Relative Prices and Climate Policy: How the Scarcity of Non-Market Goods Drives Policy Evaluation

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Abstract: Climate change not only impacts production and market consumption, but also the relative scarcity of non-market goods, such as environmental amenities. We study fundamental drivers of the resulting relative price changes, their potential magnitude, and their implications for climate policy in the prominent DICE model, thereby addressing one of its key criticisms. We propose plausible ranges for relative prices changes based on best available evidence. Our central calibration reveals that accounting for relative prices is equivalent to decreasing pure time preference by 0.5 percentage points and leads to a more than 40 percent higher social cost of carbon.

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1 Introduction

Relative prices are central to economics. While we can easily infer them from market data for most goods, estimating relative prices for goods that are not traded on markets—including clean air, the existence of biodiversity or UNESCO World Heritage sites—poses a special challenge. In light of the growth of the global economy and a stagnation or loss of non-market goods (MEA 2005; IPCC 2014), it is crucial to account for changes in the relative price of non-market goods vis-á-vis market goods when evaluating long-term policies. For illustration, suppose that market goods grow at 2 percent, non-market amenities remain constant and there is Cobb-Douglas substitutability between the two. As the change in relative prices is determined by the difference in growth rates times the elasticity of substitution, the relative price would increase by 2 percent per year. Within 100 years, the relative value of a unit of non-market goods would thus increase by more than 600 percent due to the scarcity of non-market vis-á-vis market goods. Ignoring this can lead to large errors when evaluating climate policy.

This paper analyses the change in the relative price of non-market goods by studying its drivers and by quantifying its implications for optimal climate change policy. Our analysis is closely connected to the discussion on discounting the long-term future, as the difference in good-specific discount rates amounts to the change in relative prices. The debate on how to value future costs and benefits following the Stern Review initially focused on the contentious rate of pure time preference (Nordhaus 2007, 2008; Stern 2007), but quickly shifted to examining extensions to the standard discounting framework. Besides accounting for risk and uncertainty, considering relative prices has been one of the extensions receiving wide-spread attention.[1] Yet until today, there exists no systematic study of relative prices changes of non-market goods in relation to climate policy. The purpose of this paper is to fill this gap.

[1]See, for example, Arrow et al. (2013), Dasgupta (2008), Gollier (2010, 2012), Gollier and Hammitt (2014), Hoel and Sterner (2007), Sterner and Persson (2008), Traeger (2011), and Weitzman (2007, 2009). Limited substitutability features prominently in Heal's (2017) review on *The Economics of the Climate*. 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. 2018).

The literature has developed two approaches to dealing with relative price changes.[2] The first approach uses 'dual discount rates' and discounts consumption streams for market and non-market goods separately.[3] 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.

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 (2018) 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 market goods (Hepburn and Groom 2017; Koetse et al. 2018; 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 the relative price may play a crucial role, it is imperative to scrutinize its potential quantitative magnitude, its determinants as well as its implications for climate policy evaluation more closely.

[2]See, among others, Baumgärtner et al. (2015), Drupp (2018), Gollier (2010), Gueant et al. (2012), Guesnerie (2004), Hoel and Sterner (2007), Traeger (2011), Weikard and Zhu (2005).

[3]This 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.

We perform our analysis of relative prices in the latest version of the integrated assessment model DICE (Nordhaus 2018).[4] Section 2 defines the relative price effect of non-market goods in a stylized model and presents how DICE is 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, ranging from clean water to aesthetic beauty. How to capture and deal with climate damages on non-market goods has been a crucial question right from the beginning of integrated assessment modelling. These damages may concern ecosystem impacts on human health, like an increase in infectious diseases, or come in the form of a loss of ambient climate and biodiversity or of natural heritage sites due to sea-level rise. Nordhaus (1994) surveyed climate change experts, among others, on what proportion of climate impacts will fall on non-market goods. It was a "surprise" for Nordhaus (1994: 50) that the respondents believed that, on average, 'only' between 33 and 38 percent of climate impacts fall on non-market goods. In a more recent expert survey, Howard and Sylvain (2015) find that respondents expect that 50 percent of climate impacts fall on non-market goods. While there is large heterogeneity in responses, it is clear that the integrated assessment of climate change cannot ignore these substantial expected losses on non-market goods due to climate change.

To study how the scarcity of non-market goods affects the evaluation of climate policy, we initially follow Sterner and Persson (2008) in augmenting the standard DICE model to explicitly feature non-market goods in Section 3 . Many readers will consider Sterner and Persson (2008) as a natural benchmark for our paper and it is therefore of interest what relative price changes their setting entails. Building on this replication also allows us to clarify what explicitly introducing relative prices into DICE implies in this familiar context and how relative price changes should be interpreted. We show that the standard DICE model already—implicitly—contains a sizable relative price effect, which has so far not been observed in the literature. This implies that explicitly

[4]Integrated 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 are emerging (van den Bijgaart et al. 2016; Rezai and van der Ploeg 2016; Traeger 2015), IAMs still represent a useful tool for such purposes.

introducing relative prices into DICE can lead to more but also less stringent optimal climate policy as compared to the standard DICE model of Nordhaus. Our analysis also reveals that if non-market goods are as complementary to market goods as assumed by Sterner and Persson (2008), the full impact of considering relative prices will be even more pronounced than previously suggested.

Section 4 scrutinizes the impact of different determinants of relative price changes. These 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 (comprehensive) 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 and pure time preference matter considerably in the short-run, technological progress exerts its influence only in the longer run.

In Section 5, we construct plausible ranges for each of the drivers and perform a Monte Carlo analysis to determine a range of values for the relative price effect and three climate policy measures. The resulting 95 percent interval for the relative price effect ranges from 1.3 to 9.6 percent in 2020, declining to a range 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 6 , we overall conclude that changes in relative prices are of substantial magnitude compared to other conventional determinants of the economic evaluation of climate change policy. Section 7 closes by considering implications for governmental project appraisal and climate policy.

2 Modeling relative prices

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 public good E. Both goods are composites with continuously scalable amounts. The agent may further require an amount $\overline{E}$ of the non-market good to satisfy her subsistence needs (Baumgärtner et al. 2017; Heal 2009, 2017). Examples for such a requirement 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. The agent's preferences at time t are represented by an instantaneous utility function

$$u = \begin{cases} u^l(E_t) & \text{for } E_t \leq \overline{E} \\ u^h(E_t, c_t) & \text{else} \,. \end{cases} \tag{1}$$

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

$$u = u^h = \left[\alpha\left(E_t - \overline{E}\right)^{\theta} + (1-\alpha)\, c_t^{\theta}\right]^{1/\theta} \text{ with } -\infty < \theta \leq +1,\ \theta \neq 0;\ 0 < \alpha < 1, \tag{2}$$

where θ is the substitutability parameter, and α is a share parameter for the weight of the environmental good in utility.[5] In the standard constant elasticity of substitution (CES) case without a subsistence requirement ($\overline{E} = 0$), 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 $\sigma = \dfrac{1}{1-\theta}$. Important special cases of substitutability are perfect substitutes ($\theta = 1$; $\sigma = \infty$), Cobb-Douglas ($\theta = 0$; $\sigma = 1$) and perfect complements ($\theta \to -\infty$; $\sigma = 0$). In the presence of a subsistence requirement ($\overline{E} > 0$), this direct relationship breaks down and the elasticity of substitution depends also on other determinants besides θ, in particular on the consumption of the subsistence good relative to the subsistence requirement (Baumgärtner et al. 2017).

The intertemporal utility function takes the standard isoelastic form:

$$U = \frac{1}{1-\eta}\left[\alpha\left(E_t - \overline{E}\right)^{\theta} + (1-\alpha)\, c_t^{\theta}\right]^{\frac{1-\eta}{\theta}}, \tag{3}$$

[5] The extension of $u^h(E, c)$ for $\theta \to 0$ is a special Cobb-Douglas-Stone-Geory case: $\left(E - \overline{E}\right)^{\alpha} c^{(1-\alpha)}$.

where η is the inverse of the constant intertemporal elasticity of substitution (CIES) for the aggregate consumption bundle, or the elasticity of the marginal utility of comprehensive consumption.

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 given by the marginal rate of substitution (u_E/u_c), which is the implicit price of non-market goods.[6] 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):

$$RPE_t = \frac{\frac{d}{dt}\left(\frac{U_{E_t}}{U_{c_t}}\right)}{\left(\frac{U_{E_t}}{U_{c_t}}\right)} . \tag{4}$$

For our utility function (Equation 2), the relative price effect of non-market goods, RPE, at time t reads (see Appendix A.1 for a derivation):

$$RPE_t = (1-\theta)\left[g_{c_t} - \frac{E_t}{E_t - \overline{\overline{E}}}\, g_{E_t}\right] . \tag{5}$$

The RPE is equivalent to the difference in the good-specfic discount rates for market and non-market goods (Weikard and Zhu 2005; Drupp 2018). It 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 $\frac{E_t}{E_t - \overline{\overline{E}}}$. In the standard CES case, which we consider in Sections 2.2 and 3 to replicate Sterner and Persson (2008), the subsistence factor simply drops out.

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

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

Integrated Climate-Economy (DICE-2016R2) model by Nordhaus (1992 - 2018). It combines a climate module through a negative feedback loop of the atmospheric temperature on economic output with a Ramsey-economy, in which 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-2016R2, we need to modify the welfare function and the damage function from climate change. First we present how Nordhaus (2018) models welfare and damages and, second, report the changes necessary to explicitly include relative prices.

The welfare function in Nordhaus (2018) is given by:

$$W_0(\widetilde{c}_t, L_t) = \sum_{t=0}^{100} L_t \frac{1}{(1+\delta)^{5t}} \frac{\widetilde{c}_t^{1-\eta}}{1-\eta}. \tag{6}$$

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 for the aggregate consumption bundle, or the elasticity of the marginal utility of of comprehensive consumption. Comprehensive consumption per-capita $\widetilde{c}_t$ is defined as an index of generalized consumption (Nordhaus and Szork 2013), which is meant to also include non-market goods consumption in most of the papers by Nordhaus (cf. Section 3.2). Total climate damages D_t^{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:

$$D_t^{\phi} = \phi \, T_t^2 \tag{7}$$

Nordhaus (2018) calibrates the aggregate scaling parameter for the damages on all generalized consumption goods via production-damages, ϕ (Equation 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.[7] The DICE model therefore does not properly deal with non-market effects, as these are treated just

[7]Nordhaus (2018) 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

as market damages that affect production output. As damages are simply added up, there is perfect substitutability between market and non-market damages. One might therefore infer that there is also perfect substitutability between market and non-market goods in DICE (Neumayer 1999; Sterner and Persson 2008). Yet, our analysis suggests that this is not the case. The argument goes as follows:

First, overall damages—which include non-market damages in DICE—enter multiplicatively into what is a Cobb-Douglas production function of capital, K_t, labor, L_t, and total factor productivity, A_t, at its core. Net output Y_t is given by (Nordhaus 2008 Eq. A.4, 2018 Eq. 2): $Y_t = (1 - D_t^{\phi})\,(1 - \Lambda_t)\,A_t\,K_t^{\gamma}\,L_t^{1-\gamma}$, where Λ_t denotes spending on abatement. In DICE, $(1 - D_t^{\phi})$, which includes both market and non-market damages and is solely driven by temperature change, can thus—in part—be viewed as a form of non-market (natural) capital. Since this enters multiplicatively into the net production function, there is Cobb-Douglas type substitutability between this non-market component and the rest of production. This is related to Weitzman's (2010) discussion of an equivalence between what he calls 'multiplicative' and 'additive' damage functions, where damages either hit consumption multiplicatively or are added additionally as an input to utility, as in our explicit relative prices model. Indeed, Weitzman (2010: 68) remarks that "the prototype multiplicative [damage function] used in DICE [implies an] elasticity of substitution [of] $\sigma = 1$", that is it implies the Cobb-Douglas case.

Second, there is a relationship between substitutability on the production and the consumption side. In a simple model set-up with exogenous consumption streams, including limited substitutability between market and non-market goods in utility or limited substitutability between natural capital and other forms of production would be equivalent. Thus, while there is perfect substitutability in damages, the standard DICE includes non-market damages in net production such that there is an implicit equivalence of limited substitutability close to Cobb-Douglas in terms of goods. Yet, of course, the DICE model is very reduced form and does not feature different goods explicitly. Backing out the implicit degree of substitutability contained in the DICE model is therefore not

of squared temperature change on climate damage estimates from an median, quadratic, weighted regression (see Nordhaus and Moffat (2017) for more details).

straightforward. We will estimate the implicit degree of substitutability and thus of equivalent relative price changes in the standard DICE quantitatively in Section 3.

To replicate the results of Sterner and Persson (2008) within DICE-2016R2, we follow their approach of explicitly introducing relative prices. This includes (i) disentangling the consumption equivalents of Nordhaus into a two good representation; (ii) defining the development of the non-market good over time and (iii) specifying the initial value of the non-market good; (iv) disentangling market and non-market damages via appropriate calibration; and finally (v) raising the level of non-market good damages from Nordhaus's 25 percent to 100 percent additional damages to ensure comparability with Sterner and Persson's (2008) analysis.

