

Drupp, Moritz A.; Hänsel, Martin C.

Working Paper

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

CESifo Working Paper, No. 8052

Provided in Cooperation with:

Ifo Institute – Leibniz Institute for Economic Research at the University of Munich

Suggested Citation: Drupp, Moritz A.; Hänsel, Martin C. (2020) : Relative Prices and Climate Policy: How the Scarcity of Non-Market Goods Drives Policy Evaluation, CESifo Working Paper, No. 8052, Center for Economic Studies and ifo Institute (CESifo), Munich

This Version is available at:

<https://hdl.handle.net/10419/215054>

Standard-Nutzungsbedingungen:

Die Dokumente auf EconStor dürfen zu eigenen wissenschaftlichen Zwecken und zum Privatgebrauch gespeichert und kopiert werden.

Sie dürfen die Dokumente nicht für öffentliche oder kommerzielle Zwecke vervielfältigen, öffentlich ausstellen, öffentlich zugänglich machen, vertreiben oder anderweitig nutzen.

Sofern die Verfasser die Dokumente unter Open-Content-Lizenzen (insbesondere CC-Lizenzen) zur Verfügung gestellt haben sollten, gelten abweichend von diesen Nutzungsbedingungen die in der dort genannten Lizenz gewährten Nutzungsrechte.

Terms of use:

Documents in EconStor may be saved and copied for your personal and scholarly purposes.

You are not to copy documents for public or commercial purposes, to exhibit the documents publicly, to make them publicly available on the internet, or to distribute or otherwise use the documents in public.

If the documents have been made available under an Open Content Licence (especially Creative Commons Licences), you may exercise further usage rights as specified in the indicated licence.

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

Moritz A. Drupp, Martin C. Hänsel

Impressum:

CESifo Working Papers

ISSN 2364-1428 (electronic version)

Publisher and distributor: Munich Society for the Promotion of Economic Research - CESifo GmbH

The international platform of Ludwigs-Maximilians University's Center for Economic Studies and the ifo Institute

Poschingerstr. 5, 81679 Munich, Germany

Telephone +49 (0)89 2180-2740, Telefax +49 (0)89 2180-17845, email office@cesifo.de

Editor: Clemens Fuest

www.cesifo-group.org/wp

An electronic version of the paper may be downloaded

- from the SSRN website: www.SSRN.com
- from the RePEc website: www.RePEc.org
- from the CESifo website: www.CESifo-group.org/wp

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

Abstract

Climate change not only impacts production and market consumption, but also the relative scarcity of non-market goods, such as environmental amenities. We study fundamental drivers of the resulting relative price changes, their potential magnitude, and their implications for climate policy in Nordhaus' prominent DICE model, thereby addressing one of its key criticisms. We propose plausible ranges for these relative prices changes based on best available evidence. Our central calibration reveals that accounting for relative prices is equivalent to decreasing pure time preference by 0.6 percentage points and leads to a more than 50 percent higher social cost of carbon.

JEL-Codes: Q010, Q540, H430, D610, D900.

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

Moritz A. Drupp
Department of Economics
University of Hamburg
Von-Melle-Park 5
Germany – 20146 Hamburg
Moritz.Drupp@uni-hamburg.de

Martin C. Hänsel
Potsdam Institute for Climate Impact Research
(PIK)
Telegraphenberg A31
Potsdam / Germany
haensel@pik-potsdam.de

January 1, 2020

Both authors have contributed equally to this work.

We thank Stefan Baumgärtner, Marion Dupoux, Ottmar Edenhofer, Johannes Emmerling, Mark Fleurbaey, Reyer Gerlagh, Christian Gollier, Ben Groom, Frikk Nesje, Martin Persson, Martin Quaas, Sjak Smulders, Thomas Sterner, Christian Traeger and Jeroen van den Bergh as well as seminar audiences at BIOECON 2017, CESifo 2019, EAERE 2017, EAERE-FEEM-VIU 2017 and 2018, EEA 2018, Gothenburg, MCC Berlin, Rimini, SEED 2017, Wageningen, Verein für Socialpolitik 2018 and WCERE 2018 for helpful discussions. We gratefully acknowledge support from the German Federal Ministry of Education and Research under grants 01UT1410 and 03F0772B, the Deutsche Forschungsgemeinschaft (DFG, German Research Foundation) under Germany's Excellence Strategy - EXC 2037 'CLICCS - Climate, Climatic Change, and Society' - Project Number: 390683824, contribution to the Center for Earth System Research and Sustainability (CEN) of Universität Hamburg, and LSE STICERD.

