the depicted time span at the lower bound of the 95 percentile range, while it is far beyond commonly-assumed

²⁷For non-market damages and for \bar{E} and τ^A , we truncate the distribution to exclude negative values.

²⁸With respect to δ , for instance, more than 10 percent of experts in Drupp et al. (2015) recommended rates of 3 percent or higher. The 95 percent interval includes 6 percent as the highest value.

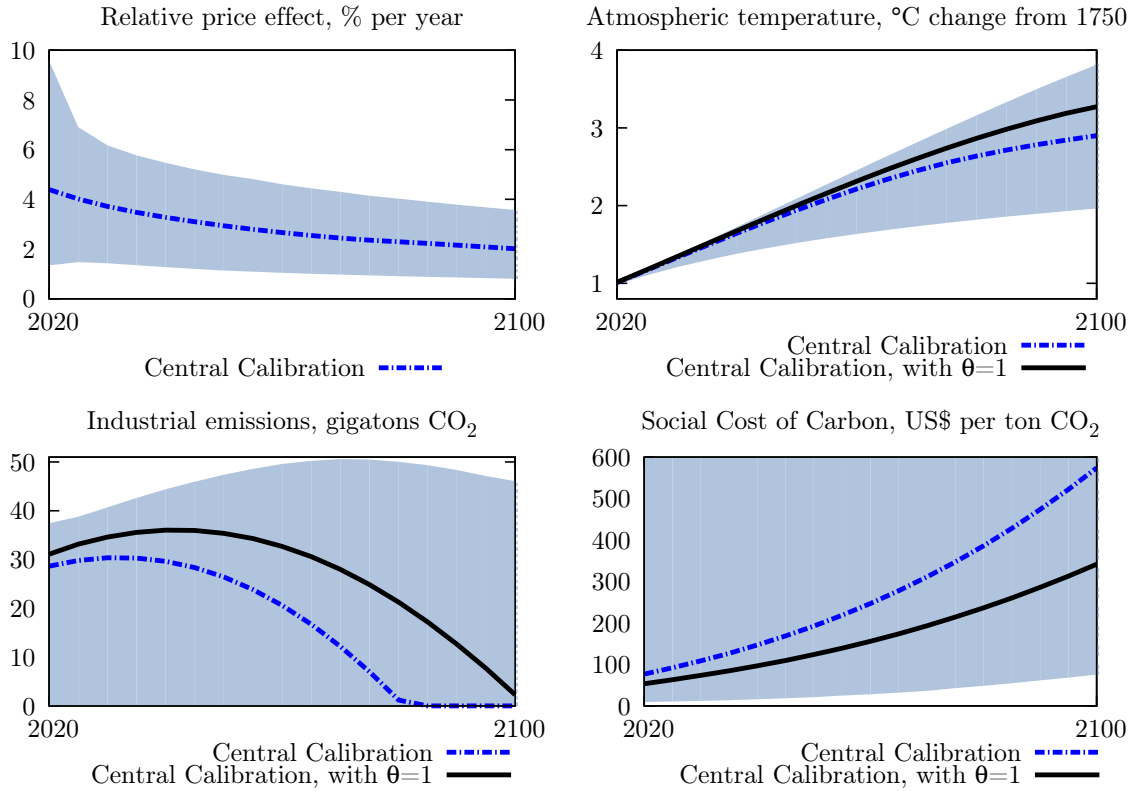


Figure 3.5: Relative price effect (*RPE*) and comparison of climate policy paths for a best-guess central calibration and a plausible range of the drivers of the *RPE*. The blue line represents the central calibration of the *RPE*, while the black line depicts the perfect substitutability comparison ($\theta = 1$) in which the *RPE* vanishes. The blue-shaded area represents the 95 percentile range considering uncertainty in all of the drivers of the *RPE*.

Table 3.2: Parameter specifications for the range and central calibration (CC) of the *RPE*

Parameter	Source	Distribution	CC
θ	S&P (2008), Drupp (2016)	Normal; $\mu = -0.2, \sigma = 0.41$	-0.2
NMD^*	Howard and Sylvain (2015)	Normal; $\mu = 1.65\%, \sigma = 4.15\%$	1.65%
\bar{E}/E_0	Assumption	Normal; $\mu = 10\%, \sigma = 5.10\%$	10%
δ	Drupp et al. (2015)	Raw expert data	1.10%
η	Drupp et al. (2015)	Raw experts data	1.35
τ^A	Nordhaus (2017)	Normal; $\mu = 0.1\%, \sigma = 0.05\%$	0.1%

* NMD denotes non-market damages under 3°C warming. NMD of 1.65% (4.15%) correspond to a ψ of 0.0162414 (0.0419335).

prices of backstop technologies at the upper bound.²⁹ In terms of industrial emissions, the parameter ranges can lead to both full decarbonization in 2020 as well as to cases in which it is optimal that emissions still increase until mid century.

For the central calibration, we find that the *RPE* decreases from 4.4 percent in 2020 to 2.0 percent in 2100. This leads to a full decarbonization in the year 2085 and a peak

²⁹At the upper bound of the 95 percentile range the SCC is 2459 (10899) US\$ per ton of CO_2 in 2020 (2100). For better visibility we only show the range up to 600 US\$ per ton of CO_2 .

temperature of 3.2°C. The SCC in 2020 is 77 US\$ per ton of CO_2 and increases up to 574 US\$ per ton of CO_2 in 2100. In contrast, in the perfect substitutability comparison case without relative prices, decarbonization is only achieved in 2105. Compared to the central calibration, neglecting relative prices would lead to an underestimation of the SCC of 43 (68) percent in the year 2020 (2100). The peak temperature in the case without the *RPE* is 3.7°C, that is temperature peaks at 0.5°C higher as compared to our central calibration with relative prices. If we again translate this into an equivalent change of the rate of pure time preference analogously to the analysis in Section 3.3.2, we find that introducing relative prices with the degree of substitutability assumed in our central calibration ($\theta = -0.2$) is equivalent to reducing the rate of pure time preference by 0.53 percentage points in a model without relative prices.

3.6 Discussion

In this section, we discuss to what extent assumptions made in this analysis limit our results. In particular, we examine issues of (i) the growth of non-market goods, (ii) technological progress, (iii) data availability on substitutability and non-market damages, (iv) preference change, (v) behavioral influences as well as (vi) uncertainty.

First, we find that the drivers related to the growth of non-market goods are not of quantitative importance for the *RPE* in the optimal management framework of DICE. Yet, we assumed—following the previous literature—that the consumption of non-market goods would stay constant in absence of climate change. Yet, non-market goods could also decline in absence of climate change, for example resulting from biodiversity loss due to other drivers. Indeed, empirical evidence suggests that environmental good growth is not close to zero, as under optimal management in DICE, but of considerable negative magnitude (Baumgärtner et al. 2015).³⁰ Conversely, non-market goods may also increase due to technical change that positively affects non-market goods, for example relating to health improvements. Future studies could explore cases in which non-market goods can grow or decline irrespective of the management problem at hand

³⁰While much of the literature suggests that climate change leads to a loss of ecosystem services (e.g. MEA 2005), this does not constitute a consensus (Mendelsohn et al. 2016). It is clear, however, that climate change is not the only driver of biodiversity loss.

as well as explicitly deal with the heterogeneity contained in the composite non-market good. Introducing drivers of non-market goods growth that are unrelated to climate change in a sense also relates to studying non-optimal climate policy, where we would have imperfect management control. In such cases, drivers of non-market goods may play a larger role for relative prices as in the optimal management considered here.

Second, the DICE model considers a specific kind of exogenous technological progress. We have shown that it has a considerable impact on the *RPE*. It is thus crucial to study technological progress in more detail, also considering the possibility of endogenous technological progress (e.g. Hübler et al. 2012, Popp 2004) as well as how substitutability of environmental goods and natural capital interact with technological progress (e.g. Bretschger 1998; Bretschger and Smulders 2012).

Third, the availability of reliable data on the magnitude of non-market damages and the degree of substitutability of non-market goods represents a key challenge in estimating relative price effects. There is only scarce empirical evidence on its potential magnitude, which suggests substitutability at the margin (Drupp 2016) in contrast to the mild complementarity relationship assumed in our central calibration. It is therefore imperative to conduct more research to empirically estimate substitutability of non-market goods so as to increase confidence about the likely magnitude of relative prices.

Fourth, the DICE model, and our analysis, assumes that there are ‘deep preference’ parameters that do not change across generations, such as δ , η , θ and α . This common assumption may not be appropriate. For example, a number of recent studies consider time-varying rates of pure time preference (e.g. Gerlagh and Liski 2017; Millner 2017). Fleurbaey and Zuber (2016) examine the impact of preference change in terms of substitutability on dual discount rates. It could also be the case that preference evolution, for example with respect to θ and α , is endogenous (Fenichel and Zhao 2015; Krutilla 1967), or that there is simply heterogeneity in agent’s preferences within a society at a given point in time, with the composition of agents changing over time. There are thus ample possibilities to depart from this standard approach. As of yet, it is not clear which extension would be the best to follow for analyses such as ours.

Fifth, we have abstracted from any behavioral effects related to relative price

changes. Dietz and Venmans (2017) study the impact of the endowment effect on dual discounting. Other possibilities may include extending the theory of relative prices to studying relative consumption concerns (e.g. Johansson-Stenman and Sterner 2015).

Finally, the long term future is inherently uncertain. Yet, the DICE model is deterministic. While a deterministic analysis such as ours can yield important insights, it is clear that the analysis should be extended to cover different forms of uncertainty.³¹ For example, Jensen and Traeger (2014) analyze long term uncertainty about technological progress as the main driver of growth in the DICE model, Dietz et al. (2017) study the combined effect of uncertainty about baseline growth as well as about the payoff of a mitigation project in DICE, while Gollier (2010) analyzes uncertainty in the growth rates of environmental and consumption goods and Gollier (2017) considers uncertainty about the degree of substitutability. We find substitutability and technological progress to be among the most important drivers of the *RPE* in DICE. Hence, taking into account uncertainty about these drivers would be an important next step.