We extend the model such that utility depends not only on market but also on non-market goods, as in Equation (2). However, since a subsistence requirement was absent in the analysis of Sterner and Persson (2008), we set $\overline{E} = 0$ here and for the replication and analysis in Section 3.[8] Thus, comprehensive consumption is now given by $\widetilde{c_t} = \left[\alpha E_t^\theta + (1-\alpha)\, c_t^\theta\right]^{1/\theta}$. The initial level of the aggregate non-market good E_0 is assumed to be equal to the initial level of consumption of market goods ($C_0 = c_0 \times L_0$). Accordingly, the welfare function is given by:

$$W_0(E_t, c_t, L_t) = \sum_{t=0}^{100} L_t \frac{1}{(1+\delta)^{5t}} \frac{1}{1-\eta} \left[\alpha E_t^\theta + (1-\alpha) {c_t}^\theta\right]^{\frac{(1-\eta)}{\theta}} . \tag{8}$$

The evolution of the non-market good depends (inversely) on the square of atmospheric temperature T change compared to pre-industrial levels and the damage parameter ψ:

$$E_t = \frac{E_0}{[1 + \psi T_t^2]}. \tag{9}$$

To ensure comparability with Sterner and Persson's (2008), we assume that non-market damages double climate damages to re-calibrate ϕ. Thus, we include an additional 100 percent non-market damages on top of market damages. Hence, for the baseline Nordhaus (2018) 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

[8] We again consider the subsistence requirement in Sections 4 and 5 when studying the role of the potential drivers of relative price changes and its effect on climate policy evaluation more generally.

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_t^κ. The damage function for market goods becomes:

$$D_t^\kappa = \kappa \, T_t^2 \, . \tag{10}$$

To account for the non-market damages on top of market damages a la Sterner and Persson (2008), the non-market climate damage parameter ψ is calibrated by comparing two different model specifications:[9] On the one hand, a model in which non-market damages D_t^ψ for a given temperature increase are perfectly substitutable for damages on market goods and are included in consumption directly. On the other hand, a model in which damages are attributed to market goods D_t^κ and non-market goods D_t^ψ. The parameter ψ is calibrated as a residual, with $C_0 = E_0$ (see Appendix A.2), and depends in particular on non-market damage costs but also the degree of substitutability. Given this set-up, the RPE (cf. Equation 5) in DICE is given by:[10]

$$RPE_t = (1-\theta) \left[g_{c_t}(\delta, \eta, ...) + \underbrace{\frac{2\,\psi\, T_t^2 \, g_{T_t}}{(1+\psi\, T_t^2)}}_{g_{E_t}} \right] . \tag{11}$$

Accordingly the RPE in DICE depends on the following components: First, the growth rate of the market good g_{c_t}, which is optimally determined by the environmentally-extended Ramsey Rule in DICE and thus depends on a number of key variables and parameters (see Dasgupta (2008) and Hänsel and Quaas (2018) for derivations in the single good case). Among others, it depends on the distributional parameters of the social welfare function: the rate of pure time preference, δ, and the elasticity of the marginal utility of comprehensive consumption, η. It is further driven by the net marginal productivity of capital, $Y_{K_t} - \xi$, where ξ denotes the proportional rate of capital depreciation.

[9]See Barrage (2018) for an alternative approach to calibrating non-market damages.

[10] The 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 $T_t^2 - T_{t-1}^2 = \dot{T_t^2} = 2T_t\dot{T}_t = 2T_t^2\, g_{T_t}$ this is equivalent to the continuous time version.

The marginal productivity of capital Y_{K_t} depends on labor L_t, capital K_t, climate damages $D_t^{\phi}(T_t)$ and is in particular driven by exogenous total factor productivity A_t.[11] 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}.[12] Finally, the difference in the two good-specific growth driver categories is scaled by the degree of substitutability, θ, between market and non-market goods.

3 Relative prices and climate policy evaluation

3.1 The relative price effect and climate policy outcomes

To evaluate the impact of the 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).[13] 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 (2018) DICE-2016R2, 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). Table 1 provides an overview of the parameter specifications used in the Sterner and Persson case, which we abbreviate as "S&P-RPE". Figure 1 depicts how the S&P-RPE evolves over time from

[11]Total factor productivity $A_t = \frac{A_{t-1}}{1-g_{t-1}^A}$ 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 exogenous decline rate of technological progress.

[12]In the presence of a subsistence requirement ($\overline{E} > 0$) that we consider in Sections 4 and 5, the RPE has an additional term that magnifies the importance of the growth rate of non-market goods on the RPE (see Equation 5): $RPE_t = (1-\theta)\left[g_{c_t}(\delta,\eta,...) + \frac{2\,\psi\,T_t^2\,g_{T_t}}{(1+\psi\,T_t^2)}\left(\frac{E_0}{E_0-\overline{E}\,(1+\psi\,T_t^2)}\right)\right]$.

[13]The SCC is defined as the ratio of the marginal impact of total CO_{2_t} emissions on welfare to the marginal impact of consumption C_t on welfare at time t: $SCC_t = -\frac{\partial W_t/\partial CO_{2_t}}{\partial W_t/\partial C_t}$ (Nordhaus 2017).

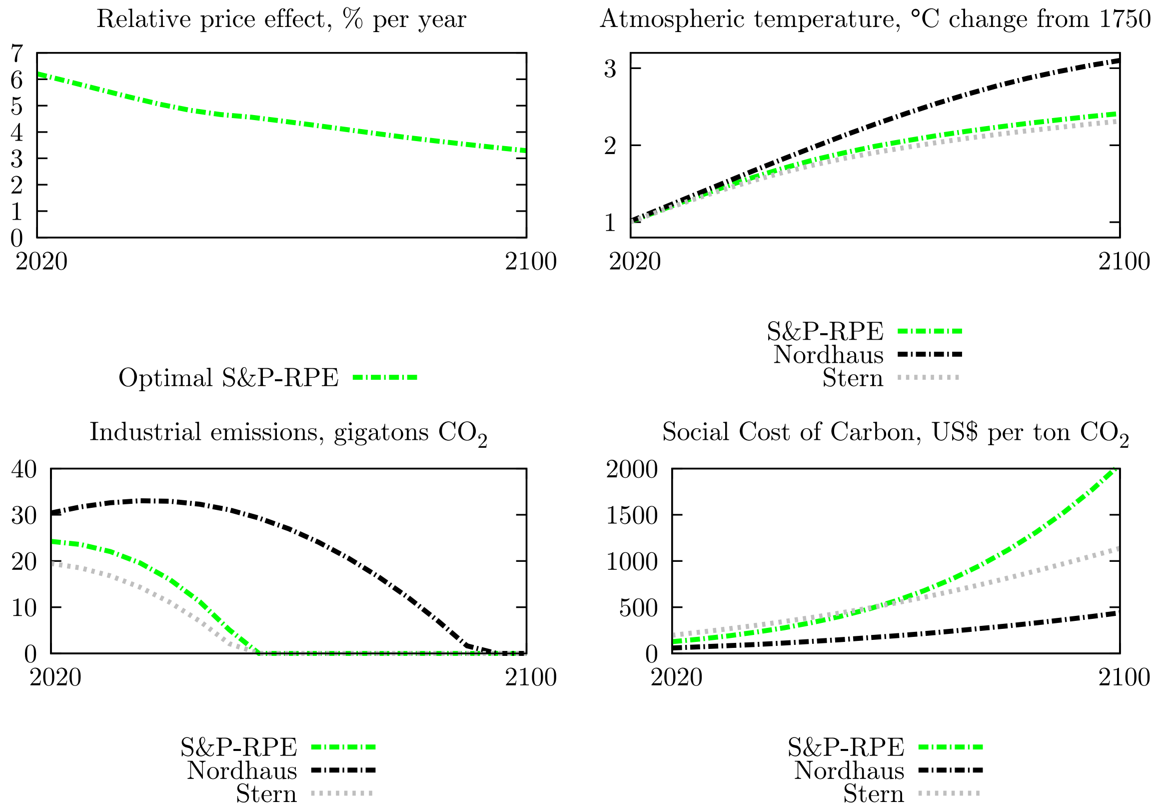

Figure 1: Relative price effect of non-market goods (RPE) and comparison of climate policy paths. The green line shows the relative price changes according to the Sterner and Persson (2008) case, S&P-*RPE*. The black line depicts the 'Nordhaus' comparison case without explicit relative price changes (with comparable and thus higher damages as in DICE-2016R2). The dotted grey line features another standard comparison case, yet with the lower rate of pure time preference, δ, of Stern.

Table 1: Parameter values for replicating Sterner and Persson (2008) in DICE-2016R2

Parameter	δ	η	MD**	NMD***	α	θ	$\overline{E}$
Baseline	1.5%	1.45	1.63%	1.63%	0.1	-1	0
Source*	N	N	N	S&P	S&P	S&P	N, S&P

* N denotes values taken from Nordhaus (2018), 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 year of 2020 to 2100, and how it impacts industrial CO_2 emissions, temperature change and the SCC.[14] We report equivalent yearly values of the 5-year time steps.

[14]The computations consider the full planning horizon of DICE. Appendix A.4 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 with the AMPL optimization software. The programming code is provided in Appendix A.7.

The time path of the S&P-*RPE* depicted in the upper-left corner of Figure 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. Hence, although non-market goods become scarcer in absolute terms until peak temperature is reached (cf. Equation 9), 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 1 compares this S&P-*RPE* to two cases that do not change the DICE-2016R2 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.[15] 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-2016R2 modelling 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 1 depicts the time path for industrial emissions, which corresponds to the results figure in Sterner and Persson (2008, p. 70).[16] In DICE-2016R2, 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 increased until 2100 in the older DICE-2006 version. When considering the S&P-

[15]Climate damages are higher in the 'Nordhaus' run than in Nordhaus (2018) for comparability with Sterner and Persson (2008). In Appendix A.5, we perform the same analysis with Nordhaus' (2018) estimate of lower non-market damages and briefly relate to it in Section 3.2.

[16]Following Nordhaus (2018), we depict industrial emissions in terms of CO_2, not carbon. There are a number of changes between the DICE-2006 that Sterner and Persson (2008) refer to and DICE-2016R2. Therefore we obtain a different profile of industrial emissions in Figure 1 as depicted in their key results figure. These changes, among others, include lowering the rate of pure time preference and including the possibility of negative emissions.

RPE, industrial emissions decrease immediately and become almost zero in 2055. Full decarbonization of the global economy is achieved as early as when using Stern's (2007) rate of pure time preference. Yet, cumulative emissions are higher when considering the S&P-*RPE* as compared to the optimization under Stern's lower δ of 0.1 percent. The upper-right panel of Figure 1 shows the development of atmospheric temperature 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 (cf. lower-right corner of Figure 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 'Nordhaus' and 'Stern', we find that the latter leads to a SCC that is 229 (159) percent higher in 2020 (2100). Overall, Figure 1 underscores the need to distinguish between standard discounting and relative price changes as related but distinct drivers of climate policy evaluation.

3.2 Stern, Sterner, Sternest? Clarifying the influence of relative prices on the stringency of climate policy

The discussion of Figure 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 regarding welfare parameters against which to compare the influence of introducing relative prices? Fourth, how can we deal with altered savings dynamics due to introducing the non-market good explicitly. We will address these questions in turn.

First, Sterner and Persson (2008) base their finding of an "even Sterner" report on an examination of yearly carbon emissions. In their comparison within DICE-2006, yearly emissions in the S&P-*RPE* run 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 in the ‘Stern’ case. In DICE-2016R2 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 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.

When we use peak temperature change relative to pre-industrial levels as the comparison metric to examine the impact of introducing the S&P-RPE as compared to changes in the 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 (2018) 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 obtained 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, it still represents a very substantial impact on optimal climate policy.

Second, what is the appropriate comparison variable? How meaningful is the direct comparison of the S&P-RPE with the ‘Nordhaus’ and ‘Stern’ cases given that explicitly introducing relative prices entails a number of changes to the DICE framework, which already implicitly deals with relative price changes? 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 explicitly includes the RPE to a case with perfect substitutability ($\theta = 1$), as the RPE vanishes in this case (cf. Equations 5 and 11). We therefore examine 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

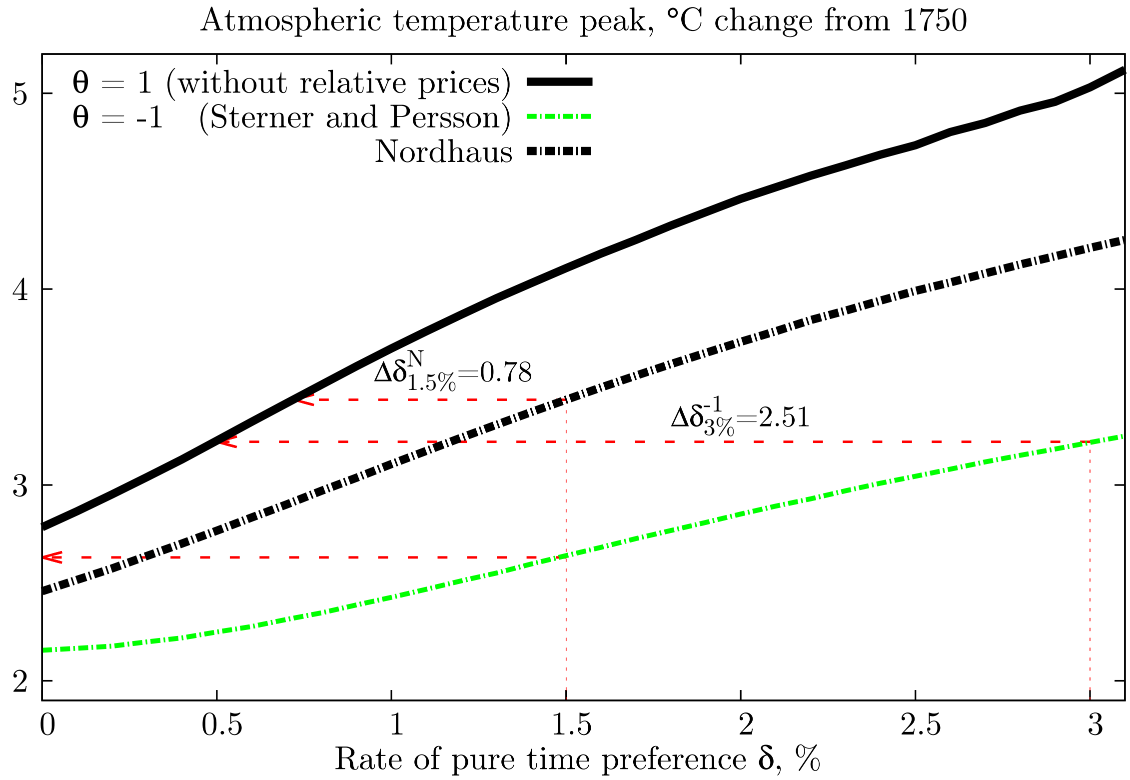

Figure 2: The comparative influence of introducing relative prices on peak temperature. The Figure depicts peak temperature as a function of the rate of pure time preference, δ, for different degrees of substitutability, θ. The solid black line shows the comparison case of perfect substitutability, that is without relative prices. The green line depicts the substitutability assumption of Sterner and Persson (2008), and the dashed black line the 'Nordhaus' case. A model run with relative prices can be compared to a run without 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 $\Delta\delta^N_{1.5\%} = 0.78$ percentage points.