1 Introduction

Relative prices are central to economics. While we can easily infer them from market data for most goods, estimating relative prices for goods that are not traded on markets—including clean air, the existence of biodiversity or UNESCO World Heritage sites—poses a special challenge. The idea of accounting for changes in the relative price of non-market vis-à-vis market goods when evaluating long-term policies has a long history (Malinvaud 1953, Krutilla 1967, Henry 2017), but in light of the continued growth of the global economy and the loss of non-market goods (MEA 2005, IPCC 2014), it has become more urgent to do so in practice.¹ For illustration, suppose that market goods grow at 2 percent, non-market amenities remain constant and there is Cobb-Douglas substitutability. As the change in relative prices is determined by the difference in growth rates times the elasticity of substitution, the relative price would increase by 2 percent per year and, within 100 years, the relative value of a unit of non-market goods would increase by more than 600 percent. Ignoring this can lead to large errors.

This paper analyses the change in the relative price of non-market goods by studying its drivers and by quantifying its implications for optimal climate change policy within a dynamic cost-benefit analysis framework. 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 extensions to the standard discounting framework. Besides accounting for uncertainty, considering relative prices has received wide-spread attention.² Yet until today, there

¹ The Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES) documents that around 1 million species are endangered by extinction (Tollefson 2019). Relatedly, the loss of the Amazon rainforest continues and the evaluation of investment decisions for protecting the remaining forest commonly ignore the increasing scarcity of such non-market goods (Strand et al. 2018). Ito and Zhang (forthcoming) document that revealed WTP for clean air in China depends significantly on income and has increased strongly due to rising awareness of the scarcity of clean air.

²See, 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,

exists no systematic examination of how relative price changes of non-market goods affect the cost-benefit analysis of climate policy. The aim of our study is to fill this gap.

The literature has developed two approaches to dealing with relative price changes.³ The first approach uses ‘dual discount rates’ and discounts consumption streams for market and non-market goods separately. 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 (Hepburn and Groom 2017, Koetse et al. 2018, MFN 2015). Yet, in general, growth rates are non-constant and endogenous to (optimal) management choices. Following Sterner and Persson (2008), who first highlighted the importance of considering relative price changes for climate policy, our analysis builds on a dynamic integrated assessment model that allows us to consider the optimal management of the flow of costs and benefits of both market and non-market goods. Sterner and Persson (2008) assumed that non-market goods are complementary to market goods and argued that optimal climate policy—when introducing relative prices—should be more stringent than as ad-

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).

³See, 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). Zhu et al. (2019) show that this literature implicitly assumes that natural capital is substitutable as a factor of production.

vocated in the Stern Review, even when using the higher rate of pure time preference of Nordhaus (2007). As changes in relative prices may play a crucial role, it is imperative to scrutinize its potential quantitative magnitude, its determinants and its implications for climate policy in a dynamic cost-benefit framework more closely.

We perform our analysis of relative prices in the latest version of the integrated assessment model DICE (Nordhaus 2018), which allow studying how a hypothetical global government would optimally balance costs and benefits of the flow of market and non-market goods in the context of climate change.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 experts, among others, on what proportion of climate impacts will fall on non-market goods. It was a “surprise” for him (1994: 50) that the respondents believed that, on average, ‘only’ between 33 and 38 percent of climate impacts fall on non-market goods. More recently, Howard and Sylvain (2015) find that experts expect that 50 percent of climate impacts fall on non-market goods. While there is large heterogeneity in responses, it is clear that a cost-benefit analysis of climate change cannot ignore these substantial expected losses of non-market goods.

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, as many readers may consider

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

this as a natural benchmark for our paper. It is therefore informative what relative price changes their setting entails. Building on this replication allows us to clarify what explicitly introducing relative prices into DICE implies in this familiar context and how relative price changes should be interpreted. We show that the standard DICE model already—implicitly—contains a sizable relative price effect, which has so far not been observed in the literature. This implies that explicitly introducing relative prices into DICE can lead to more but also less stringent optimal climate policy as compared to the standard Nordhaus case. Our analysis also reveals that if non-market goods are as complementary to market goods as assumed by Sterner and Persson (2008), the full impact of considering relative prices will be even more pronounced than suggested.

Section 4 scrutinizes the impact of 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 and technological progress affect relative price changes through the endogenous growth rate of market goods. The degree of substitutability is a key driver of relative price changes and we gather new indirect empirical evidence to inform its calibration. While the elasticity of marginal utility and pure time preference matter considerably in the short-run, technological progress exerts its influence in the long run.

