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

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Abstract: We study how the scarcity of non-market goods, such as environmental amenities, affects the economic appraisal of climate policy. To this end, we perform a comprehensive analysis of the change in relative prices of non-market goods in the widespread climate-economy model DICE. We show that DICE already contains relative prices implicitly and that the impact of the scarcity of non-market goods on climate policy evaluation is therefore more pervasive than previously suggested. We calibrate DICE based on empirical evidence and propose a plausible range for relative price changes. The uncertainty is substantial, with relative price changes ranging from 1.3 to 9.6 percent in 2020. For our central calibration, the relative price change amounts to 4.4 percent in 2020. Neglecting relative prices leads to an underestimation of the social cost of carbon in 2020 of more than 40 percent. Accounting for these changes is equivalent to a decrease in pure time preference by more than a half percentage point. Our findings support initiatives to consider relative prices in governmental project appraisal and offer guidance for the evaluation of climate policy.

JEL-Classifications: Q01, Q54, H43, D61, D90

Keywords: Climate policy, discounting, non-market goods, social cost of carbon, substitutability

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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 natural heritage sites poses a special challenge. In light of the growth of the global economy and a stagnation or loss of non-market goods, such as environmental 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 degree of substitutability it would increase by 2 percent per year. Within 100 years, the relative value of a unit of non-market goods. Ignoring this value increase can lead to large errors when evaluating climate policy.

This paper provides a comprehensive analysis of the change in the relative price of non-market goods. In particular we study drivers of relative price changes and quantify 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 it 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. The purpose of this paper is to fill this gap.

¹See, 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 for market goods (Hepburn and Groom 2017; Koetse et al. 2017; MFN 2015). Yet, in general, the growth rate of non-market goods is non-constant and endogenous to how we manage climate change, for instance. Our analysis therefore builds on an integrated assessment model following Sterner and Persson (2008), who first highlighted the importance of considering relative prices for climate policy. They assumed that non-market goods are complementary to consumption goods and argued that optimal climate policy—when introducing relative prices—should be more stringent than as advocated in the Stern Review, even when using the considerably higher rate of pure time preference of Nordhaus (2007). As changes in 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.

²See, 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).

³This 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 2017).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. Nordhaus (1994: 50) was 'surprised' that, on average, his respondents believed that 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. Building on this replication allows us to clarify what explicitly introducing relative prices into DICE implies in this well-understood 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 introducing relative prices into DICE can lead to more but also less stringent

⁴Integrated assessment models (IAM), such as DICE, are subject to substantial critique (Pindyck 2017). Our aim is to systematically explore the relative effect sizes of different drivers of climate policy evaluation. Although closed-form analytic climate models start to emerge (van den Bijgaart et al. 2016; Rezai and van der Ploeg 2016; Traeger 2015), IAMs still represent a useful tool for such purposes.

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

Section 4 scrutinizes the impact of the 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 consumption and technological progress affect relative price changes through the endogenous growth rate of market goods. The degree of substitutability turns out to be the key driver of relative price changes. While the elasticity of marginal utility of consumption and pure time preference matter considerably in the short-run, technological progress exerts its influence on relative price changes 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 the 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 conventional considerations in 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 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 a utility function

$$U = \begin{cases} U^{l}(E_{t}) & \text{for } E_{t} \leq \overline{E} \\ U^{h}(E_{t}, c_{t}) & \text{else.} \end{cases}$$
(1)

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

$$U = \left[\alpha \left(E_t - \overline{E}\right)^{\theta} + (1 - \alpha) c_t^{\theta}\right]^{1/\theta} \text{ with } -\infty < \theta \le +1, \ \theta \ne 0; \ 0 < \alpha < 1,$$
(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 $\sigma = \frac{1}{1-\theta}$. In the presence of a subsistence requirement, this direct relationship breaks down and the elasticity of substitution depends also on other determinants besides θ (Baumgärtner et al. 2017). Important special cases of substitutability are perfect substitutes ($\theta = 1$; $\sigma = \infty$), Cobb-Douglas ($\theta = 0$; $\sigma = 1$) and perfect complements ($\theta \to -\infty$; $\sigma = 0$).

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

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

of the market good numeraire is given by the marginal rate of substitution (U_E/U_c) , which is the implicit price of environmental goods.⁶ This tells us by how much the consumption of market goods would need to increase for a marginal decrease in nonmarket 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):

$$RPE_t = \frac{\frac{d}{dt} \left(\frac{U_{E_t}}{U_{c_t}}\right)}{\left(\frac{U_{E_t}}{U_{c_t}}\right)}.$$
(3)

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):

$$RPE_t = (1 - \theta) \left[g_{c_t} - \frac{E_t}{E_t - \overline{E}} g_{E_t} \right].$$
(4)

The *RPE* is equivalent to the difference in the good-specific 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 $\frac{E_t}{E_t - \overline{E}}$. For the standard CES case, which we consider in Sections 2.2 and 3 to replicate Sterner and Persson (2008), the latter subsistence term 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 Integrated Climate-Economy (DICE-2016R) model by Nordhaus (1992 - 2017). 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.

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

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

The welfare function in Nordhaus (2017) is given by:

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

where L_t is period t's population size, δ is the rate of pure time preference and 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 consumption (equivalents). Comprehensive consumption per-capita \tilde{c}_t is defined as an index of generalized consumption (Nordhaus and Szork 2013), which is meant to also include non-market damages. 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:

$$D_t^{\phi} = \phi \ T_t^2 \tag{6}$$

Nordhaus (2017) calibrates the aggregate scaling parameter for the damages on all generalized consumption goods via production-damages, ϕ (Equation 6), 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 Thus, there is perfect substitutability between market and non-market damages. From this one might infer that there is also perfect substitutability between market and non-market goods in DICE (e.g. Neumayer 1999; Sterner and Persson 2008).

⁷Nordhaus (2017) builds on 36 studies that estimate climate damages and adds 25 percent to each damage estimate to incorporate non-market damages. These estimates are treated as data drawn from an underlying damage function and ϕ is calibrated by equating it with the coefficient of the impact of squared temperature change on climate damage estimates from an median, quadratic, weighted regression (see Nordhaus and Moffat (2017) for more details).