3.7 Conclusion

This paper provides a comprehensive analysis of the change in the relative price of non-market goods by studying its quantitative magnitude, its fundamental drivers, and its implications for climate policy in the integrated assessment of climate change. Our analysis in the most recent version of the widely-used DICE model (Nordhaus 2017) reveals that the relative price effect of non-market goods is substantial in quantitative terms: it amounts to 4.4 (2.0) percent in the year 2020 (2100) in our central calibration. When combining plausible ranges of all individual drivers the 95 percentile ranges from a Monte Carlo analysis yield relative price effects that range from 9.6 to 1.3 percent in 2020 and from 3.6 to 0.8 percent in 2100. This highlights a considerable degree of uncertainty concerning key drivers, in particular regarding the degree of substitutability between market and non-market goods, the elasticity of the marginal

³¹See Heal and Millner (2014) for an overview of decision-making under uncertainty in the area of climate change economics. Traeger (2014) adapts the 2007-DICE version such as to be able to analyze effects of uncertainty quantitatively.

utility of consumption, pure time preference as well as the development of technological progress.

In terms of climate policy evaluation, we find that neglecting relative prices would lead to an underestimation of the social cost of carbon of more than 40 (60) percent in the year 2020 (2100) compared to our central calibration that considers relative price effects. Furthermore, atmospheric temperature peaks at 0.5°C lower when considering relative price effects. Introducing relative prices thus leads to recommending more stringent climate policies and its influence on climate policy is of considerable magnitude.

Our study furthermore clarifies how the influence of the relative price effect on climate policy evaluation can be appropriately interpreted. We find that statements such as ‘introducing relative prices leads to an “even Sterner review” are sensitive to what we choose as comparison metric and variable as well as how we specify the baseline. As an unambiguous comparison metric across different model runs, we use peak temperature, exploiting the fact that each considered optimization run results in a unique peak temperature in the 500 year time horizon that allows for comparability across model runs. Introducing relative prices in the spirit of Sterner and Persson (2008) in DICE-2016R, we find that this yields an equivalent reduction in the rate of pure time preference of 1.2 percentage points when compared to the ‘Nordhaus’ run. Yet, since we show that the standard DICE model of Nordhaus (2017) already contains a considerable relative price effect of non-market goods due to a kind of Cobb-Douglas substitutability between (non-market) climate damages and production, this value may underestimate the impact if introducing relative prices. Indeed, we show that the cleanest comparison to establish the influence of relative prices on climate policy evaluation is within a model that explicitly models them. This allows us to only vary the degree of substitutability as compared to the case of perfect substitutes, which lead relative prices to vanish, and then compute equivalent changes in the rate of pure time preferences. This direct comparison reveals that there would be no positive pure time preference that is equivalent to considering relative prices with the complementary assumption of Sterner and Persson (2008). In our central calibration that is informed by a systematic study of the determinants of the relative price effect

and assumes higher substitutability as compared to Sterner and Persson (2008), we show that considering relative prices is equivalent to decreasing the rate of pure time preference by 0.53 percentage points. While we believe that relative price effects should be modeled explicitly given their importance for climate policy evaluation, our analysis reveals that the implicit degree of mild complementarity of non-market goods already contained in the standard DICE model of Nordhaus (2017) comes close to our central calibration and is therefore a rather plausible assumption. This also implies that if market and non-market goods are considered substitutes, explicitly introducing relative prices into DICE would lead to less stringent optimal climate policy.

While relative prices thus clearly matter considerably for climate policy evaluation, our results likewise suggest an enduring importance of the two key ‘normative’ discounting parameters determining the intertemporal distribution of well-being. Indeed, we find that in the short-run, the rate of pure time preference and the elasticity of marginal utility of consumption indirectly influence the relative price effect quite considerably, since the growth of consumption is endogenous in DICE.

Finally, our analysis provides guidance for the revision of discounting policy guidelines. Our findings suggest that the relative price effect of non-market goods is more substantial than the one percent result presented in the literature for the relative price effect of environmental goods that has informed policy guidance in the Netherlands (Baumgärtner et al. 2015; Drupp 2016; Koetse et al. 2017). Our analysis also points towards the most crucial determinants of relative prices, such as the degree of substitutability and technological progress. This suggests that it is imperative to obtain better estimates for these drivers globally as well as at local or national levels to better inform governmental guidance. All in all, our results support recent initiatives, such as in the Netherlands, to consider relative price effects in project appraisal.

B.1 Appendix to Chapter 3

B.1.1 Derivation of the relative price effect

To derive the relative price effect of non-market goods, $RPE_t = \frac{d}{dt} \left(\frac{U_E}{U_c} \right) \left(\frac{U_E}{U_c} \right)^{-1}$ (Equation 3.4), we first compute marginal utilities with respect to the two goods for utility function (3.2):

$$U_{h_{E_t}} = \alpha(E_t - \bar{E})^{\theta-1} [\alpha(E_t - \bar{E})^\theta + (1 - \alpha)c_t^\theta]^{\frac{1-\theta}{\theta}} \quad (\text{A.1})$$

$$U_{h_{c_t}} = (1 - \alpha)c_t^{\theta-1} [\alpha(E_t - \bar{E})^\theta + (1 - \alpha)c_t^\theta]^{\frac{1-\theta}{\theta}}. \quad (\text{A.2})$$

We thus have

$$\frac{U_{h_{E_t}}}{U_{h_{c_t}}} = \frac{\alpha}{(1 - \alpha)} \left(\frac{E_t - \bar{E}}{c_t} \right)^{\theta-1} \quad (\text{A.3})$$

The time derivative of this marginal rate of substitution is given by:

$$\frac{d}{dt} \left(\frac{U_E}{U_c} \right) = (\theta - 1) \frac{\alpha}{(1 - \alpha)} \left(\frac{E_t - \bar{E}}{c_t} \right)^{\theta-2} \left[\frac{\dot{E}_t}{c_t} - \frac{(E_t - \bar{E})\dot{c}_t}{c_t^2} \right] \quad (\text{A.4})$$

With the growth rates g_i of the two goods $i \in (E, c)$ defined as $g_{i_t} = \frac{\dot{i}_t}{i_t}$, we can rewrite this time derivative using $\dot{i}_t = g_{i_t} i_t$ as:

$$\begin{aligned} \frac{d}{dt} \left(\frac{U_E}{U_c} \right) &= \frac{\alpha}{(1 - \alpha)} \left(\frac{E_t - \bar{E}}{c_t} \right)^{\theta-1} (\theta - 1) \left(\frac{c_t}{E_t - \bar{E}} \right) \left[\frac{g_{E_t} E_t}{c_t} - \frac{(E_t - \bar{E})g_{c_t} c_t}{c_t^2} \right] \\ &= (1 - \theta) \frac{\alpha}{(1 - \alpha)} \left(\frac{E_t - \bar{E}}{c_t} \right)^{\theta-1} \left[g_{c_t} - \frac{E_t}{E_t - \bar{E}} g_{E_t} \right]. \end{aligned} \quad (\text{A.5})$$

The relative price effect of environmental goods is therefore given by

$$RPE_t = \frac{\frac{d}{dt} \left(\frac{U_E}{U_c} \right)}{\left(\frac{U_E}{U_c} \right)} = (1 - \theta) \left[g_{c_t} - \frac{E_t}{E_t - \bar{E}} g_{E_t} \right]. \quad (\text{A.6})$$

The relative price effect of non-market goods, i.e. the change in relative prices over time, is thus the same as the difference in the two good-specific discount rates (see Drupp 2016 for a derivation in continuous time).

B.1.2 Calibration of non-market damages

The non-market good climate damage coefficient ψ is calibrated for a temperature increase of $T = 3^\circ\text{C}$ as follows:

$$W_0(E_0, (1 - D_\phi)C_0, L_0) = W_0((1 - D_\psi)E_0, (1 - D_\kappa)C_0, L_0) \Leftrightarrow \quad (\text{A.7})$$

$$\alpha(E_0 - \bar{E})^\theta + (1 - \alpha)((1 - D_\phi)C_0)^\theta = \alpha\left(\frac{E_0}{1 + \psi T^2} - \bar{E}\right)^\theta + (1 - \alpha)((1 - D_\kappa)C_0)^\theta$$

We can solve this for the non-market climate damage parameter ψ as follows:

$$\psi = \left[E_0 \left(\bar{E} + \left[(E_0 - \bar{E})^\theta + \frac{1 - \alpha}{\alpha} \left(((1 - D_\phi)C_0)^\theta - ((1 - D_\kappa)C_0)^\theta \right) \right]^{\frac{1}{\theta}} \right)^{-1} - 1 \right] T^{-2}. \quad (\text{A.8})$$

Stern and Persson (2008) assume that the initial amount of the non-market good is equal to the starting value for material consumption as well as no subsistence requirement in the consumption of the non-market good, i.e. $C_0 = E_0$ and $\bar{E} = 0$. In this case equation (A.8) reduces to

$$\psi = \frac{1}{T^2} \left[\left(\frac{1 - \alpha}{\alpha} (1 - D_\phi)^\theta + 1 - \frac{1 - \alpha}{\alpha} (1 - D_\kappa)^\theta \right)^{-\theta} - 1 \right]. \quad (\text{A.9})$$

B.1.3 Relative prices and comparison of climate policy paths until 2300

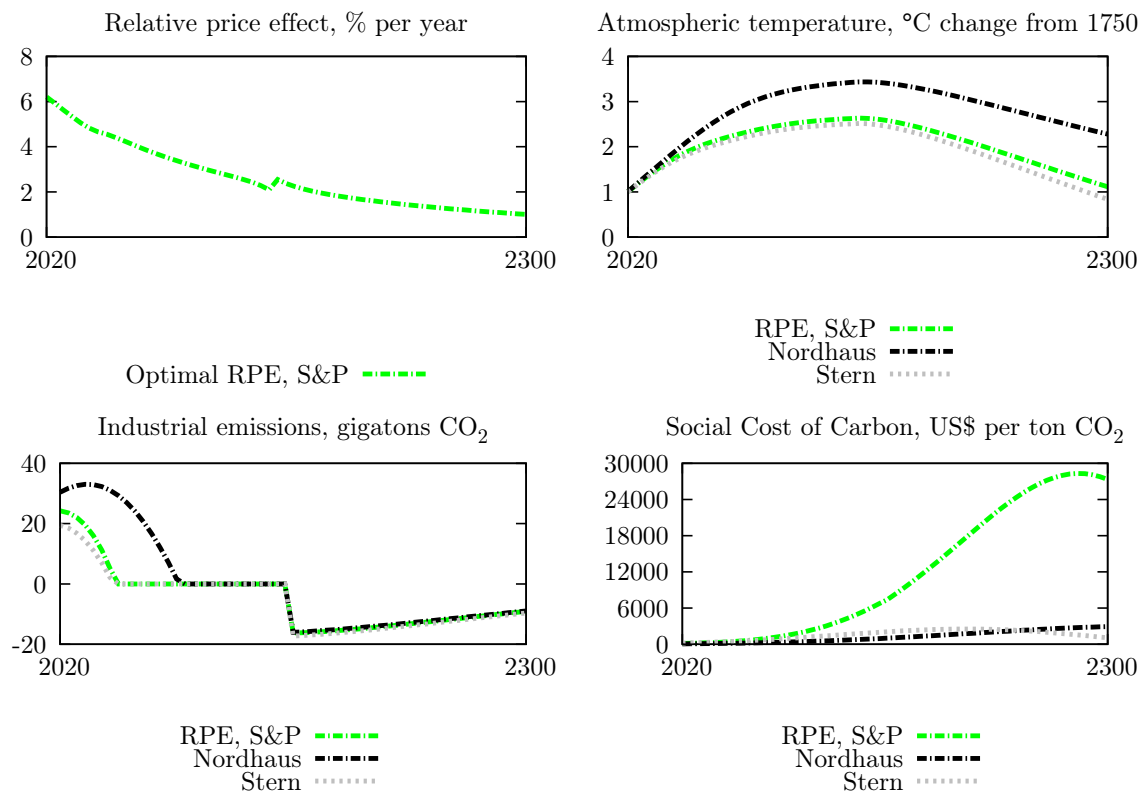


Figure 3.6: Relative price effect (*RPE*) and comparison of climate policy paths for a time horizon up to 2300. Otherwise, see description of Figure 1.