In Section 5, we construct plausible ranges for each of the drivers and perform a Monte Carlo analysis to determine a range of values for the relative price effect and three climate policy measures. The resulting 95 percent interval for the relative price effect ranges from 2.1 to 8.8 percent in 2020, declining to a range from 1.5 to 2.7 percent in 2100. In our central calibration, the relative price effect amounts to 4.1 percent in the year 2020 and decreases to 1.9 percent in the year 2100. In terms of climate policy evaluation, we find that neglecting relative price changes would lead to an underestimation of the social cost of carbon of 56 (81) percent in the year 2020 (2100), and to a stabilization of temperature change that is 0.6°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 0.6 percentage points.

There are inevitably a number of limitations of our analysis, which we discuss in Section 6. In particular, it is important to stress early on that our analysis only focuses on relative prices changes between market and non-market goods. Yet, relative price changes are relevant also in other related contexts, such as when considering non-market goods as scarce inputs to production (e.g. Zhu et al. 2019) as well as when considering relative price changes among different market goods due to climate change, such as potentially depreciating property values in coastal areas due to sea level rise (e.g. Bakkensen and Barrage 2018, Bernstein et al. 2019). Despite these caveats, we conclude in Section 7 that changes in relative prices of non-market goods can be of substantial magnitude compared to other conventional determinants of the cost-benefit analysis of climate change mitigation. We close by considering implications for governmental cost-benefit analysis and the appraisal of global climate policy.

2 Modeling relative prices

2.1 A simple model of relative price changes

The well-being of a representative agent is determined by the consumption of two goods – a market-traded private consumption good C , with c as consumption per-capita, and a non-market public good E . Both goods are composites with continuously scalable amounts. The agent may further require an amount \bar{E} of the non-market good to satisfy her subsistence needs (Heal 2009, 2017; Baumgärtner et al. 2017). Examples for such a requirement may include food, water and air necessary for survival, or cultural goods such as sacred sites that the agent would not be willing to trade-off. The agent's preferences at time t are represented by an instantaneous utility function

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

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

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

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 ($\bar{E} = 0$), which forms the workhorse of previous research on relative prices, the elasticity of substitution σ is solely determined by the exogenous substitutability parameter θ , with $\sigma = \frac{1}{1-\theta}$. Important special cases of substitutability are perfect substitutes ($\theta = 1$; $\sigma = \infty$), Cobb-Douglas ($\theta = 0$; $\sigma = 1$) and perfect complements ($\theta \rightarrow -\infty$; $\sigma = 0$). In the presence of a subsistence requirement ($\bar{E} > 0$), this direct relationship breaks down and the elasticity of substitution depends also on other determinants besides θ , in particular on the consumption of the subsistence good relative to the subsistence requirement (Baumgärtner et al. 2017).

The intertemporal utility function takes the standard isoelastic form:

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

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

We now turn to the focus of our analysis: the ‘relative price effect’ of non-market goods (hereafter denoted as RPE). The value of non-market goods measured in terms of the market good numeraire is given by the marginal rate of substitution (u_E/u_c), which is the implicit price of non-market goods.⁶ This tells us by how much the consumption of market goods would need to increase for a marginal decrease in non-market goods to hold utility constant. The RPE measures the change in this valuation of non-market goods, and thus their relative scarcity over time (Hoel and Sterner 2007):

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

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

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

⁵ The extension of $u^h(E, c)$ for $\theta \rightarrow 0$ is a special Cobb-Douglas-Stone-Georgy case: $(E - \bar{E})^\alpha c^{(1-\alpha)}$.

⁶ This assumes that the two goods are imperfect complements: $\theta > -\infty$ (cf. Weikard and Zhu 2005).

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 $\frac{E_t}{E_t - \bar{E}}$. In the standard CES case, which we consider in Sections 2.2 and 3 to replicate Sterner and Persson (2008), the subsistence factor simply drops out.

2.2 Relative prices in integrated assessment

Integrated assessment models (IAM) are a widespread tool for the cost-benefit analysis of 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-2016R2) model by Nordhaus (1992 - 2018). It combines a climate module through a negative feedback loop of the atmospheric temperature on economic output with a Ramsey-economy, in which a representative agent maximizes her population-weighted and discounted value of the utility of per capita consumption within a finite time horizon of 100 periods each encompassing 5 years.

To explicitly incorporate relative prices in the spirit of Sterner and Persson (2008) into DICE-2016R2, we need to modify the welfare function and the damage function from climate change. First we present how Nordhaus (2018) models welfare and damages and, second, report the changes necessary to explicitly include relative prices.