Yet, this is not the case and the DICE model implicitly includes a relative price effect of non-market goods. The reason is that, first, overall damages—which include nonmarket damages—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 denoted spending on abatement. In DICE, temperature can thus be viewed as a sort of natural capital. 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, for example Cobb-Douglas, or limited substitutability between natural capital and other forms of production would be equivalent. Thus, while there is perfect substitutability in damages in the standard DICE, it includes non-market damages in net production such that there is an equivalent of limited substitutability in terms of goods. However, backing out the implicit degree of substitutability contained in the complex DICE model is not straightforward, among others due to intertemporal consumption smoothing through savings and due to abatement activities. We will therefore estimate the implicit degree of substitutability and thus of relative price changes in the standard DICE quantitatively in Section 3.

To replicate the results of Sterner and Persson (2008) within DICE-2016R, we follow their approach of explicitely introducing relative prices. This includes, in particular, (i) disentangling the consumption equivalents of Nordhaus into a two good representation; (ii) dropping the subsistence requirement in terms of non-market goods; (iii) defining the development of the non-market good over time and (iv) specifying its initial value; (v) disentangling market and non-market damages; and finally (vi) 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 nonmarket 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. 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. Thus, comprehensive consumption is now given by $\tilde{c}_t = \left[\alpha E_t^{\theta} + (1-\alpha) c_t^{\theta}\right]^{1/\theta}$. 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:

$$W_0(E_t, c_t, L_t) = \sum_{t=0}^{100} L_t \frac{1}{(1+\delta)^{5t}} \frac{1}{1-\eta} \left[\alpha E_t^{\theta} + (1-\alpha)c_t^{\theta} \right]^{\frac{(1-\eta)}{\theta}}.$$
 (7)

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

$$E_t = \frac{E_0}{[1 + \psi T_t^2]}.$$
(8)

To ensure comparability with Sterner and Persson's (2008), we need to assume that non-market damages double the loss in consumption of marketed goods to re-calibrate ϕ . Thus, we include an additional 100 percent non-market damages on top of market damages. Hence, for the baseline Nordhaus (2017) model we assume that market plus non-market damages are equal to 3.26 percent of global output for a temperature increase of 3°C. These total climate damages have to be disentangled into damages on market and non-market goods. Two new damage parameters ψ [κ] now scale up the magnitude of non-market [market] damages. Based on Nordhaus and Moffat (2017), we re-calibrate damages on market-good consumption D_t^{κ} . The damage function for market goods becomes:

$$D_t^{\kappa} = \kappa \ T_t^2 \,. \tag{9}$$

To account for the non-market damages on top of market damages, the nonmarket climate damage parameter ψ is calibrated by comparing two different model specifications:⁸ On the one hand, a model in which non-market damages D_t^{ϕ} 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

⁸See Barrage (2016) for an alternative approach to calibrating non-market damages.

as a residual, with $C_0 = E_0$ (see Appendix A.2), and depends in particular on non-market damage costs. Given this set-up, the *RPE* in DICE is given by:⁹

$$RPE_{t} = (1 - \theta) \left[\underbrace{\left[\frac{1}{\left(1 + \delta\right)^{5t}} \left(1 + Y_{K_{t}} - \xi\right) \right]^{\frac{1}{\eta}} - 1}_{g_{c_{t}}} \underbrace{+ \frac{2 \psi T_{t}^{2} g_{T_{t}}}{\left(1 + \psi T_{t}^{2}\right)}}_{g_{E_{t}}} \right] .$$
(10)

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 Ramsey Rule in DICE and thus depends on a number of key variables and parameters (see Hänsel and Quaas (2018) for a derivation). On the one hand, it is determined by the distributional parameters of the social welfare function: the rate of pure time preference, δ , and the elasticity of the marginal utility of consumption (equivalents), η . On the other hand, it is driven by the net marginal productivity of capital, $Y_{K_t} - \xi$, where ξ denotes the proportional rate of capital depreciation. 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 .¹⁰ Third, 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} .¹¹ Finally, the difference in the two good-specific growth driver categories is scaled by the degree of substitutability, θ , between market and nonmarket goods.

⁹ 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.

¹⁰Total 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.

¹¹ In the presence of a subsistence requirement in terms of non-market goods ($\overline{E} > 0$) that we later 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 4). In this case, the *RPE* is given by: $RPE_t = (1 - \theta) \left[\left[\frac{1}{(1+\delta)^{5t}} \left(1 + Y_{K_t} - \xi \right) \right]^{\frac{1}{\eta}} - 1 + \frac{2 \psi T_t^2 g_{T_t}}{(1+\psi T_t^2)} \left(\frac{E_0}{E_0 - \overline{E} (1+\psi T_t^2)} \right) \right].$

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).¹² Industrial emissions and atmospheric temperature change are climate policy measures often referred to in science and policy circles, while the SCC is widely used by governmental bodies to inform carbon pricing.

We draw all parameter inputs from Nordhaus's (2017) DICE-2016R, except for those that concern the explicit introduction of the non-market good—the preference share parameter α , the degree of substitutability θ as well as the magnitude of nonmarket damages—which are based on Sterner and Persson (2008). Table 1 provides an overview of the parameter specifications used in Sterner and Persson case, which we abbreviate as "S&P-*RPE*". Figure 1 depicts how the S&P-*RPE* evolves over time from the year of 2020 to 2100, and how it impacts industrial CO_2 emissions, temperature change and the SCC.¹³ We report equivalent yearly values of the 5-year time steps.

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 8), and in relative terms as compared to market goods throughout the planning horizon, the change in relative scarcity, as measured by the relative price change, falls over time.

¹²The 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).

¹³The computations consider the full planning horizon of DICE. Appendix A.3 depicts the overview figure for a longer time horizon, from 2020 to 2300. The numerical dynamic optimization results presented in the following are calculated using the Knitro solver (version 10.2) together with the AMPL optimization software. The programming code is provided in Appendix A.5.



Figure 1: Relative price effect (RPE) and comparison of climate policy paths. The green line shows the Sterner and Persson (2008) case. The black line depicts the 'Nordhaus' comparison case (with comparable and thus higher damages as in DICE-2016R). The dotted grey line features another comparison case, yet with the lower rate of pure time preference, δ , of Stern.