B.1.4 AMPL programming code

```
# DICE 2016R with Relative Prices
# The additional code for the Monte Carlo Analysis in section 3.5
#can be requested from the authors.

# PARAMETERS

#Time horizon
param T default 100;

# Preferences
param eta default 1.45; #I-EMUC
param rho default 0.015; #time preference rate

# relative prices additions
param zeta default -1; #substitution parameter
param beta default 0.1; #share of environmental good in utility function
param EQbar default 0; #subsistence level of environmental good
param cbar default 0; #subsistence level of consumption per capita
# Discount factor
param R {t in 0..T} = 1*exp(-rho*5*t);

# Population and its dynamics
param L0:=7403; #initial world population 2015 (millions)
param gL0:=0.134; #growthrate to calibrate to 2050 pop projection
param L {t in 0..T}>=0;
let L[0]:=L0;
let {t in 1..T} L[t]:=L[t-1]*((11500/L[t-1])^gL0);

# Technology and its dynamics
param gamma:=0.3; #capital elasticity in production function
param deltaK:=0.1; #depreciation rate on capital (per year)
param Qgross0:=105.5; #Initial world gross output 2015 (trill 2010 USD)
param K0:=223; #initial capital value 2015 (trillions 2010 USD)
param A0:=5.115; #initial level of total factor productivity
param gA0 :=0.076; #initial growth rate for TFP per 5 years
```

```

param deltaA default 0.005; #decline rate of TFP per 5 years

param gA {t in 0..T} := gA0*exp(-deltaA*5*t); # growth rate for TFP per period

param A {t in 0..T}>=0;
let A[0]:=A0;
let {t in 1..T} A[t]:=A[t-1]/(1-gA[t-1]);

# Emission parameters
param gsigma0:=-0.0152; #initial growth of sigma (coninuous per year )
param deltasigma:=-0.001; #decline rate of decarbonization per period
param ELand0:=2.6; #initial Carbon emissions from land 2015 (GtCO2 per period)
param deltaLand:=0.115; #decline rate of land emissions (per period)
param EInd0:=35.85; #Industrial emissions 2015 (GtCO2 per year)
param Ecum0:=400; #Initial cumulative emissions (GtCO2)
param mu0:=.03; #Initial emissions control rate for base year 2010
param Lambda0:=0; #Initial abatement costs
param sigma0:=EInd0/(Qgross0*(1-mu0));#initial sigma
#(kgCO2 per output 2005 USD in 2010)

param gsigma {t in 0..T};
let gsigma[0]:=gsigma0;
let {t in 1..T} gsigma[t]:=gsigma[t-1]*((1+deltasigma)^5);

param sigma {t in 0..T}>=0;
let sigma[0]:=sigma0;
let {t in 1..T} sigma[t]:=sigma[t-1]*exp(gsigma[t-1]*5);

param ELand {t in 0..T}>=0;
let ELand[0]:=ELand0;
let {t in 1..T} ELand[t]:=ELand [t-1]*(1-deltaLand);

# Carbon cycle
param MATO=851; # Initial Concentration in atmosphere 2015 (GtC)
param MUP0:=460; # Initial Concentration in upper strata 2015 (GtC)
param MLO0:=1740; # Initial Concentration in lower strata 2015 (GtC)
param MATEQ:=588; # Equilibrium concentration in atmosphere
#(pre-industrial atmos. carbon) (GtC)

```

```

param MUPEQ:=360; # Equilibrium concentration in upper strata (GtC)
param MLOEQ:=1720; # Equilibrium concentration in lower strata (GtC)

# Flow parameters
param phi12:=0.12;
param phi23:=0.007;
param phi11=1-phi12;
param phi21=phi12*MATEQ/MUPEQ;
param phi22=1-phi21-phi23;
param phi32=phi23*MUPEQ/MLOEQ;
param phi33=1-phi32;

# Climate model parameters
param nu:=3.1; # Equilibrium temperature impact (°C per doubling CO2)
param Fex0:=0.5; # 2015 forcings of non-CO2 GHG (Wm-2)
param Fex1:=1.0; # 2100 forcings of non-CO2 GHG (Wm-2)
param TLO0:=0.0068; # Initial lower stratum temperature change (°C from 1900)
param TAT0:=0.85; # Initial atmospheric temp change (°C from 1900)
param xi1:=0.1005; # Speed of adjustment parameter for atmospheric temperature
param xi3:=0.088; # Coefficient of heat loss from atmosphere to oceans
param xi4:=0.025; # Coefficient of heat gain by deep oceans
param kappa:=3.6813; # Forcings of equilibrium CO2 doubling (Wm-2)
param xi2=kappa/nu; # climate model parameter

# external forcing (Wm-2)
#assumed to be constant and equal to Fex1 from 2100 onward,
#see e.g. Traeger (2014, Fig.1)
param Fex {t in 0..T}>=0;
let {t in 0..18} Fex[t]:=Fex0+1/18*(Fex1-Fex0)*(t);
let {t in 19..T} Fex[t]:=Fex1;

# Climate damage parameters
param Psi default 0.00181; # damage term without 25% adjustment;
damage quadratic term with 25% adjustment is 0.00236
param MD default 0.0163;
# market damages for 3°C warming above preindustrial according to Nordhaus (2017)
param TD default 0.0326;
# TD including 100% adjustment for NMD Stern (2007)=0.0326;

```



```

#Nordhaus(2014) assumes 25% adjustment for NMD cooresponding to TD =0.02124,
#62.5%=0.0264857
param NMD:=TD-MD;
param TATlim default 12; # upper bound on atm. temperature change

# Abatement cost
param Theta:=2.6; # Exponent of control cost function
param pback0:=550; # Cost of backstop 2010 $ per tCO2 2015
param gback:=0.025; # Initial cost decline backstop cost per period

param pback {t in 0..T}>=0;
let pback[0]:=pback0;
let {t in 1..T} pback[t]:=pback[t-1]*(1-gback);

param phead {t in 0..T}=pback[t]*sigma[t]/Theta/1000;

# VARIABLES

# capital (trillions 2010 USD)
var K {t in 0..T}>=1;

# Gross output (trillions 2010 USD)
var Qgross {t in 0..T}=A[t]*((L[t]/1000)^(1-gamma))*(K[t]^gamma);

# carbon reservoir atmosphere (GtC)
var MAT {t in 0..T}>=10;

# carbon reservoir upper ocean (GtC)
var MUP {t in 0..T}>=100;

# carbon reservoir lower ocean (GtC)
var MLO {t in 0..T}>=1000;

# total radiative forcing (Wm-2)
var F {t in 0..T}=kappa*((log(MAT[t]/MATEQ))/log(2))+Fex[t];

# atmospheric temperature change (°C from 1750)
var TAT {t in 0..T}>=0, <=TATlim;

```

```

# ocean temperature (°C from 1750)
var TLO {t in 0..T}>=-1, <=20;

# damage fraction
var Omega {t in 0..T}=Psi*(TAT[t])^2;

# damages (trillions 2010 USD)
var damage {t in 0..T}=Omega[t]*Qgross[t];

# emission control
var mu {t in 0..T}>=0;

# abatement costs (fraction of output)
var Lambda {t in 0..T}=Qgross[t]*phead[t]*(mu[t]^Theta);

# industrial emissions
var EInd {t in 0..T}=sigma[t]*Qgross[t]*(1-mu[t]);

# total emissions
var E {t in 0..T};

# maximum cumulative extraction fossil fuels (GtC)
var Ecum {t in 0..T}<=6000;

# Marginal cost of abatement (carbon price)
var cprice {t in 0..T}=pback[t]*mu[t]^(Theta-1);

# output net of damages and abatement(trillions 2010 USD)
var Q {t in 0..T}=(Qgross[t]*(1-Omega[t]))-Lambda[t];

# per capita consumption (1000s 2010 USD)
var c {t in 0..T} >= .1;

# aggregate consumption
var C {t in 0..T} = L[t]*c[t]/1000;

```

```

# Investment(trillions 2005 USD)
var I {t in 0..T}>=0;

# Non-market good
var EQ {t in 0..T}>=0.0000001 <=1000;

# Non-market damages scaling parameter including subsistence requirement

# including sub
var a {t in 0..T} = (1/(nu^2))*(EQ[0]*(EQbar+((EQ[0]-EQbar)^(zeta)
+((1-beta)/beta)*(((1-TD)*C[0])^(zeta)-((1-MD)*C[0])^(zeta))))^(1/zeta))^(-1)-1);

var g_C {t in 0..T-1} = (C[t+1]-C[t])/C[t];

# growth rate of non-market goods

var g_EQ {t in 0..T-1} = ((EQ[t+1]-EQ[t])/EQ[t]);

# relative price effect

var RPE {t in 0..T-1} = (1-zeta)*(g_C[t]-((EQ[t]/(EQ[t]-EQbar))*g_EQ[t]));

# utility

var U {t in 0..T}= (((1-beta)*(c[t])^(zeta)+
beta*((EQ[t]-EQbar)*1000/L[t])^(zeta))^(1-eta)/zeta)/(1-eta);

# welfare/objective function
var W=sum{t in 0..T} L[t]*U[t]*R[t];

maximize objective_function: W;
subject to initial_consumption: c[0]=10.4893;
subject to constr_accounting {t in 0..T}:
C[t]=Q[t]-I[t];
subject to constr_emissions {t in 0..T}:
E[t]=EInd[t]+ELand[t];
subject to constr_capital_dynamics {t in 1..T}:
K[t]=(1-deltaK)^5*K[t-1]+5*I[t-1];