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

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

where L_t is period t 's population size, δ is the rate of pure time preference and η is the inverse of the CIES for the aggregate consumption bundle, or the elasticity of the marginal utility of comprehensive consumption. 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 goods consumption in most of the papers by Nordhaus (cf. Section 3.2). Total climate damages D_t^ϕ are expressed as a percentage of

the global economy’s aggregate output and depend on the squared change in atmospheric temperature T compared to pre-industrial levels:

$$D_t^\phi = \phi T_t^2 \quad (7)$$

Nordhaus (2018) calibrates the aggregate scaling parameter for the damages on all generalized consumption goods via production-damages, ϕ (Equation 7), such that market plus non-market damages are equal to 2.12 percent of global output for a temperature increase of 3°C. These total damages include 25 percent non-market damages additional to market damages, which amount to 1.63 percent of global output.⁷ The DICE model therefore does not properly deal with non-market effects, as these are treated just as market damages that affect production output. As damages are simply added up, there is perfect substitutability between market and non-market damages. One might therefore infer that there is also perfect substitutability between market and non-market goods in DICE (Neumayer 1999, Sterner and Persson 2008). Yet, our analysis suggests that this is not the case. The argument goes as follows:

First, overall damages—which include non-market damages in DICE—enter multiplicatively into what is a Cobb-Douglas production function of capital, K_t , labor, L_t , and total factor productivity, A_t , at its core. Net output Y_t is given by (Nordhaus 2008 Eq. A.4, 2018 Eq. 2): $Y_t = (1 - D_t^\phi) (1 - \Lambda_t) A_t K_t^\gamma L_t^{1-\gamma}$, where Λ_t denotes spending on abatement. In DICE, the term $(1 - D_t^\phi)$, which includes both market and non-market damages and is solely driven by temperature change, can thus—in part—be viewed as a form of non-market (natural) capital. Since this enters multiplicatively into the net production function, there is Cobb-Douglas type substitutability between this non-market component and the rest of production. This is related to Weitzman’s (2010) discussion

⁷Nordhaus (2018) builds on 36 studies that estimate climate damages and adds 25 percent to each damage estimate to incorporate non-market damages. These estimates are treated as data drawn from an underlying damage function and ϕ is calibrated by equating it with the coefficient of the impact of squared temperature change on climate damage estimates from an median, quadratic, weighted regression (see Nordhaus and Moffat (2017) for more details). Howard and Sterner (2017) criticize Nordhaus and Moffat (2017) for relying on a limited number of non-independent studies and provide an alternative calibration for ϕ based on an updated meta-analysis of the temperature-damage relationship.

of an equivalence between what he calls ‘multiplicative’ and ‘additive’ damage functions, where damages either hit consumption multiplicatively or are added additionally as an input to utility, as in our explicit relative prices model. Indeed, Weitzman (2010: 68) remarks that “the prototype multiplicative [damage function] used in DICE [implies an] elasticity of substitution [of] $\sigma = 1$ ”, that is it implies the Cobb-Douglas case.

Second, there is a relationship between substitutability on the production and the consumption side. In a simple model set-up with exogenous consumption streams, including limited substitutability between market and non-market goods in utility or limited substitutability between natural capital and other forms of production would be equivalent. Thus, while there is perfect substitutability in damages, the standard DICE includes non-market damages in net production such that there is an implicit equivalence of limited substitutability close to Cobb-Douglas in terms of goods. Yet, of course, the DICE model is very reduced form and does not feature different goods explicitly. Backing out the implicit degree of substitutability contained in the DICE model is therefore not straightforward. We will estimate the implicit degree of substitutability and thus of equivalent relative price changes in the standard DICE quantitatively in Section 3.

To replicate the results of Sterner and Persson (2008) within DICE-2016R2, we follow their approach of explicitly introducing relative prices. This includes (i) disentangling the consumption equivalents of Nordhaus into a two good representation; (ii) defining the development of the non-market good over time and (iii) specifying the initial value of the non-market good; (iv) disentangling market and non-market damages via appropriate calibration; and finally (v) raising the level of non-market good damages from Nordhaus’s 25 percent to 100 percent additional damages to ensure comparability with Sterner and Persson’s (2008) analysis. We extend the model such that utility depends not only on market but also on non-market goods, as in Equation (2). However, since a subsistence requirement was absent in the analysis of Sterner and Persson (2008), we set $\bar{E} = 0$ here and for the replication and analysis in Section 3.⁸ Thus, comprehensive consumption is now given by $\tilde{c}_t = [\alpha E_t^\theta + (1 - \alpha) c_t^\theta]^{1/\theta}$. The initial level of the

⁸We 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.