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 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 models and degrees of substitutability, θ. The bold black line shows the comparison case of perfect substitutability and thus without relative prices.[17] In contrast, the dashed

[17]When 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.

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. 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, $\Delta\delta^{sup}_{sub}$, of introducing relative prices into climate policy evaluation, where the *sub*script denotes the baseline δ and the *sup*erscript the degree of substitutability, θ, of the considered RPE. For example, introducing relative prices with Cobb-Douglas substitutability ($\theta = 0$) at a baseline of Nordhaus's (2018) pure rate of time preference of $\delta = 1.5$ is equivalent in terms of optimal peak temperature to decreasing δ by $\Delta\delta^{0}_{1.5\%} = 0.6$ percentage points.

In the same fashion, we can compare the black dashed line of the 'Nordhaus' case to the bold black line of perfect substitutes to back out the implicit degree of relative prices contained in the 'Nordhaus' case. We find that a simple comparison of these two lines reveals that the 'Nordhaus' case is equivalent to a model without relative prices if we decrease δ by about $\Delta\delta^{N}_{1.5\%} = 0.78$ percentage points. We can also re-estimate the black-dashed line in the explicit relative prices model to see what implicit degree of limited substitutability it contains. This analysis reveals that the equivalent degree of substitutability is not simply Cobb-Douglas but non-constant: We estimate the implicit θ for 2020 and 2100 to be -0.09 and -0.17, respectively. Taking the (constant) mean of these two estimates of substitutability to re-estimate the black-dashed line, we find that the resulting $\Delta\delta^{-0.13}_{1.5\%}$ would be 0.77 percentage points and thus very close to that of the 'Nordhaus' case. This analysis of the 'Nordhaus' case does not reveal the implicit degree of substitutability and relative prices contained in the standard DICE-2016R2 model, as our analysis considers higher damages for comparability with Sterner and Persson (2008). In Appendix A.5 we re-run the analysis within the standard DICE-2016R2 model with its lower damages. Here, we find that the implicit degree of substitutability, θ, for 2020 and 2100 is 0.10 and -0.06, respectively. The mean of these two, θ =0.02, is thus very close to Cobb-Douglas and the implicit RPE in the years 2020 and 2100 amounts to 3.56 and 1.66 percent. The corresponding $\Delta\delta^{0.02}_{1.5\%}$ in DICE-2016R2 would be 0.33 percent. Thus, the 'Nordhaus' case with higher damages and also the standard DICE-2016R2 model contain sizable implicit relative price effects. This implies that one has to be very careful in interpreting effects when explicitly introducing relative prices to the DICE model. Our analysis thus reveals that if market and non-market goods are considered substitutes, explicitly introducing an *RPE* into DICE may lead to less stringent optimal climate policy as compared to the 'Nordhaus' case.

Figure 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 induced by introducing the S&P-*RPE* ($\Delta\delta^{-1}_{1.5\%}$ is not defined) compared to a run with perfect substitutability. Already a degree of substitutability of θ =-0.66 would be equivalent to reducing pure time preference from the value employed by Nordhaus to that of Stern, that is $\Delta\delta^{-0.66}_{1.5\%} = 1.4$ percentage points. Viewed as such, the effect of considering relative prices with the complementarity assumption of Sterner and Persson (2008) may thus be considered as even stringer than has previously been suggested.

Third, we address the question of what is the appropriate baseline specification, in terms of social welfare parameters. The analysis depicted in Figures 1 and 2 is built on the baseline specification of the most recent DICE version from Nordhaus (2018), with the exception of the parameters needed to introduce relative prices explicitly as well as higher damages as compared to Nordhaus (2018) to allow for better 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 we use the higher (initial) rate of pure 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 $\Delta\delta^{-1}_{3\%} = 2.5$ 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.

Fourth, it is an open question how comparable the cases considered in Figures 1 and 2 are in terms of their implied savings and investment dynamics. At a fundamental level, these Figures compare different models: a usual DICE model, in which non-market damages are treated as market damages that hit production, and the extended model in which non-market damages hit a non-market good that is explicitly featured as a source of utility. Although both models are calibrated to entail the same base year welfare costs at $T = 3°$C warming (cf. Appendix A.2), the explicit introduction of non-market goods in the welfare function (Equation 8) changes the dynamics of the extended model. Specifically, the optimal path of market goods consumption and the associated savings dynamics will be different compared to the standard DICE version where non-market damages are treated as market damages and thus reduce future output of the comprehensive consumption good. At least in most publications on the DICE model, consumption is introduced as comprehensive consumption that "should be viewed broadly to include not only food and shelter but also nonmarket environmental amenities and services" (Nordhaus 2008: 34). Yet in other publications (e.g. Nordhaus 2018), the comprehensive nature is not mentioned. While the calibration of consumption and savings is based on observed market information or forecasts, the dynamics of the model do depend on non-market damages. Specifically, Nordhaus (2018) deals with non-market goods by scaling up the damage coefficient (see Equation 7) and thus implicitly assumes the same savings dynamics for market and non-market goods. It is therefore somewhat ambiguous whether the savings dynamics in the standard DICE model's business as usual case should be viewed as only pertaining to the market good dynamics. Exploring the effects of re-calibrating savings dynamics is therefore warranted. The key mechanism behind the different savings dynamics is that the effective elasticity of marginal utility of market consumption or intertemporal elasticity of substitution for the market consumption good changes when the non-market good is introduced explicitly. This complicates comparing results across models as the business as usual paths for market consumption and savings will differ. To ensure that the standard DICE and the extended model yield savings dynamics that are as comparable as possible, we re-calibrate the latter. This is achieved by adjusting the elasticity of marginal utility of comprehensive consumption, η, which concerns the comprehensive consumption bundle of both market and non-market goods, in each period such that the effective elasticity of marginal utility of market consumption takes the value of 1.45, as in DICE. While the analysis so far has not considered how the introduction of non-market goods affects market dynamics, the re-calibration assumes that the business as usual market consumption and savings dynamics are not affected by the introduction of non-market goods. Both approaches are therefore extreme but illuminating cases.

The re-calibration proceeds as follows: From Equation 8 we can derive, following Gerlagh and van der Zwaan (2002), Hoel and Sterner (2007), and Traeger (2011), the effective elasticity of marginal utility of market consumption at each point in time t, hereafter denoted as η_{C_t}, by making use of the value share of the market consumption good $\beta_t^* = \dfrac{(1-\alpha)c_t^\theta}{\alpha E_t^\theta + (1-\alpha)c_t^\theta}$ (see Appendix A.3 for a derivation):

$$\eta_{C_t} = \beta_t^* \eta + (1-\beta_t^*)(1-\theta)\,. \tag{12}$$

The effective elasticity of marginal utility of market consumption depends on the value share of market consumption, β_t^*, the elasticity of marginal utility with respect to the comprehensive consumption good, η, and the degree of substitutability, θ. Thus, whenever market goods do not make up the full value share, i.e. $0 < \beta_t^* < 1$, savings dynamics are different, as $\eta_{C_t} \neq \eta$. This even holds in the case of perfect substitutes.

By using Equation 12, we can now re-calculate the elasticity of marginal utility of comprehensive consumption such that the initial effective elasticity of marginal utility of market consumption is given as in the DICE model, with $\eta_{C_0} = 1.45$. With $\theta = -1$,

$E_0 = c_0$, and $\alpha = 0.1$, the re-calculation yields $\eta = 1.389$ in the initial period. Similarly we can re-calibrate η at each time step such that η_{C_t} remains at 1.45 for all time steps t, yielding a time path of $\eta(t)$ that makes the two models as comparable as possible in terms of their business as usual market dynamics. For this, we fix the time paths of market consumption and investment to be the same as in the standard DICE version to calculate the respective $\eta(t)$ under different degrees of substitutability θ. This allows us to reproduce Figure 2 with the re-calibrated dynamics (see Figure A.1 in the Appendix). The time-path of $\eta(t)'s$ that yields $\eta_{C_t} = 1.45 \; \forall \; t$ under $\theta = -1$ (i.e. Sterner and Persson (2008) and under $\theta = 1$ (i.e. perfect substitutatbility) are provided in Appendix A.3.[18]

We find that the re-calibration has only a minor effect on the model without relative prices, which now features slightly lower peak temperatures for low rates of pure time preference (see Figure A.1 in the Appendix). Specifically, peak temperature for a pure time preference rate of 0.01 is 3.62°C as compared to peak temperature of 3.70°C in the model without re-calibration. Furthermore, the implicit degree of substitutatbility contained in the 'Nordhaus' case is now equivalent to a model without relative prices if we decrease δ by $\Delta\delta^N_{1.5\%} = 0.70$ percentage points. This compares to a value of $\Delta\delta^N_{1.5\%} =$ 0.78 percentage points in the comparison without re-calibration.

Concerning consequences for the Sterner and Persson (2008) case, we find that there is still no rate of pure time preference that is equivalent in terms of peak temperature to a model without relative prices. Yet, reducing the rate of pure time preference from $\delta = 1.5\%$ to $\delta = 0\%$ in a model without relative prices ($\theta = 1$) is now almost equivalent to the re-calibrated relative prices run. Furthermore, the equivalent reduction in pure time preference to reach the same peak temperature in the Nordhaus run is reduced to 1.16 percentage points (down from 1.20 in the comparison without re-calibration).

[18] Note that this procedure yields the same business-as-usual market consumption paths in both models, but not exactly the same savings rates. The reason is that output-reducing climate damages are separated into market and non-market damages in the extended model and only market damages reduce output, while non market damages indirectly affect output through the social welfare function. In the standard DICE model both market and non-market damages directly reduce output. Hence, the direct effect of climate damages on output in the standard DICE model is different compared to our model and resulting savings rates are not quite be the same.

Overall, this means that introducing relative prices in the fashion of Sterner and Persson (2008) into DICE 2016R2 under a re-calibrated model has less an impact on optimal climate policy as in the case considered by Sterner and Persson (2008). Overall, this highlights the importance of considering more explicitly how non-market goods affect the economic and social welfare dynamics of integrated climate-economy models.

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

This section scrutinizes how the *RPE* depends on its potential exogenous 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 and foremost, we consider (i) the degree of substitutability between market and non-market goods. Furthermore, we study those exogenous drivers that are related to the growth rate of the non-market good: (ii) the magnitude of non-market damages, and (iii) the size of the subsistence requirement for non-market goods that we consider from now on in line with Equation 5 .[19] Furthermore, we analyze the main drivers of the growth rate of market goods: (iii) the rate of pure time preference, (iv) the elasticity of the marginal utility of comprehensive consumption and (v) the rate of technological progress.

[19]The additional determinants of the value share of non-market goods, α and E_0, do not impact the relative price effect directly (cf. Eqation 5). In Appendix A.6 we nevertheless explore how they impact the *RPE*, which reveals that they do have a small indirect effect. Regarding their calibration, we stick to the values used in Sterner and Persson (2008), as there are no better estimates available. The System of Environmental-Economic Accounting (SEEA) currently strives to include Experimental Ecosystem Accounting (EEA), but it is still debated whether its emphasis on exchange values can adequately capture the value (share) of non-market goods (Droste and Bartkowski 2017, Obst et al. 2016). In any case, there is no reliable empirical data yet to inform a parametrization of α or E_0 at the global level (C. Obst, personal communication). Values of α applied in the literature concerning non-market environmental goods range from 0.1 to 0.29 (Gollier 2010, Hoel and Sterner 2007, Kopp et al. 2012). Following Sterner and Persson (2008) in setting the value for α of 0.1 concerning all non-market goods is therefore a conservative choice.