```

```

subject to constr_cumulativeemissions {t in 1..T}:
Ecum[t]=Ecum[t-1]+(EInd[t-1]*5/3.666);
subject to constr_atmosphere {t in 1..T}:
MAT[t]=E[t]*(5/3.666)+phi11*MAT[t-1]+phi21*MUP[t-1];
subject to constr_upper_ocean {t in 1..T}:
MUP[t]=phi12*MAT[t-1]+phi22*MUP[t-1]+phi32*MLO[t-1];
subject to constr_lower_ocean {t in 1..T}:
MLO[t]=phi23*MUP[t-1]+phi33*MLO[t-1];
subject to constr_atmospheric_temp {t in 1..T}:
TAT[t]=TAT[t-1]+xi1*((F[t]-xi2*TAT[t-1])-(xi3*(TAT[t-1]-TLO[t-1])));
subject to constr_ocean_temp {t in 1..T}:
TLO[t]=TLO[t-1]+xi4*(TAT[t-1]-TLO[t-1]);

# Initial conditions
subject to initial_capital: K[0] = K0;
subject to initial_Ecum: Ecum[0]=Ecum0;
subject to initial_MAT: MAT[0]=MAT0;
subject to initial_MUP: MUP[0]=MUPO;
subject to initial_MLO: MLO[0]=MLO0;
subject to initial_TLO: TLO[0]=TLO0;
subject to initial_TAT: TAT[0]=TAT0;
subject to initial_control: mu[0]=mu0;
subject to control1 {t in 1..28}: mu[t]<=1;
subject to control2 {t in 29..T}: mu[t]<=1.2; # from 2150
subject to initial_EQ: EQ[0]=C[0];
subject to constr_EQ {t in 1..T}: EQ[t]=(EQ[0]/(1+a[t]*(TAT[t]^2)));

```

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4 Interacting Externalities of Ocean Acidification, Global Warming and Eutrophication

General Equilibrium Analysis for a Developing Country

This chapter has not been published yet. It may be referenced as:

M.C. Hänsel (2017). Interacting Externalities of Ocean Acidification, Global Warming and Eutrophication: General Equilibrium Analysis for a Developing Country. Mimeo, University of Kiel.*

Abstract: We describe an economy dependent on agriculture and fisheries to study optimal environmental policy in the face of interacting external effects of ocean acidification, global warming and eutrophication. The model captures that CO_2 emissions not only contribute to global warming through an increase of the atmospheric temperature but also cause ocean acidification. Global warming affects both sectors while ocean acidification influences fisheries. The model accounts for agriculture run-off of pesticides and fertilizers, which results in eutrophication of the ocean that negatively affects the productivity of fisheries. The utility of a representative consumer reflects both use and non-use values of agricultural and fishery resources by incorporating not only the consumption of their products but also a biodiversity value. The latter decreases in the three environmental damages. We derive optimal rules for taxes on CO_2 emissions and agricultural run-off and show how they depend on both isolated and interacting damage effects. In addition, we derive a second-best rule for a tax on agricultural run-off of pesticides and fertilizers for the realistic case that an effective internalization of CO_2 externalities is lacking. The results contribute to an understanding of the economics of ocean acidification interacting with other important environmental stressors for economies particularly sensitive to such stressors.

Keywords: ocean acidification, global warming, eutrophication, climate policy, general equilibrium

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4.1 Introduction

Climate change is a major challenge for humankind and has been termed the “greatest market failure the world has ever seen” (Stern 2007, p. viii). Consequently, the economic implications of it have been studied extensively over the last decades. In contrast, the economics of ocean acidification, a phenomenon caused by uptake of atmospheric carbon dioxide (CO_2) in the oceans, is still a rather underdeveloped research area. Nevertheless, the socioeconomic consequences of ocean acidification are expected to be considerable. Under a business as usual emission path, ocean acidification is likely to affect ecosystem services provided by the oceans, such as ocean carbon uptake, coastal protection, food security, tourism, human health and biodiversity (Turley and Gattuso 2012, Hilmi et al. 2012, Gattuso et al. 2015, Rodrigues et al. 2015).

While the largest emitters of greenhouse gas emissions are developed economies, developing economies will likely be hit the hardest by climate change. The same is true for ocean acidification: The highest risk of possible impacts is projected to occur in developing coastal economies (Cooley et al. 2012), such as Senegal and Madagascar, as they depend on fishery resources for nutrition and as a main source of income. In order to evaluate socioeconomic effects of ocean acidification and design appropriate policy instruments it is constructive to analyze ocean acidification within a broader context of global environmental and ecosystem change (Riebesell and Gattuso 2015, Turley and Gattuso 2012). Moreover, ocean acidification is often regionally intensified by regional sources of acidification, most importantly through eutrophication caused by nutrient run-off from acidic fertilizers used in agricultural production (Kelly et al. 2011).

Based on these stylized facts of ocean acidification research, this paper describes an economy that is representative of many sea-bordering developing countries, namely highly dependent on agriculture and fisheries and suffers from three negative externalities: Global warming, ocean acidification and nutrient run-off of acidic fertilizers used in agricultural production. We design a general equilibrium model to study the interaction of the three negative externalities and appropriate optimal policy responses. For the realistic case of an optimal carbon tax that internalizes the negative effects

of global warming and ocean acidification can not be implemented, we also derive a second-best optimal tax on nutrient run-off and compare it to the first-best case.

The remainder of this paper is structured as follows. Section 4.2 describes the overall structure and feedback loops in the modeled economy-environment system, while it reviews relevant notions and insights from other studies. Section 4.3 presents the general equilibrium model and derives first- and second-best policy rules. Section 4.5 summarizes the results and concludes.

4.2 Framework and related literature

The following figure sketches the structure and feedback loops in the economy-environment system we analyze in this paper.

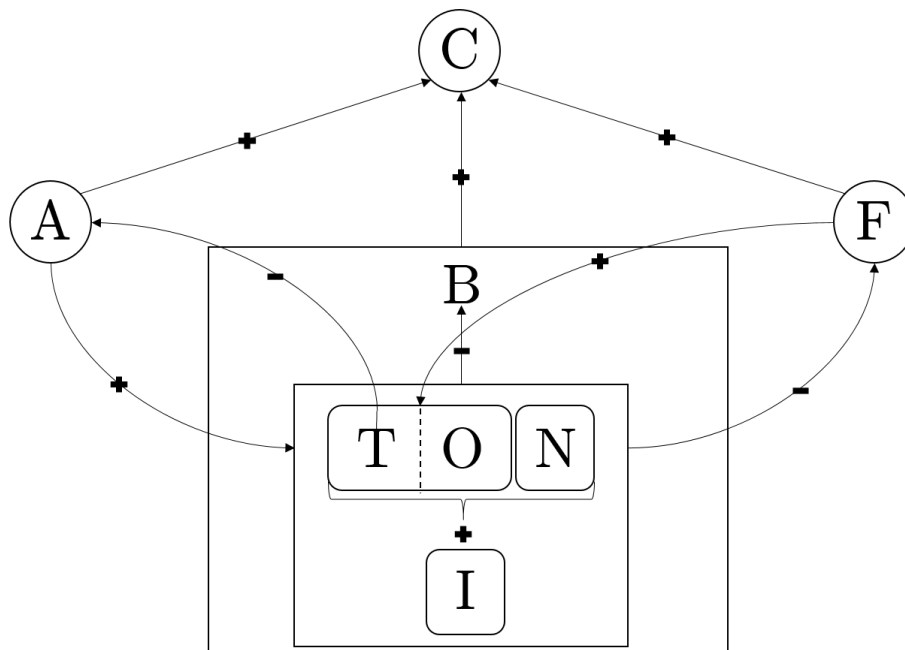


Figure 4.1: Structure and feedback loops in the economy-environment system, while “+” and “-” reflect the sign of the feedback: Agriculture (A) and fisheries (F) interact with consumers (C) and the natural environment; the latter determines the status of biodiversity (B) and is affected by the mean global temperature increase (T), ocean acidification (O), nutrient run-off (N) and their interaction (I).

The model structure reflects the economic setting of a coastal developing economy with two producing sectors: Agriculture (A) and fisheries (F). Consumers (C) depend on agricultural and fishery products for nutrition and can thus be expected to be

highly exposed to risks from shortages in food supply (Cooley et al. 2012). Consumers and both sectors interact with their natural environment determining the status of biodiversity (B) that has a positive influence on the well-being of consumers in the economy. The status of biodiversity is represented by the biggest rectangle in figure 4.1 and is modelled to be negatively affected by three environmental stressors: The mean global temperature increase (T), ocean acidification (O), nutrient run-off (N) from agricultural production and their interaction (I).

We assume that agricultural and fishery production is fossil fuel intensive¹ and hence, contributes to global warming. Mostly as a result of fossil fuel emissions and land use changes global mean atmospheric CO_2 levels have increased by 42% from about 280 ppm in pre-industrial levels to 405 ppm in the beginning of 2017 (IPCC 2013, NOAA 2017) resulting in two important global transformations. Relatively well known is the mean global surface temperature increase. According to the World Meteorological Organization 2016 was the hottest year on record with 1.1°C above pre-industrial levels. It is beyond the scope of this paper to discuss the far-reaching consequences of global warming in detail. For the current analysis it is relevant to note that agricultural and fishery production not only contribute to global warming by using fossil fuel intensive production inputs, but also suffer from it.

The relationship between crop yields in agriculture and climatic variables is well studied in both developed and developing countries (Mendelsohn et al. 1994, Schlenker et al. 2006, Deschênes and Greenstone 2007, Schlenker and Roberts 2009, Welch et al. 2010, Chen et al. 2016, Burke and Emerick 2016). Simulation models suggest that even moderate global warming could have negative effects on wheat, maize and rice production of subsistence farmers like those operating in many coastal economies (Morton 2007).

¹ We assume that fossil fuels are needed to run tractors and fishing boats.