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:

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

Note that according to Equation (8) the social planner will optimize both c_t and E_t over time subject to climate and economic constraints of DICE. The evolution of the non-market good depends (inversely) on the square of atmospheric temperature T change compared to pre-industrial levels and the damage parameter ψ :

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

To ensure comparability with Sterner and Persson's (2008), we assume that non-market damages double climate damages to re-calibrate ϕ . Thus, we include an additional 100 percent non-market damages on top of market damages. Hence, for the baseline Nordhaus (2018) model we assume that market plus non-market damages are equal to 3.26 percent of global output for a temperature increase of 3°C.⁹ 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:

$$D_t^\kappa = \kappa T_t^2. \quad (10)$$

To account for the non-market damages on top of market damages à la Sterner and Persson (2008), the non-market climate damage parameter ψ is calibrated by comparing two different model specifications:¹⁰ On the one hand, a model in which non-market damages D_t^ψ for a given temperature increase are perfectly substitutable for damages on market goods and are included in consumption directly. On the other hand, a model

⁹The 100% mark-up for non-market damages makes our *calibration approach*, but *not the absolute magnitude* of non-market damages comparable to Sterner and Persson (2008). Sterner and Persson (2008) assume, based on an older DICE version, that both market and non-market damages amount to 1.05% of global output for a temperature increase of 3°C resulting in overall damages of 2.1%.

¹⁰See Barrage (2018) for an alternative approach to calibrating non-market damages.

in which damages are attributed to market goods D_t^κ and non-market goods D_t^ψ . The parameter ψ is calibrated as a residual, with $C_0 = E_0$ (see Appendix A.2), and depends in particular on non-market damage costs but also the degree of substitutability. Given this set-up, the *RPE* (cf. Equation 5) in DICE is given by:¹¹

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

Accordingly the *RPE* in DICE depends on the following components: First, the growth rate of the market good g_{c_t} , which is optimally determined by the environmentally-extended Ramsey Rule in DICE and thus depends on a number of key variables and parameters (see Dasgupta (2008) and Hänsel and Quaas (2018) for derivations in the single good case). Among others, it depends on the distributional parameters of the social welfare function: the rate of pure time preference, δ , and the elasticity of the marginal utility of comprehensive consumption, η . It is further driven by the net marginal productivity of capital, $Y_{K_t} - \xi$, where ξ denotes the proportional rate of capital depreciation. 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 .¹² Second, the *RPE* depends on the growth rate of the non-market good g_{E_t} , which is a function of non-market damages for a particular temperature increase, summarized in the damage parameter ψ , and the growth rate of atmospheric temperature g_{T_t} .¹³ Finally, the difference in the two good-specific growth driver categories is scaled by the degree of substitutability, θ , between market and non-market goods.

¹¹ 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.

¹² Total factor productivity $A_t = \frac{A_{t-1}}{1 - g_{t-1}^A}$ grows exogenously at a decreasing rate, with $g_t^A = g_0^A e^{-5t\tau^A}$, where τ^A can be interpreted as the exogenous decline rate of technological progress.

¹³ In the presence of a subsistence requirement ($\bar{E} > 0$) that we consider in Sections 4 and 5, the *RPE* has an additional term that magnifies the importance of the growth rate of non-market goods on the *RPE* (see Equation 5): $RPE_t = (1 - \theta) \left[g_{c_t}(\delta, \eta, \dots) + \frac{2\psi T_t^2 g_{T_t}}{(1 + \psi T_t^2)} \left(\frac{E_0}{E_0 - \bar{E}(1 + \psi T_t^2)} \right) \right]$.

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).¹⁴ Industrial emissions and atmospheric temperature change are climate policy measures often referred to in science and policy circles, while the SCC is widely used by governmental bodies to inform carbon pricing.

We draw all parameter inputs from Nordhaus’s (2018) DICE-2016R2, except for those that concern the explicit introduction of the non-market good—the preference share parameter α , the degree of substitutability θ as well as the magnitude of non-market damages—which are based on Sterner and Persson (2008). Table 1 provides an overview of the parameter specifications used in the Sterner and Persson case, which we abbreviate as “S&P-*RPE*”. Figure 1 depicts how the S&P-*RPE* evolves over time from the year of 2020 to 2100, and how it impacts industrial CO_2 emissions, temperature change and the SCC.¹⁵ 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 9), and in relative terms as compared to market goods throughout the planning horizon, the change in relative scarcity, as measured by the relative price change, falls over time.

¹⁴The 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).

¹⁵The 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.10.