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

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

* N denotes values taken from Nordhaus (2017), while S&P denotes Sterner and Persson (2008). ** MD denote market damages under 3°C warming, with $\kappa = 0.0181$.

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

Moreover, Figure 1 compares this S&P-*RPE* to two cases that do not change the DICE-2016R approach of (only implicitly) dealing with relative prices but that differ in their assumptions about a key discounting parameter—the rate of pure time preference, δ . First, we compare the S&P-*RPE* case to the optimal climate policy trajectories in the 'Nordhaus' case.¹⁴ According to Sterner and Persson (2008), this provides the direct comparison case to judge the impact of introducing relative prices. To capture the findings of Sterner and Persson (2008) within the DICE-2016R 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).¹⁵ In DICE-2016R, and with the comparable assumption regarding non-market climate damages based on Sterner and Persson (2008), emissions peak in 2035, while they did not peak but increased until 2100 in the older DICE-2006 version. When considering the S&P-*RPE*, industrial emissions decrease immediately and become almost zero in 2055. Full decarbonization of the global economy is achieved as 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 using 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 an 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.

¹⁴Climate damages are higher in the 'Nordhaus' run than in Nordhaus (2017) for comparability with Sterner and Persson (2008). In Appendix A.4, we perform the same analysis with Nordhaus' (2017) estimate of lower non-market damages and briefly relate to it in Section 3.2.

¹⁵Following Nordhaus (2017), 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-2016R. Therefore we obtain a different profile of industrial emissions in Figure 1 as depicted in their key results figure. These changes, among others, include a lowering of the rate of pure time preference and the inclusion of the possibility negative emissions.

3.2 Stern or Sterner? 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 against which to compare the influence of introducing relative prices?

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-2016R this is no longer the case: Initial emissions are still in-between the 'Nordhaus' and 'Stern' comparison cases but the S&P-RPE path does not lead to earlier decarbonization as compared to the 'Stern' case. Irrespective of these differences due to changes in the DICE model over time, using yearly emissions is not a clear-cut comparison metric because emission paths can potentially cross. With crossing of emission paths it may be that even if a model run leads to earlier decarbonization, it can entail higher cumulative emissions or a higher peak temperature. Unambiguous comparison metrics would thus be peak atmospheric carbon concentration or peak temperature achieved under a given model parameterization.

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 (2017) value of 1.5 percent by 1.2 percentage points, i.e. a model run with a δ of 0.3 percent yields the same peak temperature as we obtain when introducing the S&P-*RPE*. Although this shows that explicitly considering relative prices does not yield 'an even Sterner review', as the reduction is lower than

1.4 percentage points, which would be comparable to using Stern's rate of pure time preference, it still represents a 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 contains relative prices? The cleanest comparison between a model with relative prices and models that only differ in their rate of pure time preference would be within a model that includes the *RPE* to a case with perfect substitutability ($\theta = 1$), as the *RPE* vanishes in this case (cf. Equations 4 and 10). 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 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 degrees of substitutability, θ . The bold black line shows the comparison case of perfect substitutability and thus without relative prices.¹⁶ In contrast, the dashed lines depict runs with different degrees of limited substitutability and thus with *RPEs*. The dashed green line shows the complementarity assumption of the S&P-*RPE* ($\theta = -1$), while the dashed black line depicts the 'Nordhaus' case with its implicit degree of limited substitutability. A model run with relative prices can now be compared to a run without relative prices ($\theta = 1$) but with a higher δ such that the resulting optimal peak temperature is the same across both runs. This yields the equivalent change in the pure rate of time preference, $\Delta \delta_{sub}^{sup}$, of introducing relative prices into climate policy evaluation, where the subscript denotes the baseline δ and the superscript the degree of substitutability, θ , of the considered *RPE*. For example, introducing relative prices with Cobb-Douglas substitutability ($\theta = 0$) at a baseline of Nordhaus's (2017) pure rate

¹⁶When 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.



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, 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 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 $\Delta \delta_{1.5\%}^N = 0.78$ percentage points.

of time preference of $\delta = 1.5$ is equivalent in terms of optimal peak temperature to decreasing δ by $\Delta \delta_{1.5\%}^0 = 0.6$ 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 $\Delta \delta_{1.5\%}^N =$ 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 indeed 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 $\Delta \delta_{1.5\%}^{-0.13}$ 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-2016R model, as our analysis considers higher damages for comparability with Sterner and Persson (2008). In Appendix A.4 we re-run the analysis within the standard DICE-2016R 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, $\theta = 0.02$, 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 $\Delta \delta_{1.5\%}^{0.02}$ in DICE-2016R would be 0.33 percent. Thus, also the standard DICE-2016R model contains a sizable implicit relative price effect.

The considerable relative price effect already contained in the 'Nordhaus' case as well as in the standard DICE model implies that one has to be very careful in interpreting effects when explicitly introducing relative prices to the DICE model. Our analysis for example reveals that if market and non-market goods are considered substitutes ($\theta > 0$), explicitly introducing an *RPE* into DICE will 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* ($\Delta \delta_{1.5\%}^{-1}$ is not defined). Already a degree of substitutability of $\theta = -0.66$ would be equivalent to reducing pure time preference from the value employed by Nordhaus to that of Stern, that is $\Delta \delta_{1.5\%}^{-0.66} = 1.4$ percentage points. The effect of considering relative prices with the complementarity assumption of Sterner and Persson (2008) may thus be considered as even more crucial than has previously been suggested.

Third, we address the question of what is the appropriate baseline specification? The analysis depicted in Figures 1 and 2 is based on the baseline specification of the most recent DICE version from Nordhaus (2017), with the exception of the parameters needed to introduce relative prices exlicitely as well as higher damages as compared to Nordhaus (2017) 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, for example, 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 $\Delta \delta_{3\%}^{-1} = 2.5$ percentage points. Overall, it is therefore crucial to be specific about the baseline model specification. This makes it particularly important to systematically examine how different potential determinants affect the *RPE* and its influence on climate policy evaluation.

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 4. 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 consumption and (v) the rate of technological progress.