Studies that estimate the effect of ocean warming on global fisheries predict spatial redistribution effects of fisheries catch potential (Cheung et al. 2010, Blanchard et al. 2012), higher vulnerability of coastal fisheries to climate change (Allison et al. 2009) and changes in catch composition (Cheung et al. 2013). Socioeconomic consequences are expected in particular for coastal fishing communities, which are a central element of the analysis in this paper.

Besides global warming, there is ‘the other’, less well-known, problem associated with the increasing stock of atmospheric CO_2 , namely ocean acidification (O). In our model both the agricultural and the fishery sector positively contribute to ocean acidification, but only the fishery sector, which depends on ocean resources, is negatively affected by it. Between 1750 and 2011 the world’s oceans have absorbed about 30% of atmospheric CO_2 (IPCC 2013), which basically leads to two important chemical reactions: First, dissolved CO_2 reacts with seawater and forms carbonic acid, causing hydrogen ion concentrations to increase and hence pH to fall. With high confidence CO_2 uptake has caused ocean surface pH to fall by 0.1 below the preindustrial average, which translates into a 26% increase in acidity (IPCC 2013). Under business as usual (IPCC AR5, RCP 8.5²) ocean surface pH is projected to fall by 0.42 units below pre-industrial levels by 2100 (Bopp et al. 2013). Second, CO_2 reacts with seawater and carbonate leading to a decrease in carbonate ions, which increases the dissolution rate of calcium carbonate. Main mineral forms of calcium carbonate, such as calcite and aragonite, that are used by many marine organisms to build their shells and skeletons, start dissolving at low carbonate ion concentrations (Orr et al. 2003, Turley 2013). Hence, ocean acidification could lead to important negative effects on the growth of calcifying organisms (Kroeker et al. 2010) implying negative ecological and economic impacts (Cooley and Doney 2009, Gattuso et al. 2014). Direct impacts on fisheries markets may occur because commercially important global bivalve populations could decline (Cooley and Doney 2009, Talmage and Gobler 2010). In addition, non-market impacts are possible due to restructuring of ecosystems, biodiversity loss and degradation of coral reefs (Hilmi et al. 2012, Gattuso et al. 2015, Rodrigues et al. 2015).

² Representative Concentration Pathway 8.5.

The existing literature on the economic impacts of - and appropriate policy responses to - global warming and ocean acidification mainly studies either effect in isolation from one another and from other potential environmental stressors. However, it will be key to understand ocean acidification within a more comprehensive ecosystem response to environmental change (Riebesell and Gattuso 2015, Turley and Gattuso 2012). Oftentimes, the effects of global warming and ocean acidification are regionally intensified by specific local sources of acidification like sulfur dioxide precipitation or eutrophication through run-off from acidic fertilizers (Kelly et al. 2011). As a consequence, a regional strategy to counteract ocean acidification would have to be designed in a way that integrates impacts from ocean acidification with other global ocean stressors, such as overfishing, habitat destruction, temperature change and non-acidifying pollution, and with specific regional stressors like eutrophication (Kelly et al. 2011). In this paper we build on this by designing an economic setting, which integrates ocean acidification with global warming as a key global environmental stressor as well as with nutrient run-off (N) from acidic fertilizers used in agricultural production as a key regional environmental stressor.

Human inputs of nutrients such as nitrogen and phosphorus, which are used in agricultural fertilization in order to increase food output, can result in excessive production of algae. This process, known as eutrophication, changes the structure and functioning of global ecosystems and its services provided to humans (Compton et al. 2011, Rockstrom et al. 2009, Diaz and Rosenberg 2008). The microbial decomposition of the large phytoplankton biomass originating from algae booms not only results in low oxygen concentrations (hypoxia), which can displace or kill fish and invertebrates populations. At the same time this process releases CO_2 , which lowers the pH and increases the acidity of subsurface waters in coastal regions (Cai et al. 2011). In some regions coastal eutrophication contributes more to coastal water acidity than global ocean acidification (Kelly et al. 2011). In addition eutrophication may reduce the ability of coastal waters to buffer changes in pH, such that the interaction of global and coastal ocean acidification is more than the sum of both effects (Cai et al. 2011). In our model we account for this by including an interaction effect (I) between temperature, ocean acidification and nutrient run-off. While the agricultural sector only suffers from

temperature damages, fisheries are negatively affected by all three modelled negative externalities and their interaction.

We utilize the model structure in figure 4.1 to find optimal policy responses to (i) the negative effects of carbon in the atmosphere (global warming and ocean acidification) and (ii) nutrient run-off in general equilibrium. Although an effective internalization of CO_2 externalities based on an optimal carbon tax should be the ultimate target to fight both global warming and ocean acidification, this is far from being realistic. It has been argued that the missing political willingness to support a global solution can be a reason to focus more on regional management (Rau et al. 2012). Existing global effort will not be enough to prevent marine ecosystems from serious changes and hence, regional tailor-made mitigation strategies particularly targeting those, which are most affected (e.g. small developing coastal communities), should receive more attention (Rau et al. 2012, Strong et al. 2014). In this light, we not only calculate the first-best optimal taxes on carbon and nutrient run-off, but also derive the second-best optimal tax on nutrient run-off for the case that an effective internalization of CO_2 externalities is lacking.

4.3 General equilibrium model and policy rules

We introduce a static general equilibrium model of a closed coastal economy with agriculture (A) and fisheries (F) as production sectors, which generate three externalities. CO_2 emissions contribute to global warming, captured in the model by an increase of atmospheric temperature (T) relative to the pre-industrial level. CO_2 emissions further cause ocean acidification (O). A third externality is due to agriculture run-off of pesticides and fertilizers which cause eutrophication (N for nutrient run-off) of the ocean. We assume that agricultural output is only affected by global warming. On the other hand the fisheries sector suffers from all three externalities, due to global warming, ocean acidification and eutrophication. Moreover, we include an interaction term (I) to reflect that the three effects may be synergetic in terms of the overall damage.

The two sectors produce output Q^i (with $i = A, F$) by means of emissions and labor.³ We assume that variable inputs like fertilizers or fuels are highly correlated with capital use, such as tractors or fishing boats. Thus, while capital utilization is carbon (M) emission intensive, with e_M^A and e_M^F denoting carbon emissions in the agriculture and fishery sector, emissions from eutrophication e_N^A can be thought of to be a byproduct of capital utilization in the agriculture sector.

Net output in the agricultural sector Q^A increases in labor l^A , agricultural carbon emissions e_M^A and emissions from nutrient run-off e_N^A . Q^A decreases in the global mean atmospheric temperature increase T , which determines temperature damages.

$$Q^A = f^A(l^A, e_M^A, e_N^A, T) \quad (4.1)$$

Additionally we assume that f^A is strictly concave in carbon emissions, i.e. that $\frac{\partial^2 f^A}{\partial e_M^A \partial e_M^A} < 0$ and that the second cross derivative is positive, i.e. $\frac{\partial^2 f^A}{\partial e_M^A \partial e_N^A} > 0$. The former means that carbon emissions become less productive the more carbon emissions are needed for production. The latter captures that carbon emissions and nutrient run-off are modeled as complements, reflecting that carbon-intensive fuels and acidic fertilizers are jointly used in agricultural production.⁴

Net output in the fishery sector Q^F increases in labor l^F and carbon emissions e_M^F and decreases in the global mean temperature anomaly T , ocean acidification O , nutrient run-off N and in an interaction effect I determined by all three environmental stressors.

$$Q^F = f^F(l^F, e_M^F, T, O, N, I) \quad (4.2)$$

In terms of factors of production, we assume an inelastic factor supply. Total carbon emissions E_M are the sum of carbon emissions from both sectors of the economy and carbon emissions from the rest of the world e_M^R . Total emissions from nutrient run-off E_N are the sum of nutrient emissions from agricultural production and nutrient run-off from the rest of the world e_M^R .

³In line with the literature on optimal pollution regulation (e.g Muller and Mendelsohn (2009)) we treat emissions directly as a factor of production.

⁴The cross derivative is negative when the production factors are substitutes. See Hoel (2012) for an example of energy production from fossil fuels and renewables.

$$L = l^A + l^F \quad (4.3)$$

$$E_M = e_M^A + e_M^F + e_M^R \quad (4.4)$$

$$E_N = e_N^A + e_N^R \quad (4.5)$$

We focus on a representative consumer, who derives utility from the consumption of agricultural and fish products C^A and C^F as well as from a public good B representing the status of biodiversity. The inclusion of biodiversity in the utility function reflects that there are not only direct use values of land and ocean based ecosystems but also non-use values. Utility increases in B while we model B to be negatively affected by the three environmental stressors and their interaction. The resulting utility function reads:

$$U\left(c^A, c^F, B(T, O, N, I)\right) \quad (4.6)$$

Finally, the output in both sectors of the economy is consumed entirely.

$$Q^i = c^i \quad \text{with } i = A, F \quad (4.7)$$

Both the global mean atmospheric temperature increase T and ocean acidification O increase in the total amount of carbon emissions E_M .

$$T = T(E_M) \quad \text{with } T' > 0 \quad (4.8)$$

$$O = O(E_M) \quad \text{with } O' > 0 \quad (4.9)$$

Nutrient run-off N increases in the total amount of emissions from nutrient run-off E_N .

$$N = N(E_N) \quad \text{with } N' > 0 \quad (4.10)$$

The interaction effect I increases in both total carbon emissions and total emissions

from nutrient run-off.

$$I = I(E_M, E_N) \quad \text{with} \quad \frac{\partial I}{\partial E_M} > 0 \quad \text{and} \quad \frac{\partial I}{\partial E_N} > 0 \quad (4.11)$$

4.3.1 Market solution

The representative consumer maximizes utility subject to a budget constraint, where w is the wage, p^F is the price of the final food produced in the fishery sector, while we set the price of the agricultural good to unity, i.e. $p^A = 1$ (numeraire).

$$\max_{\{c^A, c^F\}} U(c^A, c^F, B) \quad \text{subject to} \quad wL \geq c^A + p^F c^F \quad (4.12)$$

In the optimum the marginal rate of substitution between consumption of agricultural products c^A and fish consumption c^F is equal to the price ratio of the two products, i.e.:

$$\frac{\partial U / \partial c^A}{\partial U / \partial c^F} = \frac{1}{p^F} \quad (4.13)$$

In each sector the representative firms maximize profits subject to the production technology. Production costs include the payment of taxes τ_M on carbon emissions and τ_N on nutrient run-off.⁵

$$\max_{\{l^A, e_M^A, e_N^A\}} \left\{ f^A(l^A, e_M^A, e_N^A, T) - wl^A - \tau_M e_M^A - \tau_N e_N^A \right\} \quad (4.14)$$

$$\max_{\{l^F, e_M^F\}} \left\{ p^F f^F(l^F, e_M^F, T, O, N, I) - wl^F - \tau_M e_M^F \right\} \quad (4.15)$$

⁵We abstain here from complicating issues like non-point sources of pollution and assume a single tax, e.g. on fertilizers, is effective. Section 4.4 discusses some aspects of non-point source pollution in relation to our study.