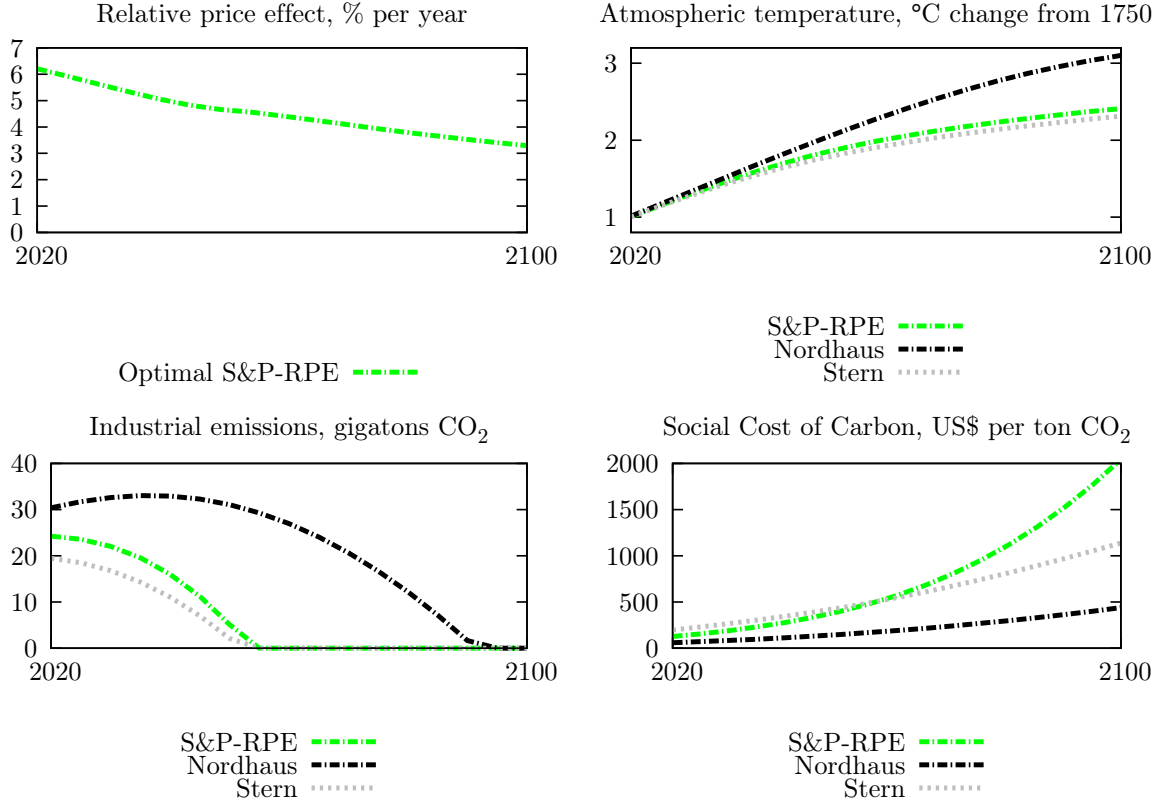


Figure 1: Relative price effect of non-market goods (RPE) and comparison of climate policy paths. The green line shows the relative price changes according to the Sterner and Persson (2008) case, *S&P-RPE*. The black line depicts the ‘Nordhaus’ comparison case without explicit relative price changes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

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

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

* N denotes values taken from Nordhaus (2018), while S&P denotes Sterner and Persson (2008).

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

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

Moreover, Figure 1 compares this *S&P-RPE* to two cases that do not change the DICE-2016R2 approach of (only implicitly) dealing with relative prices but that differ in their assumptions about a key discounting parameter—the rate of pure time preference, δ . First, we compare the *S&P-RPE* case to the optimal climate policy trajectories in the ‘Nordhaus’ case.¹⁶ According to Sterner and Persson (2008), this provides the direct comparison case to judge the impact of introducing relative prices. To capture the

findings of Sterner and Persson (2008) within the DICE-2016R2 modelling framework and to get an idea of how substantial the impact of the S&P-*RPE* is, we also consider another case with Stern’s (2007) lower rate of pure time preference of $\delta = 0.1$ percent.

The lower-left panel of Figure 1 depicts the time path for industrial emissions, which corresponds to the results figure in Sterner and Persson (2008, p. 70).¹⁷ In DICE-2016R2, and with the comparable assumption regarding non-market climate damages based on Sterner and Persson (2008), emissions peak in 2035, while they did not peak but increased until 2100 in the older DICE-2006 version. When considering the S&P-*RPE*, industrial emissions decrease immediately and become almost zero in 2055. Full decarbonization of the global economy is achieved as early as when using Stern’s (2007) rate of pure time preference. Yet, cumulative emissions are higher when considering the S&P-*RPE* as compared to the optimization under Stern’s lower δ of 0.1 percent. The upper-right panel of Figure 1 shows the development of atmospheric temperature change. We find that it stabilizes around 2.63°C with the S&P-*RPE* but increases until 3.44°C in the ‘Nordhaus’ case. For comparison, using the rate of pure time preference of 0.1 percent (‘Stern’) leads to a peak atmospheric temperature of 2.52°C.