Substitutability

A key driver of the *RPE* is the degree of substitutability between market and nonmarket goods. The upper panel of Figure 3 depicts the effects of varying the elasticity of substitution, θ , along a range of one-third to infinity. The range encompasses all benchmark values assumed in the literature on relative prices and ecological discounting, such as the Cobb-Douglas assumption of $\theta = 0$ (Gollier 2012), as well as different degrees of complementarity, e.g. $\theta = -0.333$ (Kopp et al. 2012) and $\theta = -1$ (Sterner and Persson 2008). Furthermore, it includes indirect empirical estimates of substitutability (Baumgärtner et al. 2015; Drupp 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 0.43 [0.14, 0.72], which corresponds to a CES, θ , of 0.57 [0.28 to 0.86].¹⁷ 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 values of the *RPE* in 2100 are 3.29 (4.74) percent for $\theta = -1$ ($\theta = -2$) and the *RPE* reduces to 1.73 (0.77) percent for a value of θ of 0 (0.57).

¹⁷Since 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).

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 additional damage component that doubles overall climate damages. This amounts to 1.63 percent of GDP under 3°C warming. In contrast, Nordhaus (2017) considers nonmarket damages as an additional damage component, amounting to 0.49 percent of GDP under 3°C warming. Since the climate damages share on non-market goods is inherently uncertain, the only source of evidence we may draw on are expert surveys. Nordhaus (1994) surveyed 19 experts on the economic impacts of climate change. These experts forecast that 38 percent of damages should be attributed to non-market goods (for a 3°C warming until 2090). More recently, Howard and Sylvain (2015) extended upon this study and surveyed a larger number of experts on their "best guess of the percentage of total impacts (market plus non-market) that will be borne by the market sector?". The best guess of 213 respondents is that 50 percent of damages accrue to non-market goods. This would be in line with the doubling of market-damages as assumed by Sterner and Persson (2008). A sizable standard deviation of 28 percent reveals substantial heterogeneity in responses. Figure 3 therefore depicts the effect of non-market damages on the *RPE* for a large range of non-market damages under 3°C warming in the year 2020, spanning from 0 to 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 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.¹⁸ In the year 2100 we find qualitatively the same as for 2020: the RPE declines from 3.29 to 3.28 by increasing the subsistence requirement.

¹⁸Additionally, \overline{E} slightly impacts the *RPE* also indirectly via the calibration of the non-market good climate damage coefficient ψ (Equation A.11), 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 consumption, and decline rate of total factor productivity growth—and their impact on the *RPE* in 2020 (left) and in 2100 (right).

Rate of pure time preference

The rate of pure time preference δ , measures how the utility of the representative agent at different points should be weighted in relative terms. A positive rate implies that the utility of future agents is discounted just because they live in the future. There is considerable disagreement on what constitute plausible and justifiable values for the rate of pure time preference. Figure 4 depicts the effects of the rate of pure time preference on the *RPE* over an interval of 0 to 8 percent.¹⁹ 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 (2017) assumption of $\delta = 0.015$ corresponds to a *RPE* of 6.20 percent. In the year 2100, the rate of pure time preference has almost no effect on the *RPE*: the corresponding *RPE* range is only 3.27

¹⁹Note that for computational reasons we approximate 0 with 0.000001 percent.

to 3.37 percent, i.e. the sensitivity is negligible but qualitatively the influence of the rate of pure time preference on the RPE reverses.

Elasticity of the marginal utility of consumption

The elasticity of the marginal utility of consumption (equivalents), η , is a measure of inequality aversion with respect to the intertemporal distribution of inclusive consumption \tilde{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 2017). 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 consumption.

Decline rate of total factor productivity

The growth rate of material consumption is in particular driven by total factor productivity (TFP), $A_t = \frac{A_{t-1}}{1-g_{t-1}^A}$, which grows exogenously at a decreasing rate, with $g_t^A = g_0^A e^{-5t\tau^A}$ where τ^A can be interpreted as the decline rate of TFP. It represents the key exogenous parameter determining the dynamics of productivity growth in DICE. For our sensitivity analysis, we vary this parameter while we do not change the shape of the time profile of technological progress imposed by Nordhaus (2017).²⁰ We find that the *RPE* in 2020 (2100) decreases from 6.28 (4.72) percent for $\tau^A = 0$ percent to 6.00 (1.02) percent for $\tau^A = 0.5$ percent. The baseline case of Nordhaus (2017) implies a decline rate of TFP growth of around 0.1 percent per year corresponding to a *RPE* in 2020 (2100) of 6.20 (3.29) percent. A lower decline rate of TFP growth τ^A makes non-market goods scarcer relative to human-made consumption goods as global GDP is scaled up by higher exogenous growth in TFP. However, due to the logistic shape of the dynamics of TFP, the effect on relative prices is more pronounced in 2100: Here the *RPE* decreases more than linearly in the decline rate of TFP growth per year.

²⁰Alternatively, one could vary the initial level g_0^A or compute an average productivity measure over the whole planning horizon. The latter would, however, imply to change the time profile of TFP including higher initial growth rates, which thereby artificially increases the *RPE* in 2020.

This sensitivity analysis reveals that overall the exogenous drivers have a strong influence 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 as well as 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 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 the individual determinants of the relative price effect, this section examines what might be a plausible range and a best-guess central calibration for each determinant of the RPE based on the best available empirical evidence. To compare simulations and thus the effect of the RPE on climate policy evaluation, we focus on peak temperature as the comparison metric and make comparisons against the case of perfect substitutes.

In contrast to the analysis in Section 3, we specify a central calibration as a new baseline and perform a Monte Carlo analysis with 1000 draws to construct plausible ranges. For the lower and upper bounds, we consider a 95 percentile range around the mean. We make the following assumptions regarding the distribution of the individual determinants: For the degree of substitutability, we assume a Normal distribution for which the values used in Sterner and Persson (2008), $\theta = -1$, and the mean empirical estimate from Drupp (2018), here taken as $\theta = 0.6$, encompass the 95 percent confidence interval, with a mean of $\theta = -0.2$. For non-market damages, we draw on the expert responses from the survey by Howard and Sylvain (2015) and assume a Normal distribution.

bution with mean and standard deviation taken from their expert data.²¹ 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 model runs. Finally, for the decline rate of TFP, τ^A , we assume a Normal distribution with the mean given by the value of Nordhaus (2017). The 95 percent confidence interval is calculated such that it is bounded from below by a zero decline rate.