Substitutability

A key driver of the *RPE* is the degree of substitutability between market and non-market goods. The upper panel of Figure 3 depicts the effects of varying the substitution parameter, θ, along a range of -2 to 1. 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 2018). These make use of the relationship between the elasticity of substitution and the income elasticity of willingness-to-pay for public goods to estimate the CES from non-market valuation studies. Drupp (2018) gathers indirect evidence on substitutability for environmental goods from 18 non-market valuation studies and finds a mean estimate [range] for the income elasticity of 0.4 [0.14, 1.16], which corresponds to a CES, θ, of 0.6 [-0.16 to 0.86].[20] Figure 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 $\theta = -1$ (Sterner and Persson 2008), and to 8.10 percent for $\theta = -2$. The respective value of the *RPE* in 2100 is 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).

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 1 assumes, following Sterner and Persson (2008), that non-market damages account for an

[20] Since 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 (Hammitt and Robinson 2011; Hoffmann et al. 2017; Viscusi and Masterman 2017), thus corresponding closely to income elasticities obtained from environmental valuation studies.

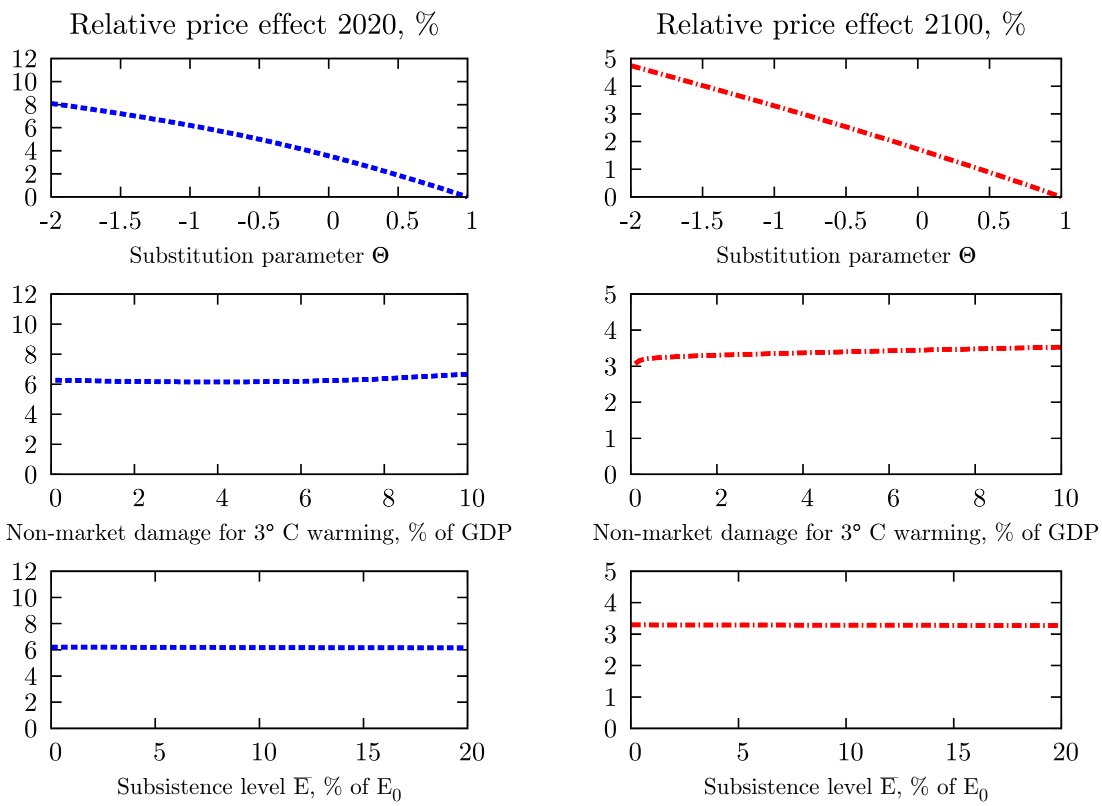

Figure 3: Drivers of the relative price effect (I). Top to bottom: The impact of substitutability, non-market damages and subsistence consumption on the *RPE* in 2020 (left) and in 2100 (right).

additional damage component that doubles overall climate damages. This amounts to 1.63 percent of GDP under 3°C warming. In contrast, Nordhaus (2018) considers non-market damages as an additional damage component, amounting to 0.49 percent of GDP under 3°C warming. As we are not aware of empirical evidence on the climate damages share on non-market goods, we draw on expert survey data. 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: 34) 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 49.76 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 standard deviation of 28 percent reveals substantial heterogeneity in responses. Figure 3 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 10 percent of GDP. In absolute terms the *RPE* remains almost flat at 6 percent. It decreases slightly from 6.28 to 6.15 for non-market damages of up to 4% and increases thereafter reaching 6.67 for non-market damages of 10%. In the year 2100 we find that the *RPE* ranges from 3.03 to 3.53. Why is it—perhaps surprisingly—the case that the non-market damages scaling parameter has such a negligible effect on the *RPE*? In the *RPE* equation (11), 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*.

Non-market good 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 shows that the *RPE* is not sensitive to changes in the stringency of the subsistence level $\overline{E}$ 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*.[21] In the year 2100 we find qualitatively the same as for 2020: the *RPE* declines from 3.29 to 3.28 when 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

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

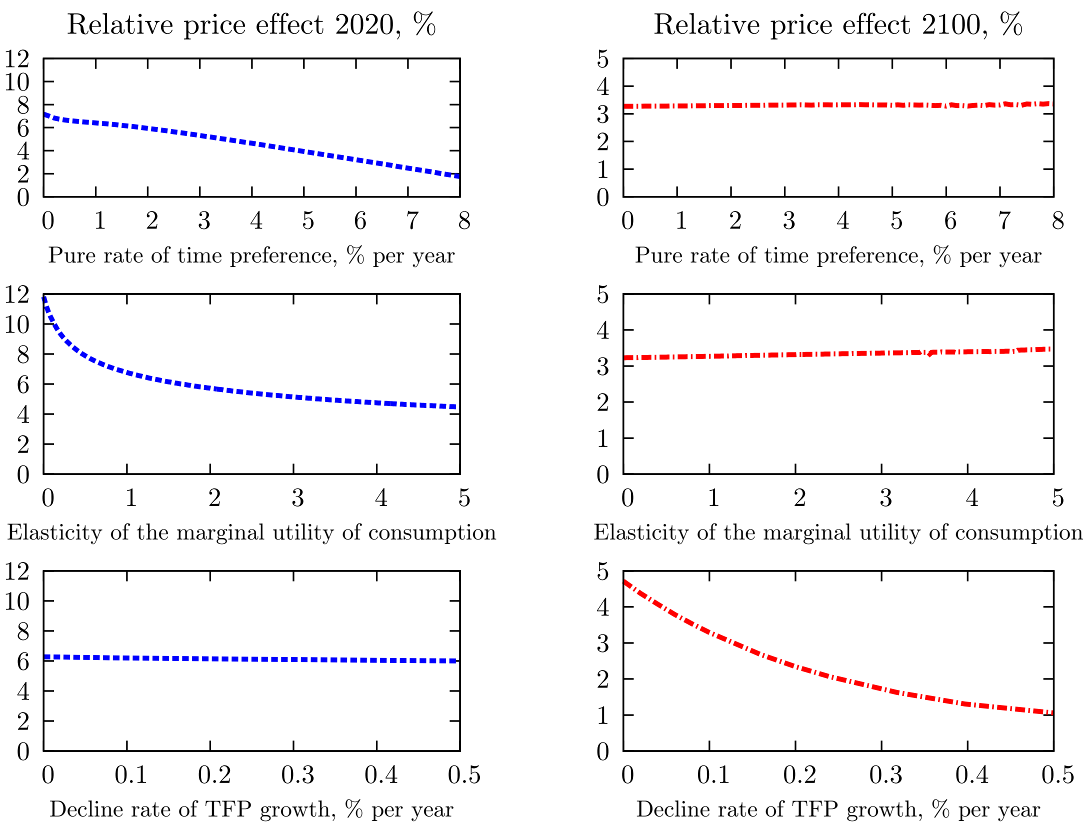

Figure 4: Drivers of the relative price effect (II). Top to bottom: rate of pure time preference, elasticity of the marginal utility of comprehensive consumption, and decline rate of total factor productivity growth—and their impact on the *RPE* in 2020 (left) and in 2100 (right).

considerable disagreement on what constitute plausible and justifiable values for the rate of pure time preference. Figure 4 depicts the effects of the rate of pure time preference on the *RPE* over an interval of 0 to 8 percent.[22] This range is taken from an expert survey on the determinants of the social discount rate by Drupp et al. (2018). 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. Nordhaus's (2018) 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.

[22]Note that for computational reasons we approximate 0 with 0.000001 percent.

Elasticity of the marginal utility of comprehensive consumption

The elasticity of the marginal utility of comprehensive consumption, η, is a measure of inequality aversion with respect to the intertemporal distribution of inclusive consumption $\widetilde{c}$. Its range considered in Figure 4, from 0 to 5, includes all recommendations by respondents to the expert survey by Drupp et al. (2018). It encompasses values used in the prominent literature, such as unity (Stern 2007) and 1.45 as used in DICE (Nordhaus 2018). We find that the *RPE* decreases with η over its range 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 comprehensive consumption.

Decline rate of total factor productivity

The growth rate of material consumption is in particular driven by total factor productivity (TFP), $A_t = \frac{A_{t-1}}{1-g^A_{t-1}}$, which grows exogenously at a decreasing rate, with $g^A_t = g^A_0 e^{-5t\tau^A}$, 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 (2018).[23] 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 (2018) 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 shape of the dynamics of TFP, the effect on relative prices is more pronounced in 2100 and the *RPE* decreases more than linearly in the decline rate of TPF growth per year.

[23] Alternatively, one could vary the initial level g^A_0 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.

This sensitivity analysis reveals that exogenous drivers have very heterogenous effects on the RPE. The degree of substitutability between market and non-market goods is the key driver of relative price changes. The magnitude of non-market damages and environmental subsistence consumption have a negligible influence on the RPE. This is because the optimal management of climate change ensures that the decline of the environmental good is restricted and never gets close to the subsistence threshold, for example. We also find that while the elasticity of marginal utility of comprehensive consumption and pure time preference matter considerably in the short-run because higher values shift consumption and consumption growth to earlier periods, technological progress exerts its influence on relative price changes only in the longer run.

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

Based on our systematic study of determinants of relative price changes, this section examines what might be a plausible range and a best-guess central calibration for each determinant of the RPE based on available evidence. To compare model runs, 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, we perform a Monte Carlo analysis with 1000 draws to construct plausible ranges of the determinants of relative price changes and specify a central calibration as a new baseline. For the lower and upper bounds, we consider both a 95 and a 66 percentile interval 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 for which the values used in Sterner and Persson (2008), $\theta = -1$, and the mean empirical estimate from Drupp (2018), 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.[24] For δ and η we use the mean expert recommendations from the survey of Drupp et al. (2018) 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 runs (see Appendix A.7.4 for the data). Finally, for the decline rate of TFP, τ^A, we assume a Normal distribution with the mean given by the value from DICE-2016R2. The 95 percent confidence interval is calculated such that it is bounded from below by a zero decline rate.

Table 2 lists all parameter choices for the optimization of the plausible ranges and of the central calibration. While some of the parameter values contained in the plausible ranges may seem objectionable to the reader, they are chosen such that a non-negligible fraction of experts may advocate employing them. For instance, with respect to δ, more than 10 percent of experts in the survey by Drupp et al. (2018) recommended rates of 3 percent or higher. The 95 (66) percent interval that we consider as the 'plausible range' includes a rate of pure time preference of 6 (2) percent as the highest value.

Figure 5 depicts the central calibration run (blue dashed line), the comparison run with perfect substitutability ($\theta = 1$) and thus without relative price changes (black dashed line), and the plausible range including both the 95 and the 66 percentile range of the RPE (blue-shaded area). Further, it displays the impact of relative price changes on climate policy outcomes—industrial emissions, atmospheric temperature change and the SCC—for the time between year 2020 and 2100.

Figure 5 shows that the 95 percentile 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 prices of backstop technologies at the upper bound.[25] 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.

[24]We truncate the distribution to exclude negative values for non-market damages and τ^A.

[25]At 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.

For the 66 percent interval (see the blue-shaded area in Figure 5), we find that the RPE ranges from 6.5 to 3.1 percent in 2020 and between 2.9 and 1.6 percent in 2010. In terms of peak temperature and industrial emissions, in particular high emissions and temperature runs drop out. Peak atmospheric temperature ranges from 2.1°C to 4.1°C for the 66 percent interval. There is no run within the 66 percent range with zero emissions in 2020. Zero emissions are only included in this range from the year 2025 onward. For the SCC the range changes such that the minimum SCC increases to 33.5 US$ in 2020 and 253.5 US$ in 2100.

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 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). 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, δ, analogously to the analysis in Section 3.2, we find that introducing relative prices with the degree of substitutability assumed in our central calibration is equivalent to reducing the rate of pure time preference by $\Delta\delta^{-0.2}_{1.1\%} = 0.53$ percentage points in a model without relative prices.