These emission and temperature developments translate into substantial differences between the time paths of the SCC (cf. lower-right corner of Figure 1). Comparing the S&P-*RPE* to the ‘Nordhaus’ case, we find that the SCC is 112 (365) percent higher in 2020 (2100) in the S&P-*RPE* case. Comparing ‘Nordhaus’ and ‘Stern’, we find that the latter leads to a SCC that is 229 (159) percent higher in 2020 (2100). Overall, Figure 1 underscores the need to distinguish between standard discounting and relative price changes as related but distinct drivers of climate policy evaluation.

¹⁶Climate damages are higher in the ‘Nordhaus’ run than in Nordhaus (2018) for comparability with Sterner and Persson (2008). In Appendix A.5, we perform the same analysis with Nordhaus’ (2018) estimate of lower non-market damages and briefly relate to it in Section 3.2.

¹⁷Following Nordhaus (2018), we depict industrial emissions in terms of CO_2 , not carbon. There are a number of changes between the DICE-2006 that Sterner and Persson (2008) refer to and DICE-2016R2. Therefore we obtain a different profile of industrial emissions in Figure 1 as depicted in their key results figure. These changes, among others, include lowering the rate of pure time preference and including the possibility of negative emissions.

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

The discussion of Figure 1 naturally leads to the question how we can meaningfully compare the stringency of climate policy across different optimization runs in order to make statements such as ‘introducing relative prices yields an “even Sterner” review’ (Sterner and Persson 2008)? Such comparisons depend on how the following questions are answered: First, what is the comparison metric? Second, what is the comparison variable? Third, what is the baseline specification regarding welfare parameters against which to compare the influence of introducing relative prices? Fourth, how can we deal with altered savings dynamics due to introducing the non-market good explicitly. We will address these questions in turn.

First, Sterner and Persson (2008) base their finding of an “even Sterner” report on an examination of yearly carbon emissions. In their comparison within DICE-2006, yearly emissions in the S&P-*RPE* run were initially in-between the ‘Nordhaus’ and ‘Stern’ comparison cases, yet the S&P-*RPE* path of optimal emissions led to an earlier decarbonization as in the ‘Stern’ case. In DICE-2016R2 this is no longer the case: Initial emissions are still in-between the ‘Nordhaus’ and ‘Stern’ comparison cases but the S&P-*RPE* path does not lead to earlier decarbonization as compared to the ‘Stern’ case. Irrespective of these differences due to changes in the DICE model over time, using yearly emissions is not a clear-cut comparison metric because emission paths can cross. With crossing of emission paths it may be that even if a model run leads to earlier decarbonization, it can entail higher cumulative emissions or a higher peak temperature. Unambiguous comparison metrics would thus be peak atmospheric carbon concentration or peak temperature achieved under a given model parameterization.

When we use peak temperature change relative to pre-industrial levels as the comparison metric to examine the impact of introducing the S&P-*RPE* as compared to changes in the rate of pure time preference, we find the following: Considering relative prices in the specification of Sterner and Persson (2008) is equivalent to reducing the pure time preference from Nordhaus’s (2018) value of 1.5 percent by 1.2 percentage points, i.e. a model run with a δ of 0.3 percent yields the same peak temperature as obtained when

introducing the S&P-*RPE*. Although this shows that explicitly considering relative prices does not yield ‘an even Sterner review’, as the reduction is lower than 1.4 percentage points, which would be comparable to using Stern’s rate of pure time preference, it still represents a very substantial impact on optimal climate policy.

Second, what is the appropriate comparison variable? How meaningful is the direct comparison of the S&P-*RPE* with the ‘Nordhaus’ and ‘Stern’ cases given that explicitly introducing relative prices entails a number of changes to the DICE framework, which already implicitly deals with relative price changes? The cleanest comparison between a model with relative prices and models that only differ in their rate of pure time preference would be within a model that explicitly includes the *RPE* to a case with perfect substitutability ($\theta = 1$), as the *RPE* vanishes in this case (cf. Equations 5 and 11). We therefore examine the effect of changing the degree of substitutability only, and compare its impact on optimal climate policy to the rate of pure time preference, which is perhaps the most vividly discussed parameter in climate economics. As climate policy comparison measure we use the peak temperature change relative to 1900 that is reached in any given optimization run, as this yields a unique maximum.