The first order conditions for both sectors are then:

$$\frac{\partial f^A}{\partial l^A} = w \quad (4.16)$$

$$\frac{\partial f^A}{\partial e_M^A} = \tau_M \quad (4.17)$$

$$\frac{\partial f^A}{\partial e_N^A} = \tau_N \quad (4.18)$$

$$\frac{p^F \partial f^F}{\partial l^F} = w \quad (4.19)$$

$$\frac{p^F \partial f^F}{\partial e_M^F} = \tau_M \quad (4.20)$$

We can equate (4.16) with (4.19) and (4.17) with (4.20) to arrive at the following two conditions:

$$\frac{\partial f^A}{\partial l^A} = \frac{p^F \partial f^F}{\partial l^F} \quad (4.21)$$

$$\frac{\partial f^A}{\partial e_M^A} = \frac{p^F \partial f^F}{\partial e_M^F} \quad (4.22)$$

Equations (4.21) and (4.22) require that in equilibrium both the value of the marginal product of labor and the value of the marginal product of carbon emissions must be the same in the two sectors. The value of the marginal product of carbon emissions can also be interpreted as the cost the representative firm has to bear when abating one unit of carbon emissions. Hence, (4.22) can be interpreted as one of the fundamental insights of environmental economics: In the equilibrium with pollution taxation marginal abatement cost must be equal across sectors. This result is due here to a uniform carbon tax, regardless of its specific value. From the first order conditions (4.17) and (4.20) we know that the optimal carbon tax must be exactly equal to the marginal abatement cost of carbon emissions. Similarly, (4.18) requires that the optimal tax on nutrient run-off from agricultural production equates to the marginal abatement cost of nutrient emissions.

Finally we can combine equation (4.13) with equations (4.21) and (4.22):

$$\frac{\frac{\partial U}{\partial c^A}}{\frac{\partial U}{\partial c^F}} = \frac{\frac{\partial f^F}{\partial l^F}}{\frac{\partial f^A}{\partial l^A}} = \frac{\frac{\partial f^F}{\partial e_M^F}}{\frac{\partial f^A}{\partial e_M^A}} \quad (4.23)$$

This means that the marginal rate of substitution between agricultural product consumption and fish consumption must equal the marginal rate of technical substitution between labor in the two sectors, which must again be equal to the marginal rate of technical substitution between carbon emissions used in production in each of the sectors.

4.3.2 Socially optimal allocation

A central planner maximizes social welfare, that is, the utility of a representative agent, while taking into consideration the entire feedback structure in the economy.

In particular, the optimization program reads:

$$\max_{\{c^A, c^F, l^A, l^F, e_M^A, e_M^F, e_N^A\}} U \left(c^A, c^F, B(T, O, N, I) \right) \text{ subject to equations} \\ (4.1), (4.2), (4.3), (4.4), (4.5), (4.7), (4.8), (4.9), (4.10), (4.11) \quad (4.24)$$

By substituting all the constraints into the objective function, the following maximization problem results:

$$\max_{\{l^A, e_M^A, e_M^F, e_N^A\}} U \left(f^A(l^A, e_M^A, e_N^A, T(E_M)), \right. \\ \left. f^F(L - l^A, e_M^F, T(E_M), O(E_M), N(E_N), I(E_M, E_N)), \right. \\ \left. B(T(E_M), O(E_M), N(E_N), I(E_M, E_N)) \right) \quad (4.25)$$

The first order conditions⁶ describing the socially optimal allocation are:

$$\frac{\partial U}{\partial e_M^A} = 0 \Leftrightarrow \frac{\partial U}{\partial c^A} \left[\frac{\partial f^A}{\partial e_M^A} + \frac{\partial f^A}{\partial T} T' \right] + \frac{\partial U}{\partial c^F} \left[\frac{\partial f^F}{\partial T} T' + \frac{\partial f^F}{\partial O} O' + \frac{\partial f^F}{\partial I} \frac{\partial I}{\partial e_M^A} \right] + \frac{\partial U}{\partial B} \left[\frac{\partial B}{\partial T} T' + \frac{\partial B}{\partial O} O' + \frac{\partial B}{\partial I} \frac{\partial I}{\partial e_M^A} \right] = 0 \quad (4.26a)$$

$$\frac{\partial U}{\partial e_M^F} = 0 \Leftrightarrow \frac{\partial U}{\partial c^A} \left[\frac{\partial f^A}{\partial T} T' \right] + \frac{\partial U}{\partial c^F} \left[\frac{\partial f^F}{\partial e_M^F} + \frac{\partial f^F}{\partial T} T' + \frac{\partial f^F}{\partial O} O' + \frac{\partial f^F}{\partial I} \frac{\partial I}{\partial e_M^F} \right] + \frac{\partial U}{\partial B} \left[\frac{\partial B}{\partial T} T' + \frac{\partial B}{\partial O} O' + \frac{\partial B}{\partial I} \frac{\partial I}{\partial e_M^F} \right] = 0 \quad (4.26b)$$

$$\frac{\partial U}{\partial e_N^A} = 0 \Leftrightarrow \frac{\partial U}{\partial c^A} \frac{\partial f^A}{\partial e_N^A} + \frac{\partial U}{\partial c^F} \left[\frac{\partial f^F}{\partial N} N' + \frac{\partial f^F}{\partial I} \frac{\partial I}{\partial e_N^A} \right] + \frac{\partial U}{\partial B} \left[\frac{\partial B}{\partial N} N' + \frac{\partial B}{\partial I} \frac{\partial I}{\partial e_N^A} \right] = 0 \quad (4.26c)$$

$$\frac{\partial U}{\partial l^A} = 0 \Leftrightarrow \frac{\partial U}{\partial c^A} \frac{\partial f^A}{\partial l^A} - \frac{\partial U}{\partial c^F} \frac{\partial f^F}{\partial l^F} = 0 \quad (4.26d)$$

From (4.26d) we obtain the well known condition for the socially optimal allocation in the private good markets, which is identical to (4.23).

$$\frac{\frac{\partial U}{\partial c^A}}{\frac{\partial U}{\partial c^F}} = \frac{\frac{\partial f^F}{\partial l^F}}{\frac{\partial f^A}{\partial l^A}} \quad (4.27)$$

The marginal rate of substitution between agricultural product consumption and fish consumption must equal the marginal rate of technical substitution between labor in the two markets.

⁶Note that $\frac{\partial T}{\partial e_M^A} = \frac{\partial T}{\partial e_M^F} = T'$, $\frac{\partial O}{\partial e_M^A} = \frac{\partial O}{\partial e_M^F} = O'$, $\frac{\partial N}{\partial e_N^A} = N'$.

We rearrange (4.26a) and use (4.17) to obtain the optimal tax on carbon emissions τ_M^* , which is equal to the Pigouvian carbon tax $\widehat{\tau}_M^*$ capturing the marginal social damage from carbon emissions.⁷

$$\begin{aligned}
\tau_M^* = \widehat{\tau}_M^* &= \left[\overbrace{-\frac{\partial U}{\partial B} \left(\frac{\partial B}{\partial T} T' + \frac{\partial B}{\partial O} O' + \frac{\partial B}{\partial I} \frac{\partial I}{\partial e_M^A} \right)}^{\text{MD Biodiversity}} \overbrace{-\frac{\partial U}{\partial c^A} \frac{\partial f^A}{\partial T} T'}^{\text{MD Own-Sector}} \right. \\
&\quad \left. \overbrace{-\frac{\partial U}{\partial c^F} \left(\frac{\partial f^F}{\partial T} T' + \frac{\partial f^F}{\partial O} O' + \frac{\partial f^F}{\partial I} \frac{\partial I}{\partial e_M^A} \right)}^{\text{MD Other-Sector}} \right] \frac{1}{\frac{\partial U}{\partial c^A}} \\
&= \left[\overbrace{\left(-\frac{\partial U}{\partial B} \frac{\partial B}{\partial T} - \frac{\partial U}{\partial c^A} \frac{\partial f^A}{\partial T} - \frac{\partial U}{\partial c^F} \frac{\partial f^F}{\partial T} \right)}^{\text{MD Temperature}} T' + \overbrace{\left(-\frac{\partial U}{\partial B} \frac{\partial B}{\partial O} - \frac{\partial U}{\partial c^F} \frac{\partial f^F}{\partial O} \right)}^{\text{MD Ocean Acidification}} O' \right. \\
&\quad \left. + \overbrace{\left(-\frac{\partial U}{\partial B} \frac{\partial B}{\partial I} - \frac{\partial U}{\partial c^F} \frac{\partial f^F}{\partial I} \right) \frac{\partial I}{\partial e_M^A}}^{\text{MD Interaction}} \right] \frac{1}{\frac{\partial U}{\partial c^A}} \tag{4.28}
\end{aligned}$$

Equation (4.28) shows two decompositions, allowing two interpretations of the optimal tax. According to the first decomposition the optimal carbon tax is the sum of marginal damages (MD) from temperature increase, ocean acidification, nutrient run-off and the interaction term measured in terms of consumption of the (own) agricultural sector. The second decomposition illustrates that the optimal tax includes marginal damages on the biodiversity value as well as marginal damages on production in the own agricultural sector (own-sector effect) and the fishery sector (other-sector effect).

⁷Note that the Pigouvian tax must not always be equal to the optimal tax, see for example Cremer et al. (1998).