While the central calibration reveals that the effect of considering relative prices in climate policy evaluation is considerable, a main take-away from Figure 5 is that the 'plausible ranges' for the RPE and the climate policy measures are substantial. But what are the main determinants of this range? Table 3 shows the influence of changing, each time, one parameter to its upper or lower 95 percentile parameter bound, while keeping all other inputs at the central calibration baseline. The 95 percentile ranges for the different determinants are given in column two of Table 3 . For the degree of substitutability, θ, for example, we run the central calibration both with a θ of 0.58, indicating a substitutive relationship between market and non-market goods, and with a

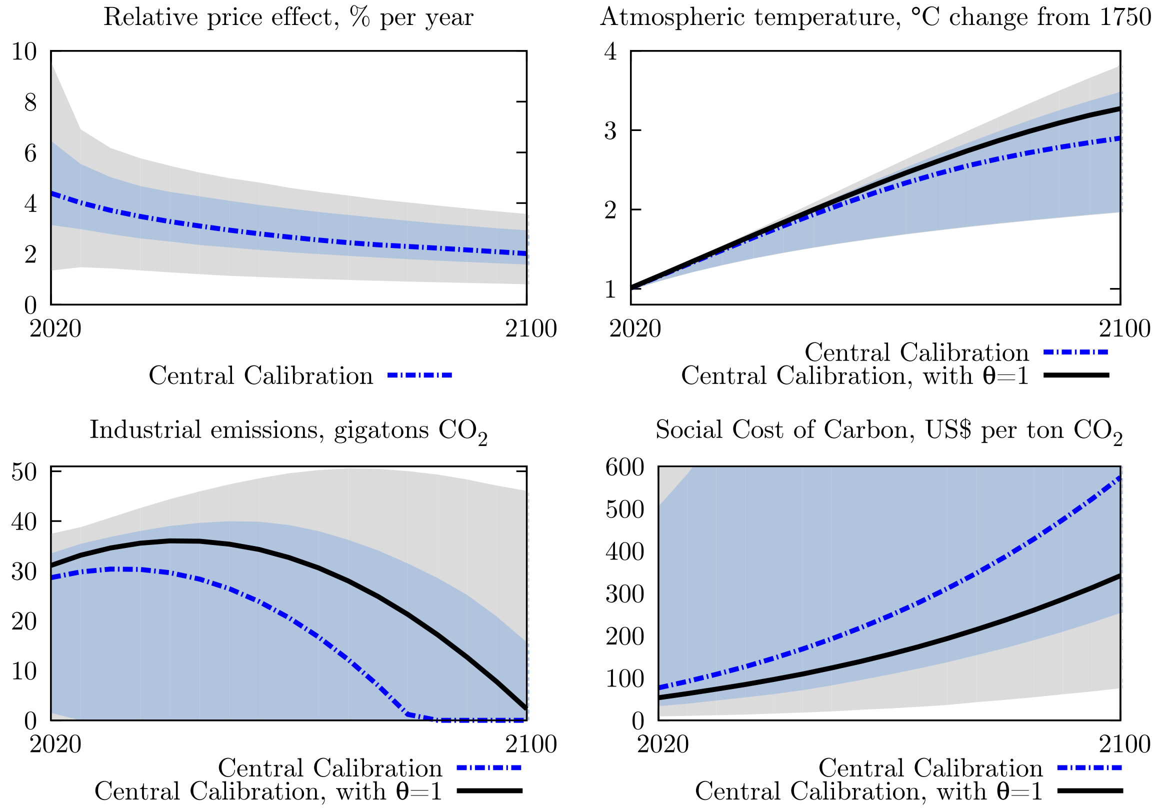

Figure 5: Relative price effect of non-market goods (RPE) and comparison of climate policy paths for plausible ranges and a central calibration of the drivers of relative price changes. The blue line represents the central calibration of the RPE, while the black line depicts the perfect substitutability comparison ($\theta = 1$) in which the RPE vanishes. The blue-shaded (grey-shaded) area represents the 66 (95) percentile range around the mean of the individual drivers.

Table 2: Parameter specifications for the range and central calibration of the RPE

Parameter	Source	Distribution	Central Calibration
θ	S&P (2008), Drupp (2018)	Normal; $\mu = -0.2, \sigma = 0.41$	-0.2
$NMD^{\star}$	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. (2018)	Raw expert data	1.10%
η	Drupp et al. (2018)	Raw expert data	1.35
τ^A	Nordhaus (2018)	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).

θ of -0.97, implying a complementary relationship. We consider how these 95 percentile 'plausible ranges' in the individual parameters affect the RPE in 2020 and 2100, the peak temperature within the whole planning horizon and the SCC in 2020 and 2100.

Our analysis of the plausible ranges confirms that substitutability is overall the key driver of the RPE, driving it from 1.71 to 6.39 percent in 2020 (column 3 of Table 3), and from 0.75 to 3.23 in 2100 (column 4). Most other drivers are negligible for the RPE in 2020 except for the rate of pure time preference, δ as well as the elasticity of the marginal utility of comprehensive consumption, η. Indeed, the 95 percentile range for η changes the RPE in 2020 from 8.64 to 3.41 and is thus a stronger driver compared to the degree of substitutability. The decline rate of TFP has the second strongest influence on the RPE in 2100, altering it by 1.5 percentage points, followed by the influence of non-market damages driving the RPE by 0.3 percentage points. For peak temperature (column 5), the strongest effect comes from the standard social welfare parameters, δ and η. These alter peak temperature by 3.01°C and 5.22°C, respectively. The degree of substitutability and the amount of non-market damages also have a considerable influence on peak temperature, driving it by 1.12°C and 1.45°C, respectively. For the SCC in the year 2020 (column 6), the plausible range in the year 2020 is substantial and all but subsistence consumption and the decline rate of technological progress are important drivers. Non-market damages and the rate of pure time preference alter the SCC in 2020 by 252 and 254 US$ per ton of CO_2, while the elasticity of the marginal utility of comprehensive consumption has about twice their quantitative effect on the SCC, with a range of 526 US$. For the SCC in the year 2100 (column 7), the degree of substitutability and the amount of non-market damages are the strongest drivers, leading to a range in the SCC of 2194 US$ and 1949 US$, respectively. This is followed by the influence of the two welfare parameters, at 1407 US$ and 1255 US$, while subsistence consumption and the decline rate of technological progress have a negligible impact on the longer-run SCC.

Most of the influence of the range in the social welfare parameters, δ and η, on peak temperature and the SCC is, of course, due to their well-known direct effect on optimal climate policy and only part of it accrues to the indirect effect through their impact on relative price changes. We can estimate this indirect effect by comparing the central calibration to a case without relative price effects ($\theta = 1$). We find that the net effects of δ and η on peak temperature amount to 1.21 °C and 2.52°C, corresponding to 40 percent

Table 3: The 'plausible ranges' in the RPE's drivers and their influence on the RPE and climate policy outcomes

Driver	95%-ile range	RPE 2020 [%]	RPE 2100 [%]	Peak T [°C]	$SCC^{\dagger}$ 2020	SCC 2100
θ	-0.97 – 0.58	6.39 – 1.71	3.23 – 0.75	2.45 – 3.57	187 – 62	2568 – 374
$NMD^{\#}$	0 – 9.54%	4.37 – 4.68	1.90 – 2.24	3.72 – 2.27	48 – 300	342 – 2291
$\bar{E}/E_0$	0 – 20%	4.41 – 4.41	2.05 – 2.04	3.01 – 3.00	94-95	707 – 713
δ	0 – 6%	4.74 – 2.15	2.02 – 2.18	2.33 – 5.34	265 – 11	1496 – 89
η	0.1 – 3	8.64 – 3.41	2.02 – 2.11	2.16 – 7.38	549 – 23	1506 – 251
τ^A	0 – 0.2%	4.48 – 4.35	2.97 – 1.45	3.17 – 2.93	79 – 104	704 – 633

NMD denotes non-market damages under 3°C warming.
† SCC is measured in US$ per ton of CO_2.

and 48 percent of the overall effect, respectively. The net effect on the SCC in 2020 (2100) is 100 (641) US$ and 117 (514) US$, respectively. The biggest net effect, though, we find for non-market damages: They alter peak temperature by 1.4°C amounting to 97% of the overall effect and the SCC in 2020 (2100) by 228 (1945) US$ corresponding to 90% (99.79%) of the overall effect. While the net effect of the subsistence level of non-market goods is negligible the impact of the RPE via technological progress on the SCC is notable, changing the SCC in 2020 (2100) by 7 (53) US$, thus accounting for 27% (74%) of the overall effect.

6 Discussion

In this section, we discuss to what extent assumptions made in this analysis may 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. 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).[26] 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 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 also relates to studying non-optimal climate policy, for example in settings with 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 environmenmental 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 2018) 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

[26] While 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.

2018). 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 mot fruitful 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.[27] 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.

[27]See 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.

7 Conclusion

This paper provides a comprehensive analysis of the change in the relative price of non-market goods by studying its fundamental drivers, its quantitative magnitude, 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 2018) 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 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 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" (Sterner and Persson 2008) are sensitive to what we choose as comparison metric and variable, how we specify the baseline parameters as well as how savings and investment dynamics are calibrated. 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, allowing for comparability across model runs. Introducing relative prices in the spirit of Sterner and Persson (2008) in DICE-2016R2, 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 (2018) already contains a considerable relative price effect of non-market goods due to a form of Cobb-Douglas substitutability between (non-market) climate damages and production, this value underestimates the impact of introducing relative prices. 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 causes 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 featurs 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 substitutability of non-market goods already contained in the standard DICE model of Nordhaus (2018), which is close to Cobb-Douglas, is well contained within the plausible range considered. Our analysis thus also implies that if market and non-market goods have a somewhat higher substitutability than Cobb-Douglas, explicitly introducing relative prices into DICE may lead to less stringent optimal climate policy as suggested by the standard DICE model.

While relative prices thus clearly matter considerably for climate policy evaluation, our results likewise suggest an enduring importance of the key standard discounting parameters. We find that in the short-run, the rate of pure time preference and the elasticity of marginal utility of (comprehensive) consumption indirectly influence the relative price effect, as the growth of consumption is endogenous in DICE. Furthermore, both their direct and indirect effects through relative prices on optimal climate policy outcomes are substantial. The net effects of pure time preference and the elasticity of marginal utility via relative price changes on peak temperature amount to 1.21 °C and 2.92°C, corresponding to 20 percent and 52 percent of the overall effect.

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 likely 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 2018; Koetse et al. 2018). Our analysis also points towards the most crucial determinants of relative prices, such as the degree of substitutability, the standard welfare parameters and technological progress. This suggests that it is imperative to obtain better estimates or more agreement on acceptable values 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 govnermental project appraisal.

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ONLINE APPENDIX

A.1 Derivation of the relative price effect

To derive the relative price effect of non-market goods, $RPE_t = \frac{d}{dt}\left(\frac{U_{E_t}}{U_{c_t}}\right)\left(\frac{U_{E_t}}{U_{c_t}}\right)^{-1}$ (Equation 4), we first compute marginal utilities with respect to the two goods for utility function (2):

$$U_{E_t} = \alpha(E_t - \overline{E})^{\theta-1}\left[\alpha(E_t - \overline{E})^{\theta} + (1-\alpha)c_t^{\theta}\right]^{\frac{1-\eta-\theta}{\theta}} \tag{A.1}$$

$$U_{c_t} = (1-\alpha)c_t^{\theta-1}\left[\alpha(E_t - \overline{E})^{\theta} + (1-\alpha)c_t^{\theta}\right]^{\frac{1-\eta-\theta}{\theta}} . \tag{A.2}$$

We thus have

$$\frac{U_{E_t}}{U_{c_t}} = \frac{\alpha}{(1-\alpha)}\left(\frac{E_t - \overline{E}}{c_t}\right)^{\theta-1} \tag{A.3}$$

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

$$\frac{d}{dt}\left(\frac{U_{E_t}}{U_{c_t}}\right) = (\theta-1)\frac{\alpha}{(1-\alpha)}\left(\frac{E_t - \overline{E}}{c_t}\right)^{\theta-2}\left[\frac{\dot{E}_t}{c_t} - \frac{(E_t - \overline{E})\dot{c}_t}{{c_t}^2}\right] \tag{A.4}$$

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:

$$\begin{aligned}\frac{d}{dt}\left(\frac{U_{E_t}}{U_{c_t}}\right) &= \frac{\alpha}{(1-\alpha)}\left(\frac{E_t - \overline{E}}{c_t}\right)^{\theta-1}(\theta-1)\left(\frac{c_t}{E_t - \overline{E}}\right)\left[\frac{g_{E_t}E_t}{c_t} - \frac{(E_t - \overline{E})g_{c_t}c_t}{{c_t}^2}\right] \\ &= (1-\theta)\frac{\alpha}{(1-\alpha)}\left(\frac{E_t - \overline{E}}{c_t}\right)^{\theta-1}\left[g_{c_t} - \frac{E_t}{E_t - \overline{E}}g_{E_t}\right] .\end{aligned} \tag{A.5}$$

The relative price effect of non-market goods is therefore given by

$$RPE_t = \frac{\frac{d}{dt}\left(\frac{U_{E_t}}{U_{c_t}}\right)}{\left(\frac{U_{E_t}}{U_{c_t}}\right)} = (1-\theta)\left[g_{c_t} - \frac{E_t}{E_t - \overline{E}}g_{E_t}\right] . \tag{A.6}$$

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 Weikard and Zhu (2005) or Drupp (2018) for derivations in continuous time).