Table 2 lists all the 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 nonnegligible 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 percent interval that we consider as the 'plausible range' includes a rate of pure time preference of 6 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 an *RPE* (black dashed line), and the plausible 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.²² In terms of industrial emissions, the parameter ranges can lead to both full decarbonization in 2020 as well as to cases in which it is optimal that emissions still increase until mid century.

For the central calibration, we find that the RPE decreases from 4.4 percent in 2020

²¹We truncate the distribution to exclude negative values for non-market damages and τ^A .

²²At 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 .

Figure 5: Relative price effect (RPE) and comparison of climate policy paths for a best-guess central calibration and a plausible range of the drivers of the *RPE*. The blue line represents the central calibration of the *RPE*, while the black line depicts the perfect substitutability comparison ($\theta = 1$) in which the *RPE* vanishes. The blue-shaded area represents the 95 percentil range considering uncertainty in all of the drivers of the *RPE*.

Parameter	Source	Distribution	Central Calibration	
θ	S&P (2008), Drupp (2018)	Normal; $\mu = -0.2, \sigma = 0.41$	-0.2	
NMD*	Howard and Sylvain (2015)	Normal; $\mu = 1.65\%, \sigma = 4.15\%$	1.65%	
\bar{E}/E_0	Assumption	Normal; $\mu = 10\%, \sigma = 5.10\%$	10%	
δ	Drupp et al. (2018)	Raw expert data	1.10%	
η	Drupp et al. (2018)	Raw expert data	1.35	
τ^A	Nordhaus (2017)	Normal; $\mu = 0.1\%, \sigma = 0.05\%$	0.1%	

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

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

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). The peak temperature in the case without the *RPE* is 3.7°C, that is temperature peaks at 0.5°C higher as compared to our central calibration with relative prices. If we again translate this into an equivalent change of the rate of pure time preference, 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 ($\theta = -0.2$) is equivalent to reducing the rate of pure time preference by $\Delta \delta_{1.1\%}^{-0.2} = 0.53$ 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 at the baseline of the central calibration as in Figure 5. 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 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' shows that substitutability is 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 RPEin 2020 except for the rate of pure time preference, δ as well as the elasticity of the marginal utility of consumption, η . Indeed, the 95 percentile range for η changes the RPE in 2020 from 8.62 to 3.41 and is thus a stronger driver compared to the degree of substitutability. In 2100 we find that the decline rate of TFP has the second strongest influence on the RPE, 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) we obtain that the strongest effect comes from the standard social welfare

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 - 3.58	185 - 61	2558 - 372
NMD#	0-9.54%	4.37 - 4.68	1.90 - 2.24	3.72 - 2.28	48 - 299	340 - 2282
\bar{E}/E_0	0-20%	4.41 - 4.40	2.05 - 2.04	3.01 - 3.00	94	704 - 710
δ	0-6%	4.74-2.07	2.02-2.18	2.33 - 8.28	265 - 11	1496 - 85
η	0.1 - 3	8.62 - 3.41	$\boxed{2.02-2.14}$	2.16 - 7.78	545 - 23	1498 - 238
$ au^A$	0-0.2%	4.47 - 4.35	2.97 - 1.44	3.17 - 2.94	79 - 104	703 - 628

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

[#] NMD denotes non-market damages under 3°C warming.

[†] SCC is measured in US\$ per ton of CO_2 .

parameters, δ and η . These are about equally important and alter peak temperature by 5.95°C and 5.62°C, respectively. The degree of substitutability and the amount of non-market damages also have a considerable influence on peak temperature, driving it by 1.13°C and 1.44°C, respectively. For the SCC in the year 2020 (column 6), we find that the plausible range in the year 2020 is substantial and all but subsistence consumption and the decline rate of technological progress are important drivers. Nonmarket damages and the rate of pure time preference alter the SCC in 2020 by 251 and 254 US\$ per ton of CO_2 , while the elasticity of the marginal utility of consumption has about twice their quantitative effect on the SCC, with a range of 522 US\$. For the SCC in the year 2100 (column 7), we find that the degree of substitutability and the amount of non-market damages are the strongest drivers, leading to a range in the SCC of 2186 US\$ and 1942 US\$, respectively. This is followed by the influence of the two welfare parameters, at 1411 US\$ and 1260 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 capture 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 2.92°C, corresponding to 20 percent and 52 percent of the overall effect, respectively. The net effect on the SCC in 2020 (2100) is 71 (642) and 81 (512), respectively.

6 Discussion

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

First, we find that the drivers related to the growth of non-market goods are not of quantitative importance for the *RPE* in the optimal management framework of DICE. 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).²³ 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 in a sense also relates to studying non-optimal climate policy, where we would have imperfect management control. In such cases, drivers of non-market goods may play a larger role for relative prices as in the optimal management considered here.

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

 $^{^{23}}$ 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.

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 nonmarket goods so as to increase confidence about the likely magnitude of relative prices.

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

Fifth, we have abstracted from any behavioral effects related to relative price changes. Dietz and Venmans (2017) study the impact of the endowment effect on dual discounting. Other possibilities may include extending the theory of relative prices to studying relative consumption concerns (e.g. Johansson-Stenman and Sterner 2015).

Finally, the long term future is inherently uncertain. Yet, the DICE model is deterministic. While a deterministic analysis such as ours can yield important insights, it is clear that the analysis should be extended to cover different forms of uncertainty.²⁴ 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

 $^{^{24}}$ 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.

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.