In order to calculate the optimal tax on nutrient run-off τ_N^* , we use (4.18) and rearrange (4.26c).

$$\begin{aligned} \tau_N^* = \widehat{\tau}_N^* &= \left[\overbrace{-\frac{\partial U}{\partial B} \left(\frac{\partial B}{\partial N} N' + \frac{\partial B}{\partial I} \frac{\partial I}{\partial e_N^A} \right)}^{\text{MD Biodiversity}} - \overbrace{\frac{\partial U}{\partial c^F} \left(\frac{\partial f^F}{\partial N} N' + \frac{\partial f^F}{\partial I} \frac{\partial I}{\partial e_N^A} \right)}^{\text{MD Other-Sector}} \right] \frac{1}{\frac{\partial U}{\partial c^A}} \\ &= \left[\overbrace{\left(-\frac{\partial U}{\partial B} \frac{\partial B}{\partial N} - \frac{\partial U}{\partial c^F} \frac{\partial f^F}{\partial N} \right)}^{\text{MD Nutrient-Runoff}} N' + \overbrace{\left(-\frac{\partial U}{\partial B} \frac{\partial B}{\partial I} - \frac{\partial U}{\partial c^F} \frac{\partial f^F}{\partial I} \right)}^{\text{MD Interaction}} \frac{\partial I}{\partial e_N^A} \right] \frac{1}{\frac{\partial U}{\partial c^A}} \end{aligned} \quad (4.29)$$

The optimal tax on nutrient run-off τ_N^* (4.29) is equal to its Pigouvian level $\widehat{\tau}_N^*$ that internalizes the marginal social damage from nutrient run-off in agricultural production. It is the sum of marginal damages from nutrient run-off and marginal damages from the interaction of nutrient run-off with temperature and ocean acidification. The tax reflects marginal damages from nutrient run-off on the biodiversity value and on production in the fishery sector.

4.3.3 Second-best optimal allocation

We assume now that the social planner cannot implement the carbon tax at the Pigouvian level and hence, there is no effective internalization of CO_2 damages. In this case the carbon tax is exogenous such that the second-best optimal level of emissions from nutrient run-off is the value of e_N^A that satisfies (4.25), while $e_M^A = \widehat{e}_M^A(l^A, e_N^A, T, \tau_M)$ and $e_M^F = \widehat{e}_M^F(L - l^A, T, O, N, I, \tau_M)$ are implicitly⁸ defined by (4.17) and (4.20). The intuition is that in each sector the representative firm will choose its level of carbon emission once the government defines the carbon tax.

⁸We make use of the implicit function theorem here.

Hence, the optimization program determining this second-best allocation reads:

$$\begin{aligned} & \max_{\{l^A, \widehat{e}_M^A, \widehat{e}_M^F, \widehat{e}_N^A\}} U \left(f^A \left(l^A, \widehat{e}_M^A, e_N^A, T(\widehat{e}_M^A + \widehat{e}_M^F + e_M^R) \right), \right. \\ & f^F \left(L - l^A, \widehat{e}_M^F, T(\widehat{e}_M^A + \widehat{e}_M^F + e_M^R), O(\widehat{e}_M^A + \widehat{e}_M^F + e_M^R), N(E_N), I(\widehat{e}_M^A + \widehat{e}_M^F + e_M^R, E_N) \right), \\ & \left. B \left(T(\widehat{e}_M^A + \widehat{e}_M^F + e_M^R), O(\widehat{e}_M^A + \widehat{e}_M^F + e_M^R), N(E_N), I(\widehat{e}_M^A + \widehat{e}_M^F + e_M^R, E_N) \right) \right) \end{aligned} \quad (4.30)$$

The second-best tax on nutrient run-off is optimally determined by the following first order condition:

$$\begin{aligned} \frac{\partial U}{\partial e_N^A} = 0 & \Leftrightarrow \frac{\partial U}{\partial c^A} \left[\frac{\partial f^A}{\partial e_M^A} \frac{\partial \widehat{e}_M^A}{\partial e_N^A} + \frac{\partial f^A}{\partial e_N^A} + \frac{\partial f^A}{\partial T} T' \frac{\partial \widehat{e}_M^A}{\partial e_N^A} \right] \\ & + \frac{\partial U}{\partial c^F} \left[\frac{\partial f^F}{\partial T} T' \frac{\partial \widehat{e}_M^A}{\partial e_N^A} + \frac{\partial f^F}{\partial O} O' \frac{\partial \widehat{e}_M^A}{\partial e_N^A} + \frac{\partial f^F}{\partial N} N' + \frac{\partial f^F}{\partial I} \left(\frac{\partial I}{\partial e_M^A} \frac{\partial \widehat{e}_M^A}{\partial e_N^A} + \frac{\partial I}{\partial e_N^A} \right) \right] \\ & + \frac{\partial U}{\partial B} \left[\frac{\partial B}{\partial T} T' \frac{\partial \widehat{e}_M^A}{\partial e_N^A} + \frac{\partial B}{\partial O} O' \frac{\partial \widehat{e}_M^A}{\partial e_N^A} + \frac{\partial B}{\partial N} N' + \frac{\partial B}{\partial I} \left(\frac{\partial I}{\partial e_M^A} \frac{\partial \widehat{e}_M^A}{\partial e_N^A} + \frac{\partial I}{\partial e_N^A} \right) \right] = 0 \end{aligned} \quad (4.31)$$

Using (4.18) we obtain the second-best optimal tax on nutrient run-off $\widehat{\tau}_N$:

$$\begin{aligned} \widehat{\tau}_N = & \left[\overbrace{-\frac{\partial U}{\partial B} \left(\frac{\partial B}{\partial T} T' \frac{\partial \widehat{e}_M^A}{\partial e_N^A} + \frac{\partial B}{\partial O} O' \frac{\partial \widehat{e}_M^A}{\partial e_N^A} + \frac{\partial B}{\partial N} N' + \frac{\partial B}{\partial I} \left(\frac{\partial I}{\partial e_M^A} \frac{\partial \widehat{e}_M^A}{\partial e_N^A} + \frac{\partial I}{\partial e_N^A} \right) \right)}^{\text{MD Biodiversity}} \right. \\ & \left. \overbrace{-\frac{\partial U}{\partial c^F} \left(\frac{\partial f^F}{\partial T} T' \frac{\partial \widehat{e}_M^A}{\partial e_N^A} + \frac{\partial f^F}{\partial O} O' \frac{\partial \widehat{e}_M^A}{\partial e_N^A} + \frac{\partial f^F}{\partial N} N' + \frac{\partial f^F}{\partial I} \left(\frac{\partial I}{\partial e_M^A} \frac{\partial \widehat{e}_M^A}{\partial e_N^A} + \frac{\partial I}{\partial e_N^A} \right) \right)}^{\text{MD Other-Sector}} \right. \\ & \left. \overbrace{-\frac{\partial U}{\partial c^A} \left(\frac{\partial f^A}{\partial e_M^A} \frac{\partial \widehat{e}_M^A}{\partial e_N^A} + \frac{\partial f^A}{\partial T} T' \frac{\partial \widehat{e}_M^A}{\partial e_N^A} \right)}^{\text{MD Own-Sector}} \right] \frac{1}{\frac{\partial U}{\partial c^A}} \end{aligned} \quad (4.32)$$

The second-best optimal tax on nutrient run-off is the sum of marginal damages on biodiversity from nutrient run-off and its interaction with global warming and ocean acidification as well as from marginal damages on fisheries (MD Other-Sector) and agriculture (MD Own-Sector).⁹ In the following we compare the second-best optimal tax on nutrient run-off to its Pigouvian level $\widehat{\tau}_N^*$, which captures the external effects of nutrient run-off and of its interaction with global warming and ocean acidification as given in equation (4.29). This allows us to decompose $\widehat{\tau}_N^*$ according to the next equation (4.33).

$$\begin{aligned}
\widehat{\tau}_N = \widehat{\tau}_N^* + & \left[\overbrace{-\frac{\partial U}{\partial B} \left(\frac{\partial B}{\partial T} T' \frac{\partial \widehat{e}_M^A}{\partial e_N^A} + \frac{\partial B}{\partial O} O' \frac{\partial \widehat{e}_M^A}{\partial e_N^A} + \frac{\partial B}{\partial I} \frac{\partial I}{\partial e_M^A} \frac{\partial \widehat{e}_M^A}{\partial e_N^A} \right)}^{\text{Additional MD Biodiversity}} \right. \\
& \left. \overbrace{-\frac{\partial U}{\partial c^F} \left(\frac{\partial f^F}{\partial T} T' \frac{\partial \widehat{e}_M^A}{\partial e_N^A} + \frac{\partial f^F}{\partial O} O' \frac{\partial \widehat{e}_M^A}{\partial e_N^A} + \frac{\partial f^F}{\partial I} \frac{\partial I}{\partial e_M^A} \frac{\partial \widehat{e}_M^A}{\partial e_N^A} \right)}^{\text{Additional MD Other-Sector}} \right. \\
& \left. \overbrace{-\frac{\partial U}{\partial c^A} \left(\frac{\partial f^A}{\partial T} T' \frac{\partial \widehat{e}_M^A}{\partial e_N^A} \right)}^{\text{Additional MD Own-Sector}} \right] \frac{1}{\frac{\partial U}{\partial c^A}} \\
& \underbrace{-\frac{\partial f^A}{\partial e_M^A} \frac{\partial \widehat{e}_M^A}{\partial e_N^A}}_{\text{MAC Own-Sector}} \quad (4.33)
\end{aligned}$$

We find two opposing effects that either increase or decrease $\widehat{\tau}_N$ relative to its Pigouvian level $\widehat{\tau}_N^*$. First, as the carbon tax is set below the optimal level, both marginal damages on biodiversity and on production in the (own) agricultural and the (other) fishery sector from temperature increases and ocean acidification are higher compared to when the carbon tax is Pigouvian. The second-best nutrient tax covers these marginal damages in addition to the direct marginal damages from nutrient run-off, which tends to increase the second-best optimal tax on nutrient run-off relative to Pigouvian nutrient taxation. Hence, in the second-best situation also marginal damages from temperature increase on the own agricultural sector are considered, which is not the case when the nutrient tax is set at its Pigouvian level. Second, at

⁹Note that $\frac{\partial \widehat{e}_M^A(l^A, e_N^A, T, \tau_M)}{\partial e_N^A} = -\frac{\frac{\partial^2 f^A}{\partial e_M^A \partial e_N^A}}{\frac{\partial^2 f^A}{\partial e_M^A \partial e_M^A}} > 0$.