A.2 Calibration of non-market damages

A.2.1 Calibration for Section 3

In Section 3, we replicate the analysis of Sterner and Persson (2008) in DICE-2016R2. Thus, we do not consider a subsistence requirement in the consumption of non-market goods. The non-market good climate damage coefficient ψ is calibrated for a temperature increase of $T = 3°C$ as follows:

$$W_0\Big(E_0, (1-D_0^{\phi})C_0, L_0\Big) = W_0\Big((1-D_0^{\psi})E_0, (1-D_0^{\kappa})C_0, L_0\Big) \quad \Leftrightarrow \tag{A.7}$$

$$\alpha E_0^{\theta} + (1-\alpha)\Big((1-D_0^{\phi})C_0\Big)^{\theta} = \alpha\Big(\frac{E_0}{1+\psi T^2}\Big)^{\theta} + (1-\alpha)\Big((1-D_0^{\kappa})C_0\Big)^{\theta}$$

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

$$\psi = \left[E_0\left(E_0^{\theta} + \frac{1-\alpha}{\alpha}\left(\Big((1-D_0^{\phi})C_0\Big)^{\theta} - \Big((1-D_0^{\kappa})C_0\Big)^{\theta}\right)\right)^{-\frac{1}{\theta}} - 1\right]T^{-2}. \tag{A.8}$$

Sterner and Persson (2008) assume that the initial amount of the non-market good is equal to the starting value for material consumption, i.e. $C_0 = E_0$. In this case equation (A.8) reduces to

$$\psi = \frac{1}{T^2}\left[\left(\frac{1-\alpha}{\alpha}(1-D_0^{\phi})^{\theta} + 1 - \frac{1-\alpha}{\alpha}(1-D_0^{\kappa})^{\theta}\right)^{-\frac{1}{\theta}} - 1\right]. \tag{A.9}$$

A.2.2 Calibration for Sections 4 and 5

In the presence of a subsistence requirement in the consumption of non-market goods the calibration is modified as follows:

$$W_0\Big(E_0, (1-D_0^{\phi})C_0, L_0\Big) = W_0\Big((1-D_0^{\psi})E_0, (1-D_0^{\kappa})C_0, L_0\Big) \quad \Leftrightarrow \tag{A.10}$$

$$\alpha\left(E_0 - \overline{E}\right)^{\theta} + (1-\alpha)\Big((1-D_0^{\phi})C_0\Big)^{\theta} = \alpha\Big(\frac{E_0}{1+\psi T^2} - \overline{E}\Big)^{\theta} + (1-\alpha)\Big((1-D_0^{\kappa})C_0\Big)^{\theta}$$

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

$$\psi = \left[E_0\left(\overline{E} + \left[\left(E_0 - \overline{E}\right)^{\theta} + \frac{1-\alpha}{\alpha}\left(\Big((1-D_0^{\phi})C_0\Big)^{\theta} - \Big((1-D_0^{\kappa})C_0\Big)^{\theta}\right)\right]^{\frac{1}{\theta}}\right)^{-1} - 1\right]T^{-2}. \tag{A.11}$$

A.3 Re-calibration of the model

(1) Derivation of η_C

We make us of Equations 2 and Equation 8 with $\overline{E} = 0$ to recalibrate the effective elasticity of marginal utility of market consumption, η_C, such that the model with relative prices yields the same paths of market consumption and investments as the standard DICE version. We have

$$U = \frac{1}{1-\eta}\left[\alpha\left(E_t - \overline{E}\right)^{\theta} + (1-\alpha)\, c_t^{\theta}\right]^{\frac{1-\eta}{\theta}}, \tag{A.12}$$

$$U_C = (1-\alpha)c_t^{\theta-1}\left[\alpha\left(E_t - \overline{E}\right)^{\theta} + (1-\alpha)\, c_t^{\theta}\right]^{\frac{1-\eta-\theta}{\theta}}, \tag{A.13}$$

$$\begin{aligned} U_{CC} &= (1-\alpha)c^{\theta-1}\frac{1}{c}(\theta-1)\left[\alpha\left(E_t - \overline{E}\right)^{\theta} + (1-\alpha)c_t^{\theta}\right]^{\frac{1-\eta-\theta}{\theta}} \quad \text{(A.14)} \\ &+ (1-\alpha)c^{\theta-1}\left[\alpha\left(E_t - \overline{E}\right)^{\theta} + (1-\alpha)\, c_t^{\theta}\right]^{\frac{1-\eta-\theta}{\theta}} \frac{(1-\alpha)c^{\theta-1}}{\alpha E^{\theta} + (1-\alpha)c^{\theta}}(1-\eta-\theta) \\ &= (1-\alpha)c^{\theta-1}c^{-1}\left[\alpha\left(E_t - \overline{E}\right)^{\theta} + (1-\alpha)\, c_t^{\theta}\right]^{\frac{1-\eta-\theta}{\theta}} \times \quad \text{(A.15)} \\ &\left[(\theta-1) + (1-\eta-\theta)\frac{(1-\alpha)c^{\theta}}{\alpha\left(E_t - \overline{E}\right)^{\theta} + (1-\alpha)\, c_t^{\theta}}\right] \end{aligned}$$

Combining these ingredients yields the effective elasticity of marginal utility of market consumption, η_C, as

$$\eta_C = -\frac{U_{cc}c}{U_c} = (1-\theta) - (1-\eta-\theta)\,\frac{(1-\alpha)c_t^{\theta}}{\alpha\left(E_t - \overline{E}\right)^{\theta} + (1-\alpha)c_t^{\theta}}. \tag{A.16}$$

Defining the value share of the consumption good as $\beta^* = \frac{(1-\alpha)c_t^{\theta}}{\alpha\left(E_t - \overline{E}\right)^{\theta} + (1-\alpha)c_t^{\theta}}$, (cf. Gerlagh and van der Zwaan (2002), Hoel and Sterner (2007), Traeger (2011)), this can be rewritten as

$$\eta_C = \beta^*\eta + (1-\beta^*)(1-\theta) \tag{A.17}$$

That is, when the full value share accrues to market consumption goods, the effective elasticity of marginal utility of market consumption, η_C, equals the overall elasticity of marginal utility, η. Yet, as soon as non-market goods have a positive value share, the degree of substitutability matters for the effective elasticity of marginal utility of market consumption.

(2) Time-path of $\eta(t)$ used for re-calibration

$\theta = -1$ (left column)		$\theta = 1$ (right column)	
0	1.388889	0	1.611111
1	1.399128	1	1.584113
2	1.407008	2	1.563337
3	1.413283	3	1.546792
4	1.418342	4	1.533453
5	1.422468	5	1.522575
6	1.425869	6	1.513609
7	1.428699	7	1.506148
8	1.431075	8	1.499881
9	1.433088	9	1.494575
10	1.434805	10	1.490046
11	1.436281	11	1.486154
12	1.437558	12	1.482786
13	1.438670	13	1.479854
14	1.439644	14	1.477285
15	1.440501	15	1.475023
16	1.441261	16	1.473020
17	1.441937	17	1.471237
18	1.442543	18	1.469638
19	1.443090	19	1.468192
20	1.443587	20	1.466877
21	1.444036	21	1.465682
22	1.444443	22	1.464596
23	1.444813	23	1.463606
24	1.445148	24	1.462703
25	1.445452	25	1.461880
26	1.445729	26	1.461127
27	1.445982	27	1.460439
28	1.446211	28	1.459812
29	1.446423	29	1.459230
30	1.446618	30	1.458691
31	1.446798	31	1.458192
32	1.446965	32	1.457731
33	1.447119	33	1.457305
34	1.447261	34	1.456910

35	1.447393	35	1.456544
36	1.447515	36	1.456205
37	1.447629	37	1.455891
38	1.447735	38	1.455600
39	1.447833	39	1.455330
40	1.447925	40	1.455078
41	1.448011	41	1.454845
42	1.448091	42	1.454627
43	1.448166	43	1.454424
44	1.448237	44	1.454235
45	1.448303	45	1.454059
46	1.448365	46	1.453894
47	1.448423	47	1.453739
48	1.448478	48	1.453595
49	1.448530	49	1.453459
50	1.448579	50	1.453333
51	1.448625	51	1.453214
52	1.448668	52	1.453102
53	1.448710	53	1.452996
54	1.448749	54	1.452897
55	1.448786	55	1.452804
56	1.448821	56	1.452716
57	1.448855	57	1.452633
58	1.448887	58	1.452555
59	1.448917	59	1.452481
60	1.448946	60	1.452411
61	1.448973	61	1.452345
62	1.449000	62	1.452282
63	1.449025	63	1.452222
64	1.449048	64	1.452166
65	1.449071	65	1.452112
66	1.449093	66	1.452061
67	1.449114	67	1.452013
68	1.449134	68	1.451967
69	1.449153	69	1.451923
70	1.449171	70	1.451881
71	1.449188	71	1.451841
72	1.449205	72	1.451803

```
73  1.449221         73  1.451767
74  1.449236         74  1.451732
75  1.449251         75  1.451699
76  1.449265         76  1.451668
77  1.449278         77  1.451638
78  1.449291         78  1.451609
79  1.449303         79  1.451581
80  1.449315         80  1.451555
81  1.449327         81  1.451530
82  1.449337         82  1.451505
83  1.449348         83  1.451482
84  1.449358         84  1.451460
85  1.449367         85  1.451439
86  1.449377         86  1.451418
87  1.449386         87  1.451398
88  1.449394         88  1.451379
89  1.449402         89  1.451361
90  1.449410         90  1.451343
91  1.449418         91  1.451325
92  1.449426         92  1.451308
93  1.449435         93  1.451289
94  1.449443         94  1.451270
95  1.449453         95  1.451247
96  1.449466         96  1.451219
97  1.449483         97  1.451181
98  1.449508         98  1.451123
99  1.449552         99  1.451024
100 1.449493;        100 1.451158;
```

(3) Figure 2 with re-calibrated $\eta(t)$

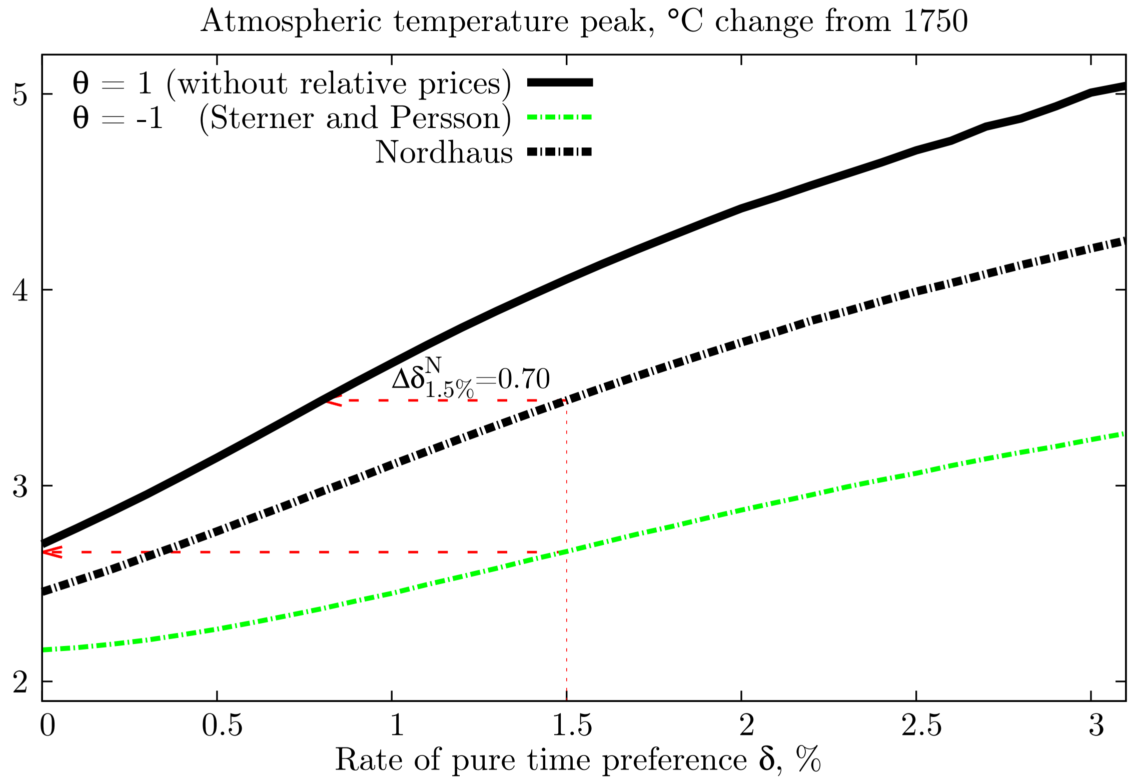

Figure A.1: The comparative influence of introducing relative prices on peak temperature with re-calibrated elasticity of marginal utility. The Figure depicts peak temperature as a function of the rate of pure time preference, δ, for different degrees of substitutability, θ. The solid black line shows the comparison case of perfect substitutability, i.e. without relative prices. The green line depicts the substitutability assumption of Sterner and Persson, with $\theta = -1$, and the dashed black line the 'Nordhaus' case. A model run with relative prices is compared to a run without but with a higher δ such that peak temperature is the same across both runs.