7 Conclusion

This paper provides a comprehensive analysis of the change in the relative price of non-market goods by studying its quantitative magnitude, its fundamental drivers, and its implications for climate policy in the integrated assessment of climate change. Our analysis in the most recent version of the widely-used DICE model (Nordhaus 2017) reveals that the relative price effect of non-market goods is substantial in quantitative terms: it amounts to 4.4 (2.0) percent in the year 2020 (2100) in our central calibration. When combining plausible ranges of all individual drivers, the 95 percentile ranges from a Monte Carlo analysis yield relative price effects 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 as well as how we specify the baseline. As an unambiguous comparison metric across different model runs, we use peak temperature, exploiting the fact that each considered optimization run results in a unique peak temperature in the 500 year time horizon, allowing for comparability across model runs. Introducing relative prices in the spirit of Sterner and Persson (2008) in DICE-2016R, we find that this yields an equivalent reduction in the rate of pure time preference of 1.2 percentage points when compared to the 'Nordhaus' run. Yet, since we show that the standard DICE model of Nordhaus (2017) already contains a considerable relative price effect of non-market goods due to a 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 lead relative prices to vanish, and then compute equivalent changes in the rate of pure time preferences. This direct comparison reveals that there would be no positive pure time preference that is equivalent to considering relative prices with the complementary assumption of Sterner and Persson (2008). In our central calibration that is informed by a systematic study of the determinants of the relative price effect, and feature 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 (2017), 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 are substitutes, explicitly introducing relative prices into DICE would lead to less stringent optimal climate policy.

While relative prices thus clearly matter considerably for climate policy evaluation, our results likewise suggest an enduring importance of the two key 'normative' discounting parameters determining the intertemporal distribution of well-being. Indeed, we find that in the short-run, the rate of pure time preference and the elasticity of marginal utility of consumption indirectly influence the relative price effect quite considerably, since the growth of consumption is endogenous in DICE. Furthermore, both their direct and indirect effects through relative prices on optimal climate policy outcomes is substantial. We find that the net effects of pure time preference and of the elasticity of marginal utility of consumption on peak temperature amount to 1.21 °C and 2.92°C, corresponding to 20 percent and 52 percent of the overall effect, respectively.

Finally, our analysis provides guidance for the revision of discounting policy guidelines. Our findings suggest that the relative price effect of non-market goods is more substantial than the one percent result presented in the literature for the relative price effect of environmental goods that has informed policy guidance in the Netherlands (Baumgärtner et al. 2015; Drupp 2018; Koetse et al. 2017). Our analysis also points towards the most crucial determinants of relative prices, such as the degree of substitutability and technological progress. This suggests that it is imperative to obtain better estimates for these drivers globally as well as at local or national levels to better inform governmental guidance. All in all, our results support recent initiatives, such as in the Netherlands, to consider relative price effects in project appraisal.

References

- Arrow, K., Cropper, M., Gollier, C., Groom, B., Heal, G., Newell, R., Nordhaus, W., Pindyck, R., Pizer, W., Portney, P., Sterner, T., Tol, R.S.J., and M. Weitzman (2013), Determining Benefits and Costs for Future Generations, *Science* **341**(6144): 349–350.
- Barrage, L. (2016), Be Careful What You Calibrate For: Social Discounting in General Equilibrium, mimeo, Brown University, available at http://www.lintbarrage.com/wpcontent/uploads/2016/12/Barrage_2016_Discounting.pdf.
- Baumgärtner, S., Klein, A.-M., Thiel, D., and K. Winkler (2015), Ramsey Discounting of Ecosystem Services, *Environmental and Resource Economics* 61(2): 273–296.
- Bretschger, L. (1998), How to substitute in order to sustain: knowledge driven growth under environmental restrictions, *Environment and Development Economics* 3: 425— 442.
- Bretschger, L., and S. Smulders (2012), Sustainability and substitution of exhaustible natural resources How structural change affects long-term R&D-investments, *Journal* of Economic Dynamics & Control 36: 536–549.
- Christensen, P., Gillingham, K., and W. Nordhaus (2016), Uncertainty in Forecasts of Long-Run Productivity Growth, GTAP Resource 5074, available at https://www.gtap.agecon.purdue.edu/resources/download/8112.pdf.
- Dasgupta, P. (2008), Discounting Climate Change, Journal of Risk and Uncertainty 37(2): 141–169.
- Dietz, S., Gollier, C., and L. Kessler (2017), The climate beta, Journal of Environmental Economics and Management, forthcoming.
- Dietz, S., and F. Venmans (2017), The endowment effect and environmental discounting, Grantham Research Institute on Climate Change and the Environment Working Paper No. 233.
- Drupp, M.A., Freeman, M.C., Groom, B., and F. Nesje (2018), Discounting Disentangled, Forthcoming in the *American Economic Journal: Economic Policy*.

- Drupp, M.A. (2018), Limits to Substitution between Ecosystem Services and Manufactured Goods and Implications for Social Discounting, *Environmental and Resource Economics* 69(1): 135–158.
- Fenichel, E.P., and J. Zhao (2015), Sustainability and substitutability, Bulletin of Mathematical Biology 77(2): 348–367.
- Fleurbaey, M., and S. Zuber (2016), Fairness, preference uncertainty and discounting, Paper presented at the 2016 SURED conference, available online at http://ces.univparis1.fr/SURED2016/papers/Zuber_SURED2016.pdf.
- Gerlagh, R., and M. Liski (2017), Consistent climate policies, *Journal of the European Economic Association*, forthcoming.
- Gollier, C., and J.K. Hammitt (2014), The long-run discount rate controversy, Annual Review of Resource Economics 6(1): 273–295.
- Gollier, C. (2010), Ecological discounting, Journal of Economic Theory 145: 812–829.
- Gollier, C. (2017), Valuation of natural capital under uncertain substitutability, TSE Working Paper No. TSE-813. Available at: https://www.tsefr.eu/sites/default/files/TSE/documents/doc/wp/2017/wp_tse_813.pdf
- Groom, B., and C. Hepburn (2017), Looking Back at Social Discounting Policy: The Influence of Papers, Presentations, Political Preconditions, and Personalities, *Review* of Environmental Economics and Policy 11(2): 336–356.
- Gueant, O., Guesnerie, R., and J.M. Lasry (2012) Ecological intuition versus economic reason, *Journal of Public Economic Theory* 14: 245–272.
- Guesnerie, R. (2004), Calcul economique et d'eveloppement durable, *Revue E'conomique* 55: 363–382.
- Hammitt, J.K., and L.A. Robinson (2011), The Income Elasticity of the Value per Statistical Life: Transferring Estimates between High and Low Income Populations, *Journal of Benefit-Cost Analysis* 2(1): Article 1.