the same time a carbon tax below its Pigouvian level makes carbon a relatively cheap factor of production thereby decreasing marginal abatement cost of carbon used in agricultural production. We obtain the following relation between $\widehat{\tau}_N$ and $\widehat{\tau}_N^*$:

$$\widehat{\tau}_N \geq \widehat{\tau}_N^* \text{ iff } \left[\begin{array}{c} \overbrace{-\frac{\partial U}{\partial B} \left(\frac{\partial B}{\partial T} T' + \frac{\partial B}{\partial O} O' + \frac{\partial B}{\partial I} \frac{\partial I}{\partial e_M^A} \right)}^{\text{Pigouvian MD from } CO_2 \text{ on Biodiversity}} \quad \overbrace{-\frac{\partial U}{\partial c^F} \left(\frac{\partial f^F}{\partial T} T' + \frac{\partial f^F}{\partial O} O' + \frac{\partial f^F}{\partial I} \frac{\partial I}{\partial e_M^A} \right)}^{\text{Pigouvian MD from } CO_2 \text{ on Other-Sector}} \\ \underbrace{-\frac{\partial U}{\partial c^A} \frac{\partial f^A}{\partial T} T'}_{\text{Pigouvian MD from } CO_2 \text{ on Own-Sector}} \quad \underbrace{\frac{1}{\frac{\partial U}{\partial c^A}}}_{\text{Carbon Tax Own-Sector}} \geq \underbrace{\frac{\partial f^A}{\partial e_M^A}}_{\stackrel{(4.18)}{=} \tau_M} \end{array} \right] \quad (4.34)$$

The second-best optimal tax on nutrient run-off $\widehat{\tau}_N$ is higher (lower) than the Pigouvian tax on nutrient run-off τ_N^* iff the additional marginal social damage from carbon emissions on biodiversity and on the production in both sectors are higher (lower) than the carbon tax that must be equal to the marginal abatement cost of carbon according to equation (4.18). We find that the sum of these additional marginal damages is exactly equal to the social cost of the negative externalities that are covered by the Pigouvian carbon tax (see equation (4.28)). Thus, equation (4.34) simplifies to:

$$\widehat{\tau}_N \geq \widehat{\tau}_N^* \text{ iff } \widehat{\tau}_M^* \geq \tau_M \quad (4.35)$$

A second-best carbon tax does not fully internalize the social cost of the negative externalities generated by global warming and ocean acidification. As a consequence, equation (4.35) implies that the second-best optimal nutrient tax will always be higher than its Pigouvian level. Figure 4.2 illustrates how the second-best optimal tax on nutrient run-off depends on the carbon tax τ_M that determines the marginal abatement cost of carbon.

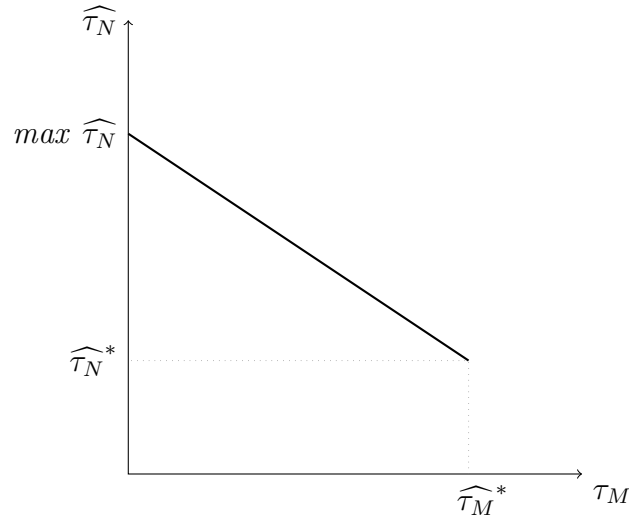


Figure 4.2: Second-best optimal tax on nutrient run-off $\widehat{\tau}_N$ as a function of the carbon tax τ_M .

The further the carbon tax is from its Pigouvian level $\widehat{\tau}_M^*$, the higher the second-best tax on nutrient run-off, while the latter will reach a maximum value $\max \widehat{\tau}_N$ for $\tau_M = 0$. Accepting carbon emissions in agricultural production to fuel machinery like tractors is very cheap without the additional tax expenses and thus, the second-best tax on nutrient run-off, which is a byproduct of agricultural production, needs to account for all additional environmental damages caused by the increased use of carbon emissions in production. The higher τ_M , the lower $\widehat{\tau}_N$ as using carbon emissions in agricultural production becomes more expensive, which lowers the associated environmental damages. When $\tau_M = \widehat{\tau}_M^*$ the social costs of negative externalities are internalized by the Pigouvian carbon tax and the second-best tax on nutrient run-off does not need to cover unregulated CO_2 emissions and hence, will be set at its Pigouvian level $\widehat{\tau}_N^*$.

4.4 Discussion

This section discusses three main limitations of the theoretical analysis presented in this paper. First, eutrophication is typically modeled as a non-point source pollution problem, complicating its control using a single policy instrument. To not over-complicate our model, we abstracted from difficulties associated with non-point source pollution and assumed that a single tax on the use of fertilizers or pesticides

was effective. This would be the case if it was levied per unit of toxicity-weighted ingredient that could, for example, be implemented by introducing mineral accounts for each farm in the country to record the application of nitrogen to crops (Pearce and Koundouri 2003).

Second, uncertainty regarding ecosystem responses to ocean acidification in interaction with other stressors is relatively high. Although a large number of studies focusing on physiological responses of calcifying organisms have been published over the last years, the findings are partly contradicting (Meyer and Riebesell 2015) and uncertainties regarding the organisms' exact sensitivity to ocean acidification remain. For example Kroeker et al. (2013) report that some organisms show enhanced responses to projected future ocean acidification conditions. Moreover, some of the key mechanisms, like calcification, are still not sufficiently understood (Waldbusser et al. 2016). Moreover, uncertainty extends to how such effects for particular organisms and species scale up to the level of marine ecosystems and to what extent these can adapt. Real world policy responses to interacting externalities of ocean acidification, global warming and eutrophication should ideally take such uncertainties regarding marine ecosystem responses to changing environmental conditions into account (Browman 2016).

Third, our study employs a national general equilibrium model that does not consider how national carbon dioxide emissions affect marginal damages due to temperature increase and ocean acidification in the rest of the world. A sufficiently high global carbon tax, which should be the goal of international negotiations, would take these additional marginal damages into account. Unfortunately it has been proven extremely difficult to find a global agreement on appropriately regulating carbon dioxide emissions. The Paris Climate Agreement does not specify any consistent policies among countries, but includes merely voluntary pledges for emissions reductions. In such a situation national environmental policy may help those regions that are likely to be most affected by a combination of global warming, ocean acidification and local stressors such as eutrophication (Kelly et al. 2011).

4.5 Conclusions

In this paper we describe a developing economy highly dependent on agriculture and fisheries, to study the interacting external effects of ocean acidification, global warming and eutrophication on socially optimal environmental policy. The analysis is based on a closed economy and hence, we do not consider the effect of sector emissions on climate change and ocean acidification on the rest of the world. Instead we focus on how national environmental policy can optimally respond to interacting environmental externalities. The structure of the general equilibrium model is consistent with recommendations formulated in recent research on socioeconomic consequences of ocean acidification and appropriate policy responses. Ocean acidification is likely to hit developing coastal economies the hardest as they particularly depend on fishery resources for nutrition and income. In addition, the literature suggests to not study ocean acidification in isolation but in combination with other global and regional environmental stressors. In this paper we combine ocean acidification with global warming and nutrient run-off from fertilizers used in agricultural production, which also contribute to regional acidification. Moreover, we assume that consumers in our economy do not only care about fish and agricultural product consumption, but also care about the status of biodiversity. Our model is the first to take into consideration three externalities in a general equilibrium setting.

We derive optimal rules for taxes on CO_2 emissions and agricultural nutrient run-off and show that they depend on both isolated and interacting damage effects. The optimal carbon tax is the sum of marginal damages from global warming, ocean acidification and their interaction with the effect of nutrient run-off on the biodiversity value as well as on production in agriculture and fisheries. The optimal carbon tax needs to account not only for isolated but also for synergetic damages captured by the interaction term. Thereby eutrophication increases the optimal carbon tax through its interaction with global warming and ocean acidification. The optimal tax on nutrient run-off is the sum of marginal damages from nutrient run-off and its interaction with global warming and ocean acidification on biodiversity as well as on production in the fishery sector. Also in this case synergetic damages, captured by the interaction term, increase the first-best nutrient tax.

In addition, we derive a second-best rule for a tax on agricultural run-off of pesticides and fertilizers for the realistic case that the carbon tax is set below its Pigouvian level such that CO_2 externalities are not fully internalized. On the one hand we find that the second-best tax on nutrient run-off will be higher than its Pigouvian level to account for the additional marginal damages from carbon emissions on biodiversity and production in both sectors that are not covered by the carbon tax. On the other hand a carbon tax below its Pigouvian level makes carbon intensive fuels, which are a necessary input for production in both sector, relatively cheap. Consequently marginal abatement costs for carbon emissions decrease, which lowers the second-best optimal tax on nutrient run-off compared to its Pigouvian level. Overall we obtain that the former positive effect will be higher than the latter negative effect and thus, the second-best nutrient tax will always be higher than its Pigouvian level.

Our analysis shows the importance of regulating ocean acidification within a framework of other important drivers of environmental change like global warming and eutrophication. Ideally marginal environmental damages from ocean acidification should be internalized by a tax on CO_2 emissions that is high enough to not only reflect marginal damages from temperature increases, but also marginal damages from ocean acidification and the interaction of both with regional sources of acidification like nutrient run-off from agriculture. Unfortunately, it is more realistic to expect that CO_2 externalities will not be fully internalized, especially in the setting of a coastal developing economy with presumably unstable political institutions. Moreover, estimating marginal economic damages from ocean acidification is a challenging task that is complicated by the uncertainty regarding actual and future ecosystem responses. When – for whatever reasons – the tax on CO_2 emissions cannot be set to its Pigouvian level, i.e. the level that internalizes CO_2 externalities, this paper demonstrates that regional environmental policy becomes relevant. A sufficiently high tax on nutrient run-off from agricultural production can mitigate not only marginal environmental damages from nutrient run-off but also account for unregulated carbon emissions. Putting such policies in place will be of particular importance for developing coastal economies that are likely to suffer the most from ocean acidification.

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Eidesstattliche Erklärung

Ich erkläre hiermit an Eides Statt, dass ich meine Doktorarbeit

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selbständig und ohne fremde Hilfe angefertigt habe und dass ich alle von anderen Autoren wörtlich übernommenen Stellen, wie auch die sich an die Gedanken anderer Autoren eng anlehnenden Ausführungen meiner Arbeit, besonders gekennzeichnet und die Quellen nach den mir angegebenen Richtlinien zitiert habe.

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