A.4 Relative prices and comparison of climate policy paths until 2300, with 100% additional non-market damages as in Sterner and Persson (2008)

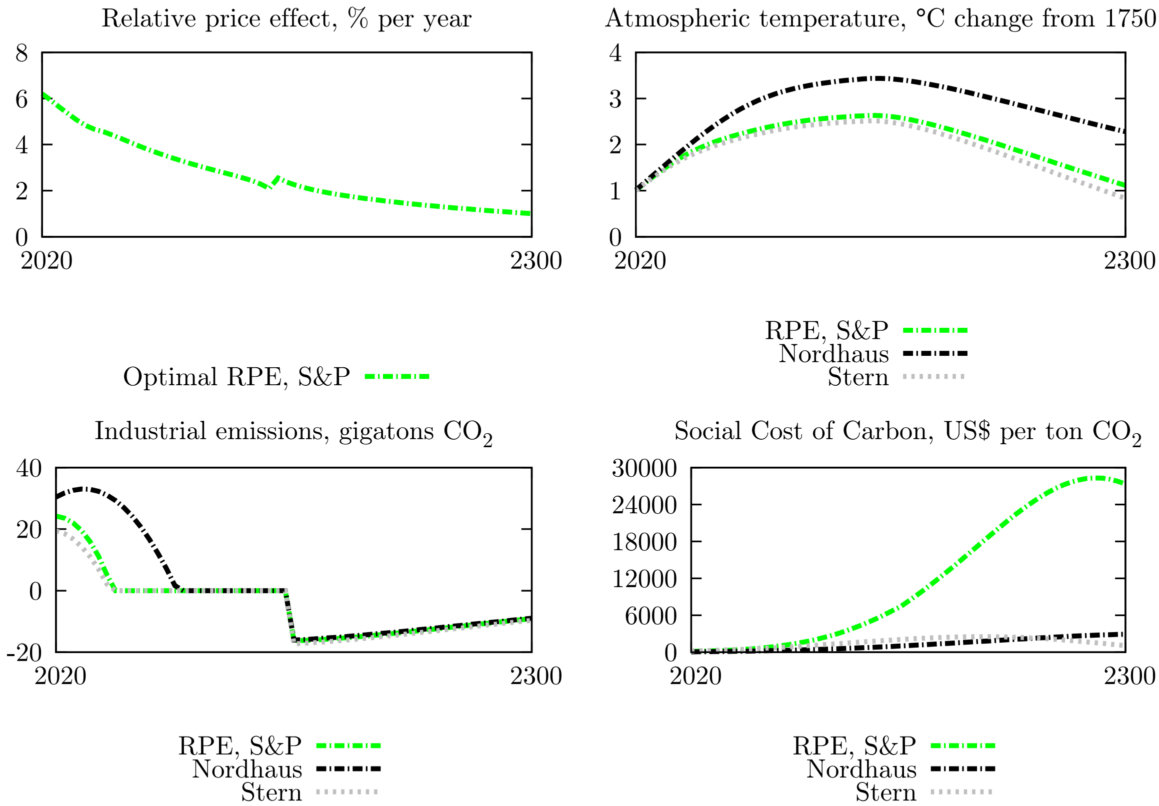

Figure A.3: Relative price effect (*RPE*) and comparison of climate policy paths for a time horizon up to 2300 and 100% additional non-market damages. Otherwise, see description of Figure 1.

A.5 Relative prices and comparison of climate policy paths until 2100, with 25% additional non-market damages as in the standard DICE-2016R2

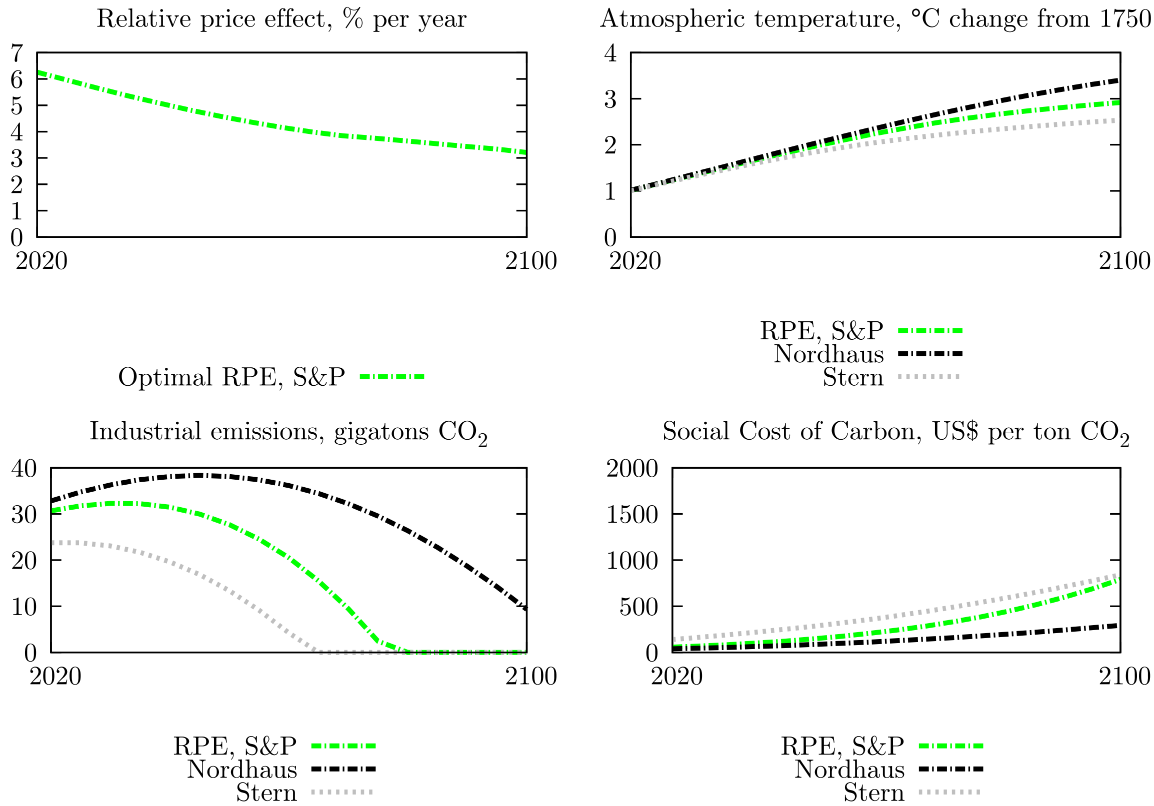

Figure A.3: Relative price effect (*RPE*) and comparison of climate policy paths for a time horizon up to 2100 and 25% additional non-market damages.

A.6 Additional drivers of the relative price effect: Initial value of non-market goods and share of non-market goods in utility

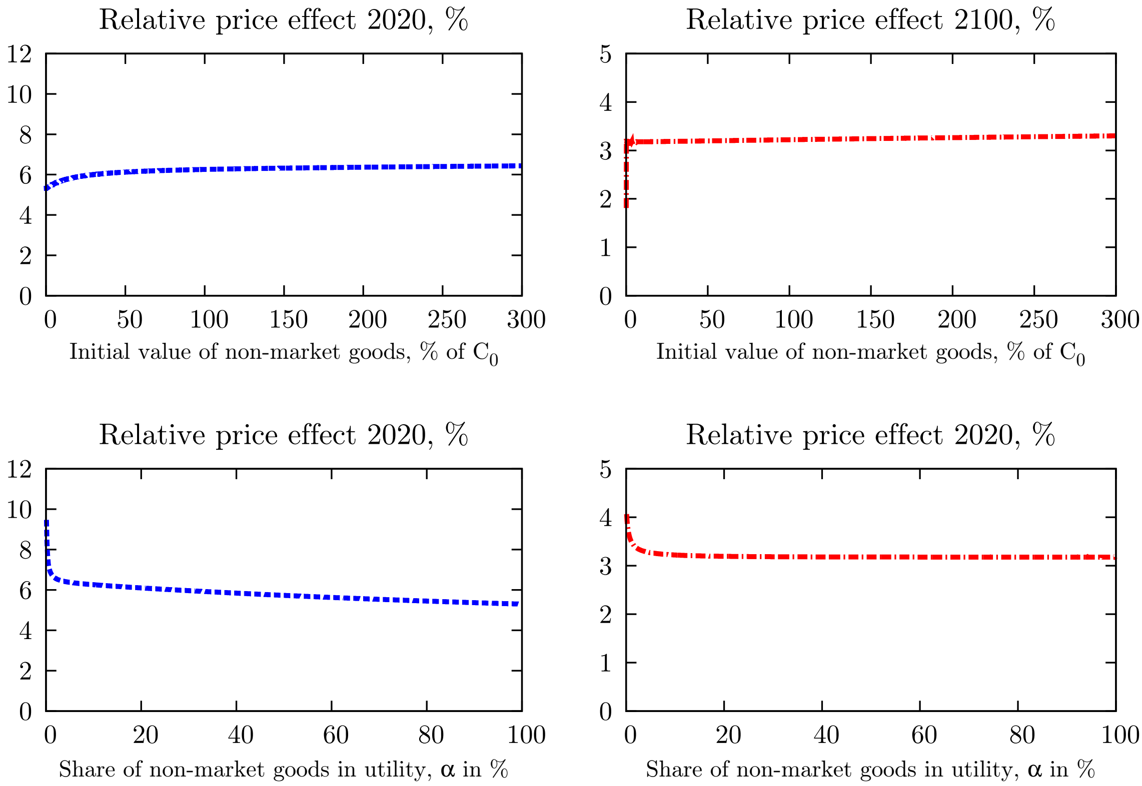

Figure A.4: Additional drivers of the relative price effect (I). Top to bottom: The impact of the initial value of non-market goods and the share of non-market goods in utility on the *RPE* in 2020 (left) and in 2100 (right).

A.7 Code

A.7.1 AMPL code to produce Figure 1

(1) AMPL mod-file Nordhaus

```
# Nordhaus, DICE 2016R2
# To work with the run-file, this mod-file should be named: DICE_Nordhaus_2016.mod

# PARAMETERS
#Time horizon
param T:=100;
# Preferences
param eta default 1.45;  # I-EMUC
param rho default 0.015;  # time preference rate
# for Stern use param rho default 0.001;
# discount factor
param R {t in 0..T}>=0;
let R[0]:=1;
let {t in 1..T} R[t] := R[t-1]/((1+rho)^5);

# for sensitivity analysis and figure 2 use: 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;  #growth rate 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:=0.100;  #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:=0.005;  #decline rate of TFP per 5 years
```

```
param gA {t in 0..T}>=0;
let {t in 0..T} gA[t]:=gA0*exp(-deltaA*5*(t));

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, where sigma is the carbon intensity or CO2-output ratio
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; under BAU: 0.00
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 MAT0=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 (GtC)
param MUPEQ:=360;  # Equilibrium concentration in upper strata (GtC)
param MLOEQ:=1720;  # Equilibrium concentration in lower strata (GtC)
```

```
# Flow parameters (carbon cycle transition matrix)
# correspond to the bXX parameters in Nordhaus)
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
param Fex {t in 0..T}>=0;
let {t in 0..17} Fex[t]:=Fex0+1/17*(Fex1-Fex0)*(t);  # external forcing (Wm-2)
let {t in 18..T} Fex[t]:=Fex1;
# external forcing (Wm-2)
# is assumed to be constant and equal to Fex1 from 2100 onward
# see e.g. Traeger (2014, Fig.1)

# climate damage parameters
param Psi:=0.003622;
# 0.00236 damage quadratic term for 25% add on NMD; for 100% add on: 0.003622
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 cprice0:=2;  # Initial base carbon price (2010$ per tC02)

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;

# utility
var U {t in 0..T} =c[t]^(1-eta)/(1-eta);

# total period utility
var U_period {t in 0..T}=U[t]*R[t];
```

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

# welfare optimization
maximize objective_function: W;
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]=MUP0;
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 control_BAU {t in 1..T}: mu[t]=0;
```

(2) AMPL mod-file, RPE, S&P

```
# DICE 2016R2 with Relative Prices
# To work with the run-file, this mod-file should be named: DICE_2016_RPE.mod

# 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 S\&P 2008
# for a model run without relative prices: param zeta default 1;
param beta default 0.1; #share of non-market good in utility function
param EQbar default 0; #subsistence level of non-market good
param cbar default 0; #subsistence level of consumption per capita

# Discount factor
param R {t in 0..T}>=0;
let R[0]:=1;
let {t in 1..T} R[t] := R[t-1]/((1+rho)^5);

# for sensitivity analysis and figure 2 use: 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 MAT0=851;  # Initial Concentration in atmosphere 2015 (GtC)
param MUP0:=460;  # Initial Concentration in upper strata 2015 (GtC)
param ML00:=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;  # market 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 NMD default 0.0163;
# corresponds to 100% NMD add on; with 25% add on 0.00494
param TD=MD+NMD; # total climate damages

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);

# growth rate of market good

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

# growth rate of non market good

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]=MUP0;
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)));
```

(3) AMPL run-file

```
reset;
model DICE_2016_RPE.mod; # add a "#" in a S\&P-RPE run
#model DICE_Nordhaus_2016.mod; # delete "#" in a Nordhaus run
option solver knitroampl;
solve;
# Produce overview of results in a csv format
# change file name to "Results_Figure1_Nordhaus.csv" during the Nordhaus run
# change file name to "Results_Figure1_RPE-SP.csv" during the RPE-SP run

for {i in 0..T-1}
{printf "%f\t", i>Results_Figure1_RPE-SP.csv;
printf "%f\t", (((RPE[i]+1)^(1/5))-1)*100>Results_Figure1_RPE-SP.csv;
# delete this RPE line during Nordhaus run
printf "%f\t", EInd[i]> Results_Figure1_RPE-SP.csv;
printf "%f\t", TAT[i]>Results_Figure1_RPE-SP.csv;
printf "%f\n", -1000*constr_emissions[i]/constr_accounting[i]>
Results_Figure1_RPE-SP.csv;}
```

A.7.2 AMPL code to produce Figure 2