- Hänsel, M. C. and M.F. Quaas (2018), Intertemporal Distribution, Sufficiency, and the Social Cost of Carbon, *Ecological Economics* 146: 520–535.
- Heal, G. (2009a), The economics of climate change: a post-Stern perspective, *Climatic Change* 96(3): 275–297.
- Heal, G. (2009b), Climate Economics: A Meta-Review and Some Suggestions for Future Research, *Review of Environmental Economics and Policy* 3(1): 4–21.
- Heal, G. (2017), The Economics of the Climate, *Journal of Economic Literature* **55**(3): 1046--1063
- Heal, G., and Millner, A. (2014), Reflections: Uncertainty and decision making in climate change economics, *Review of Environmental Economics and Policy* 8(1): 120–137.
- Hoel, M., and T. Sterner (2007), Discounting and relative prices, *Climatic Change* 84: 265–280.
- Hoffmann, S., Krupnik, A., and Qin, P. (2017), Building a Set of Internationally Comparable Value of Statistical Life Studies: Estimates of Chinese Willingness to Pay to Reduce Mortality Risk, *Journal of Benefit-Cost Analysis* 8(2): 251–289.
- Howard, P.H., and D. Sylvan (2015), The Economic Climate: Establishing Consensus on the Economics of Climate Change, In 2015 AAEA & WAEA Joint Annual Meeting, July 26-28, San Francisco, California (No. 205761). Agricultural and Applied Economics Association & Western Agricultural Economics Association.
- Hübler, M., Baumstark, L., Leimbach, M., Edenhofer, O., and N. Bauer (2012), An integrated assessment model with endogenous growth, *Ecological Economics* 83: 118– 131.
- [IPCC, 2014] Intergovernmental Panel on Climate Change (2014), Climate Change 2014: Synthesis Report. Contribution of Working Groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change, Available at http://www.ipcc.ch/report/ar5/syr.

- Jensen, S., and C.P. Traeger (2014), Optimal climate change mitigation under long-term growth uncertainty: Stochastic integrated assessment and analytic findings, *European Economic Review* 69: 104–125.
- Johansson-Stenman, O., and T. Sterner (2015), Discounting and relative consumption, Journal of Environmental Economics and Management 71: 19–33.
- Kopp, R.E., Golub, A., Keohane, N.O., and C. Onda (2012), The Influence of the Specification of Climate Change Damages on the Social Cost of Carbon, *Economics: The Open-Access, Open-Assessment E-Journal* 6.
- Koetse, M.J., Renes, G., Ruijs, A., and A.J. de Zeeuw (2017), RELATIEVE PRIJSSTI-JGING VOOR NATUUR EN ECOSYSTEEMDIENSTEN IN DE MKBA, Achtergrondstudie for the *PBL Planbureau voor de Leefomgeving*.
- Mendelsohn, R., Prentice, I.C., Schmitz, O., Stocker, B., Buchkowski, R., and B. Dawson (2016), The Ecosystem Impacts of Severe Warming, *The American Economic Review* 106(5): 612–614.
- [MEA 2005] Millennium Ecosystem Assessment (2005), Ecosystems and Human Well-Being: Synthesis, Washington, DC: Island Press.
- Millner, A. (2017), Non-paternalistic social discounting, Mimeo, LSE. Available at: http://personal.lse.ac.uk/millner/files/non-paternalism.pdf.
- [MFN 2015] Ministry of Finance of the Netherlands (2015).Rapport werkgroep discontovoet 2015.Available at: https://www.rijksoverheid.nl/documenten/rapporten/2015/11/13/rapportwerkgroep-discontovoet-2015-bijlage
- Neumayer, E. (1999), Global warming: Discounting is not the issue, but substitutability is, *Energy Policy* **27**: 33–43.
- Neumayer, E. (2007), A missed opportunity: the Stern Review on climate change fails to tackle the issue of non-substitutable loss of natural capital, *Global Environmental Change* 17: 297–201.

- Neumayer, E. (2010), Weak Versus Strong Sustainability: Exploring the Limits of Two Opposing Paradigms, Cheltenham, UK, Edward Elgar, 3rd Edition.
- Nordhaus, W.D. (1994), Expert opinion on climatic change, American Scientist 82(1): 45–51.
- Nordhaus, W. and J. Boyer (2000), *Warming the World*, MIT Press, Cambridge, MA., USA.
- Nordhaus, W.D. (2007), The Stern Review on the Economics of Climate Change, *Journal of Economic Literature* 45(3): 686–702.
- Nordhaus, W. (2008), A Question of Balance: Economic Modeling of Global Warming, Yale University Press, New Haven, USA. The DICE model is obtainable from: www.nordhaus.econ.yale.edu/DICE2007.htm
- Nordhaus, W. (2014), Estimates of the social cost of carbon: concepts and results from the DICE-2013R model and alternative approaches, *Journal of the Association of Environmental and Resource Economists* 1(1/2): 273–312.
- Nordhaus, W. (2017), Revisiting the social cost of carbon, Proceedings of the National Academy of Sciences 114(7): 1518—1523.
- Nordhaus, W. (2018), Projections and Uncertainties about Climate Change in an Era of Minimal Climate Policies, American Economic Journal: Economic Policy, forthcoming.
- Pindyck, R.S. (2017), The Use and Misuse of Models for Climate Policy, Review of Environmental Economics and Policy 11(1): 100-–114.
- Popp, D. (2004), ENTICE: endogenous technological change in the DICE model of global warming, Journal of Environmental Economics and Management 48(1): 742– 768.
- Rezai, A., and F. van der Ploeg (2016), Intergenerational inequality aversion, growth, and the role of damages: Occam's rule for the global carbon tax, *Journal of the* Association of Environmental and Resource Economists 3(2): 493–522.