```
# use the same mod files as for figure 1 with the following changes
# change equation for time preference rate to
# param R {t in 0..T}:= 1*exp(-rho*5*t);
# set the substitution parameter zeta equal to 1 for the run without RPE
# run the following AMPL run file
# change the file name of the csv-file for each run as preferred, e.g.:
# Nordhaus, Sterner and Persson (SP), without relative prices
reset;
model DICE_2016_RPE.mod; # add a "#" in a Nordhaus run
#model DICE_Nordhaus_2016.mod; # delete "#" in a Nordhaus run
option solver knitroampl;
solve;
# Produce sensitivity analysis in csv format
for {i in 0.000001 .. 0.032 by 0.001}
{ let rho:=i;
solve;
printf "%.5f\t", rho>Results_Figure2_SP.csv;
printf "%.5f\n", max {t in 0..T} TAT[t]>Results_Figure2_SP.csv;
}
```

A.7.3 AMPL code for Figure 3 and Figure 4

```
# use the AMPL mod file RPE, S\&P (as for figure 1 and 2)
# change equation for time preference rate to param R {t in 0..T}:= 1*exp(-rho*5*t);
# run the following AMPL run-file
# note that for the decline rate of TFP deltaA the sensitivity analysis
# needs to be done manually, i.e.
# change deltaA in the mod-file from 0 to 0.05 in some steps
# solve the model each time
# print the RPE in 2020 and 2100 for every deltaA similar to other variables

reset;
model DICE_2016_RPE.mod;
option solver knitroampl;
solve;

# Produce sensitivity analysis in csv format
for {i in -4 .. 1.1 by 0.03}
{let zeta:=i;
solve;
printf "%.5f\t", i>Results_Figure3_Theta.csv;
printf "%.5f\t", (((RPE[1]+1)^(1/5))-1)*100>Results_Figure3_Theta.csv;
printf "%.5f\n", (((RPE[17]+1)^(1/5))-1)*100>Results_Figure3_Theta.csv;
}

reset;
model DICE_2016_RPE.mod;
option solver knitroampl;
solve;

for {i in 0.000 .. 0.11 by 0.001}
{let NMD:=i;
solve;
printf "%.5f\t", i>Results_Figure3_NMD.csv;
printf "%.5f\t", (((RPE[1]+1)^(1/5))-1)*100>Results_Figure3_NMD.csv;
printf "%.5f\n", (((RPE[17]+1)^(1/5))-1)*100>Results_Figure3_NMD.csv;
}
```

```
reset;
model DICE_2016_RPE.mod;
option solver knitroampl;
solve;

for {i in 0 .. 40 by 0.5}
{ let EQbar:=i;
solve;
printf "%.5f\t", i>Results_Figure3_Sub.csv;
printf "%.5f\t", (((RPE[1]+1)^(1/5))-1)*100>Results_Figure3_Sub.csv;
printf "%.5f\n", (((RPE[17]+1)^(1/5))-1)*100>Results_Figure3_Sub.csv;
}

reset;
model DICE_2016_RPE.mod;
option solver knitroampl;
solve;

for {i in 0.000001 .. 0.085 by 0.001}
{let rho:=i;
solve;
printf "%.5f\t", rho>Results_Figure4_delta.csv;
printf "%.5f\t", (((RPE[1]+1)^(1/5))-1)*100>Results_Figure4_delta.csv;
printf "%.5f\n", (((RPE[17]+1)^(1/5))-1)*100>Results_Figure4_delta.csv;
}

reset;
model DICE_2016_RPE.mod;
option solver knitroampl;
solve;

for {i in 0.0001 .. 5.2 by 0.02}
{let eta:=i;
solve;
printf "%.5f\t", eta>Results_Figure4_eta.csv;
printf "%.5f\t", (((RPE[1]+1)^(1/5))-1)*100>Results_Figure4_eta.csv;
printf "%.5f\n", (((RPE[17]+1)^(1/5))-1)*100>Results_Figure4_eta.csv;}
```

A.7.4 AMPL code for figure 5

(1) AMPL dat-file, Plausible Ranges

```
# this is the random data generated from raw data by Drupp et al. (2018)
# save this file as random_delta_eta.dat to be compatible with the run-file

param nruns:=1000;

param rhos:=
1 0.015
2 0.00000001
3 0.02
4 0.01
5 0.03
6 0.03
7 0.001
8 0.005
9 0.00000001
10 0.00000001
11 0.01
12 0.00000001
13 0.001
14 0.001
15 0.005
16 0.01
17 0.00000001
18 0.02
19 0.015
20 0.00000001
21 0.04
22 0.00000001
23 0.00000001
24 0.00000001
25 0.03
26 0.00000001
27 0.00000001
28 0.001
29 0.02
```

```
30 0.04
31 0.02
32 0.00000001
33 0.01
34 0.00000001
35 0.01
36 0.03
37 0.003
38 0.03
39 0.02
40 0.00000001
41 0.00000001
42 0.02
43 0.001
44 0.02
45 0.025
46 0.005
47 0.005
48 0.01
49 0.001
50 0.01
51 0.03
52 0.02
53 0.015
54 0.01
55 0.01
56 0.01
57 0.002
58 0.01
59 0.00000001
60 0.00000001
61 0.001
62 0.025
63 0.00000001
64 0.00001
65 0.02
66 0.005
67 0.04
```

68 0.01
69 0.01
70 0.01
71 0.001
72 0.07
73 0.005
74 0.04
75 0.02
76 0.04
77 0.005
78 0.00000001
79 0.01
80 0.01
81 0.01
82 0.02
83 0.02
84 0.00000001
85 0.01
86 0.00000001
87 0.02
88 0.001
89 0.02
90 0.03
91 0.06
92 0.00000001
93 0.02
94 0.01
95 0.005
96 0.001
97 0.001
98 0.03
99 0.06
100 0.06
101 0.01
102 0.00000001
103 0.00000001
104 0.03
105 0.00001

106 0.00000001

107 0.02

108 0.005

109 0.02

110 0.00000001

111 0.00000001

112 0.00000001

113 0.00000001

114 0.008

115 0.00001

116 0.06

117 0.00000001

118 0.02

119 0.015

120 0.02

121 0.005

122 0.005

123 0.005

124 0.00000001

125 0.01

126 0.001

127 0.00001

128 0.01

129 0.01

130 0.005

131 0.00000001

132 0.01

133 0.005

134 0.08

135 0.001

136 0.00000001

137 0.00000001

138 0.00000001

139 0.00000001

140 0.00000001

141 0.001

142 0.025

143 0.00000001

144 0.01
145 0.01
146 0.003
147 0.00000001
148 0.02
149 0.015
150 0.015
151 0.00001
152 0.04
153 0.01
154 0.00000001
155 0.00000001
156 0.01
157 0.00000001
158 0.00000001
159 0.03
160 0.00005
161 0.00000001
162 0.001
163 0.01
164 0.01
165 0.00000001
166 0.001
167 0.03
168 0.02
169 0.00001
170 0.003
171 0.01
172 0.00000001
173 0.005
174 0.00000001
175 0.005
176 0.0025
177 0.07
178 0.01
179 0.01
180 0.02
181 0.02

182 0.03

183 0.001

184 0.00000001

185 0.02

186 0.0001

187 0.00000001

188 0.005

189 0.00000001

190 0.00000001

191 0.00000001

192 0.01

193 0.00001

194 0.005

195 0.01

196 0.00000001

197 0.00000001

198 0.04

199 0.01

200 0.015

201 0.01

202 0.005

203 0.002

204 0.00000001

205 0.001

206 0.02

207 0.00000001

208 0.005

209 0.02

210 0.005

211 0.001

212 0.02

213 0.00000001

214 0.02

215 0.01

216 0.001

217 0.00000001

218 0.08

219 0.00000001

```
220 0.02
221 0.00000001
222 0.04
223 0.02
224 0.00000001
225 0.025
226 0.02
227 0.005
228 0.00000001
229 0.00000001
230 0.08
231 0.005
232 0.03
233 0.00000001
234 0.001
235 0.025
236 0.00000001
237 0.04
238 0.005
239 0.03
240 0.01
241 0.015
242 0.03
243 0.02
244 0.01
245 0.02
246 0.02
247 0.001
248 0.005
249 0.02
250 0.01
251 0.01
252 0.01
253 0.02
254 0.01
255 0.01
256 0.01
257 0.02
```

258 0.01
259 0.00000001
260 0.001
261 0.008
262 0.001
263 0.01
264 0.00000001
265 0.00000001
266 0.02
267 0.00000001
268 0.005
269 0.001
270 0.00000001
271 0.03
272 0.00000001
273 0.005
274 0.01
275 0.003
276 0.025
277 0.01
278 0.06
279 0.01
280 0.00000001
281 0.0025
282 0.00000001
283 0.00000001
284 0.02
285 0.00000001
286 0.00000001
287 0.00000001
288 0.01
289 0.025
290 0.001
291 0.001
292 0.02
293 0.005
294 0.00000001
295 0.001

296 0.00000001

297 0.001

298 0.012

299 0.01

300 0.00000001

301 0.00000001

302 0.00000001

303 0.005

304 0.00000001

305 0.02

306 0.01

307 0.00000001

308 0.005

309 0.00000001

310 0.00000001

311 0.00000001

312 0.001

313 0.005

314 0.02

315 0.03

316 0.02

317 0.00000001

318 0.03

319 0.01

320 0.03

321 0.025

322 0.02

323 0.00000001

324 0.005

325 0.01

326 0.005

327 0.005

328 0.01

329 0.00000001

330 0.00000001

331 0.00000001

332 0.02

333 0.01

334 0.005
335 0.03
336 0.00000001
337 0.00000001
338 0.005
339 0.00000001
340 0.01
341 0.001
342 0.005
343 0.00000001
344 0.02
345 0.03
346 0.00000001
347 0.005
348 0.01
349 0.001
350 0.02
351 0.00000001
352 0.03
353 0.01
354 0.01
355 0.00000001
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1000 2.00000000;
```

(2) AMPL mod-file, Plausible Ranges

```
# save this as DICE_2016_RPE_MonteCarlo.mod to be compatible with the run-file

# PARAMETERS
#Time horizon
param T default 100;
# number of runs for Monte Carlo analysis
param nruns;

# Preferences
param etas {1..nruns}; #I-EMUC consumption
param eta;
param rhos {1..nruns}; #time preference rate
param rho;

# relative prices additions
param zeta=min(Normal(-0.2,0.41),1); #substitution parameter

param beta default 0.1; #share of non-market good in utility function
param EQbar=max(Normal(7.77,3.96),0); #subsistence level of non-market 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=max(Normal(0.005,0.00255),0); #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 2015
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 MAT0=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 (GtC)
param MUPEQ:=360;  # Equilibrium concentration in upper strata (GtC)
param MLOEQ:=1720;  # Equilibrium concentration in lower strata (GtC)

# Flow parameters (carbon cycle transition matrix)

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)
# is 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 (Nordhaus (2017))
param NMD=max(Normal(0.01646,0.0415),0);# non-market damages for 3°C warming
```

```
param TD=MD+NMD; # total damages
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);

# growth rate of market good

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

# growth rate of non-market good

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]=MUP0;
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)));
```

AMPL-run file, Plausible Ranges

```
# DICE_2016_RPE_MonteCarlo.run
reset;
model DICE_2016_RPE_MonteCarlo.mod;
data random_delta_eta.dat;
option solver knitroampl;
for {i in 1..nruns} {
reset data zeta,deltaA,EQbar,NMD;
let eta:=etas[i];
let rho:=rhos[i];
solve;
display eta,rho,zeta,deltaA,EQbar,NMD;
# Produce csv-file with overview of parameters
printf "%f\t", eta>Results_figure5_parameters.csv;
printf "%f\t", rho>Results_figure5_parameters.csv;
printf "%f\t", zeta>Results_figure5_parameters.csv;
printf "%f\t", deltaA>Results_figure5_parameters.csv;
printf "%f\t", EQbar>Results_figure5_parameters.csv;
printf "%f\n", NMD>Results_figure5_parameters.csv;
# Produce csv-file with data for figure 5
for {t in 0..T-2}{
printf "%f\t", EInd[t]>Results_figure5_Emissions.csv;}
printf "%f\n", EInd[T-1]>Results_figure5_Emissions.csv;;
for {t in 0..T-2}{
printf "%f\t", TAT[t]>Results_figure5_Temperature.csv;}
printf "%f\n", TAT[T-1]>Results_figure5_Temperature.csv;
for {t in 0..T-2}{
printf "%f\t", -1000*constr_emissions[t]/constr_accounting[t]>
Results_figure5_SCC.csv;}
printf "%f\n", -1000*constr_emissions[T-1]/constr_accounting[T-1]>
Results_figure5_SCC.csv;
for {t in 0..T-2}{
printf "%f\t", (((RPE[t]+1)^(1/5))-1)*100>Results_figure5_RPE.csv;}
printf "%f\n", (((RPE[T-1]+1)^(1/5))-1)*100>Results_figure5_RPE.csv;
}
end
```