- Stern, N. (2007), The Economics of Climate Change: The Stern Review, Cambridge, UK: Cambridge University Press.
- Sterner, T., and M. Persson (2008), An even sterner review: introducing relative prices into the discounting debate, *Review of Environmental Economics and Policy* 2(1): 61–76.
- Traeger, C.P. (2011), Sustainability, limited substitutability, and non-constant social discount rates, Journal of Environmental Economics and Management 62(2): 215– 228.
- Traeger, C.P. (2014), A 4-stated DICE: quantitatively addressing uncertainty effects in climate change, *Environmental and Resource Economics* 59(1): 1–37.
- Traeger, C.P. (2015), Analytic Integrated Assessment and Uncertainty, SSRN Working Paper. Available at: https://ssrn.com/abstract=2667972
- van den Bijgaart, I.M., Gerlagh R., and M. Liski (2016), A simple formula for the social cost of carbon, Journal of Environmental Economics and Management 77: 75–94.
- Viscusi, W.K., and C.J. Masterman (2017), Income Elasticities and Global Values of a Statistical Life, *Journal of Benefit-Cost Analysis* 8(2): 226—250.
- Weikard, H.-P., and X. Zhu (2005), Discounting and environmental quality: when should dual rates be used?, *Economic Modelling* 22: 868–878.
- Weitzman, M.L. (2007), A Review of The Stern Review on the Economics of Climate Change, Journal of Economic Literature 45: 703–724.
- Weitzman, M.L. (2009), On Modeling and Interpreting the Economics of Catastrophic Climate Change, *Review of Economics and Statistics* 91: 1–19.

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 3), we first compute marginal utilities with respect to the two goods for utility function (2):

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

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

We thus have

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

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

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

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

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

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

$$RPE_{t} = \frac{\frac{d}{dt} \left(\frac{U_{E_{t}}}{U_{c_{t}}}\right)}{\left(\frac{U_{E_{t}}}{U_{c_{t}}}\right)} = (1-\theta) \left[g_{c_{t}} - \frac{E_{t}}{E_{t} - \overline{E}}g_{E_{t}}\right].$$
(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-2016R. 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 $T = 3^{\circ}$ C as follows:

$$W_0\Big(E_0, (1 - D_0^{\phi})C_0, L_0\Big) = W_0\Big((1 - D_0^{\psi})E_0, (1 - D_0^{\kappa})C_0, L_0\Big) \quad \Leftrightarrow \qquad (A.7)$$
$$\alpha E_0^{\theta} + (1 - \alpha)\Big((1 - D_0^{\phi})C_0\Big)^{\theta} = \alpha\Big(\frac{E_0}{1 + \psi T^2}\Big)^{\theta} + (1 - \alpha)\Big((1 - D_0^{\kappa})C_0\Big)^{\theta}$$

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

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

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

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

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

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

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

A.3 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.4 Relative prices and comparison of climate policy paths until 2100, with 25% additional non-market damages as in the standard DICE-2016R

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.5 Code

DICE 2016R with Relative Prices

PARAMETERS

#Time horizon
param T default 100;

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

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

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

```
# Technology and its dynamics
param gamma:=0.3; #capital elasticity in production function
param deltaK:=0.1; #depreciation rate on capital (per year)
param Qgross0:=105.5; #Initial world gross output 2015 (trill 2010 USD)
param K0:=223; #initial capital value 2015 (trillions 2010 USD)
param A0:=5.115; #initial level of total factor productivity
param gA0 :=0.076; #initial growth rate for TFP per 5 years
param deltaA default 0.005; #decline rate of TFP per 5 years
```

```
param gA {t in 0..T} := gA0*exp(-deltaA*5*t); # growth rate for TFP per period
param A {t in 0..T}>=0;
let A[0]:=A0;
let {t in 1..T} A[t]:=A[t-1]/(1-gA[t-1]);
```

```
# Emission parameters
param gsigma0:=-0.0152; #initial growth of sigma (coninuous per year )
param deltasigma:=-0.001; #decline rate of decarbonization per period
param ELand0:=2.6; #initial Carbon emissions from land 2015 (GtC02 per period)
param deltaLand:=0.115; #decline rate of land emissions (per period)
param EInd0:=35.85; #Industrial emissions 2015 (GtC02 per year)
param Ecum0:=400; #Initial cumulative emissions (GtC02)
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
#(kgC02 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
```

#(pre-industrial atmos. carbon) (GtC)
param MUPEQ:=360; # Equilibrium concentration in upper strata (GtC)
param MLOEQ:=1720; # Equilibrium concentration in lower strata (GtC)

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

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

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

Climate damage parameters
param Psi default 0.00181; # damage term without 25% adjustment;
damage quadratic term with 25% adjustment is 0.00236

```
param MD default 0.0163;
# market damages for 3°C warming above preindustrial according to Nordhaus (2017)
param TD default 0.0326;
# TD including 100% adjustment for NMD Stern (2007)=0.0326;
#Nordhaus(2014) assumes 25% adjustment for NMD cooresponding to TD =0.02124,
#62.5%=0.0264857
param NMD:=TD-MD;
param TATlim default 12; # upper bound on atm. temperature change
# Abatement cost
param Theta:=2.6; # Exponent of control cost function
param pback0:=550; # Cost of backstop 2010 $ per tCO2 2015
param gback:=0.025; # Initial cost decline backstop cost per period
param pback {t in 0..T}>=0;
let pback[0]:=pback0;
let {t in 1..T} pback[t]:=pback[t-1]*(1-gback);
param phead {t in 0...T}=pback[t]*sigma[t]/Theta/1000;
# VARTABLES
# 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;
```

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```

```
# 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;</pre>
# ocean temperature (°C from 1750)
var TLO {t in 0..T}>=-1, <=20;</pre>
# 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;</pre>
# 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;
# Environmental Quality
var EQ {t in 0..T}>=0.0000001 <=1000;</pre>
# Non-market damages scaling parameter including subsistence requirement
# including sub
var a {t in 0..T} =(1/(nu<sup>2</sup>))*(EQ[0]*(EQbar+((EQ[0]-EQbar)<sup>(zeta)</sup>)
+((1-beta)/beta)*(((1-TD)*C[0])^(zeta)-((1-MD)*C[0])^(zeta)))^(1/zeta))^(-1)-1);
var g_C {t in 0...T-1} = (C[t+1]-C[t])/C[t];
# growth rate of environmental quality
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];
```

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```

```
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*ML0[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_ML0: ML0[0]=ML00;
subject to initial_TL0: TL0[0]=TL00;
subject to initial_TAT: TAT[0]=TAT0;
subject to initial_control: mu[0]=mu0;
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)));
```