Figure 2 depicts the optimal atmospheric peak temperature obtained over the whole planning horizon as a function of the rate of pure time preference, δ , for different models and degrees of substitutability, θ . The bold black line shows the comparison case of perfect substitutability and thus without relative prices.¹⁸ 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

¹⁸When 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.

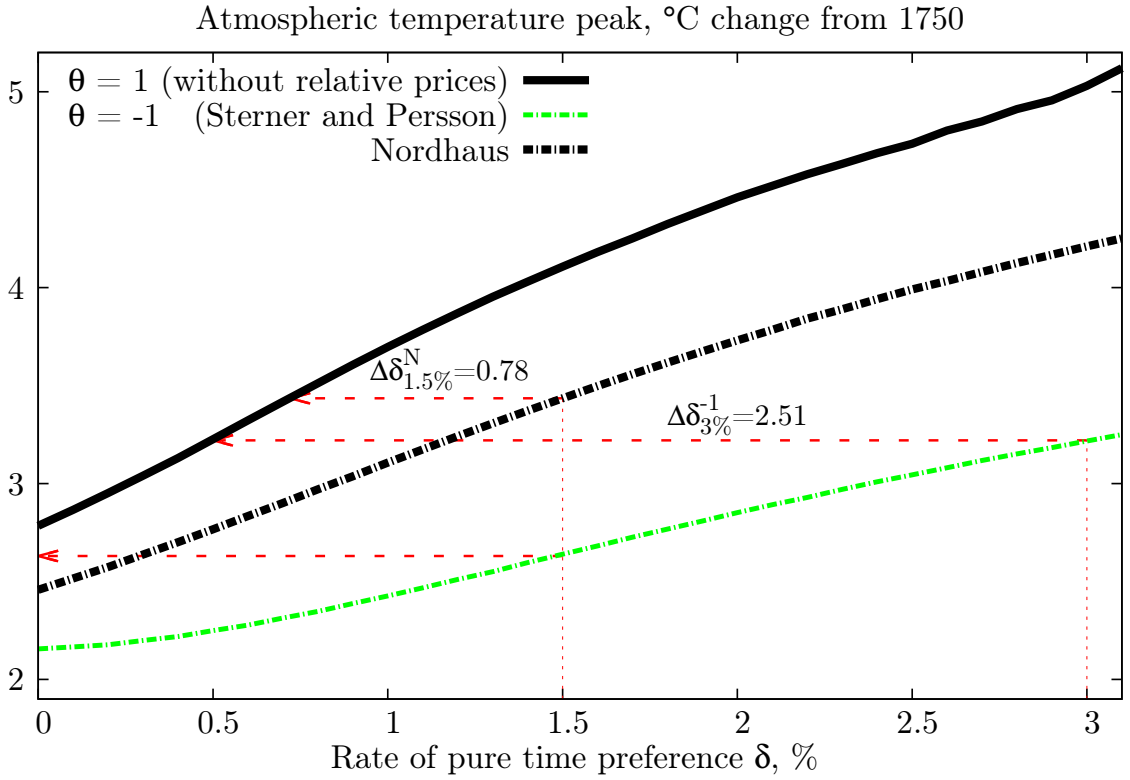


Figure 2: The comparative influence of introducing relative prices on peak temperature. The Figure depicts peak temperature as a function of the rate of pure time preference, δ , for different degrees of substitutability, θ . The solid black line shows the comparison case of perfect substitutability, that is without relative prices. The green line depicts the substitutability assumption of Sterner and Persson (2008), and the dashed black line the ‘Nordhaus’ case. A model run with relative prices can be compared to a run without but with a higher δ such that peak temperature is the same across both runs. For example, the implicit degree of limited substitutability contained in the ‘Nordhaus’ case is equivalent to a model without relative prices if we decrease δ by $\Delta\delta_{1.5\%}^N = 0.78$ percentage points.

of substitutability, θ , of the considered *RPE*. For example, introducing relative prices with Cobb-Douglas substitutability ($\theta = 0$) at a baseline of Nordhaus’s (2018) pure rate of time preference of $\delta = 1.5$ is equivalent in terms of optimal peak temperature to decreasing δ by $\Delta\delta_{1.5\%}^0 = 0.6$ 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 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-2016R2 model, as our analysis considers higher damages for comparability with Sterner and Persson (2008). In Appendix A.5 we re-run the analysis within the lower damages of the standard DICE-2016R2 model. 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 year 2020 (2100) is 3.56 (1.66) percent. The corresponding $\Delta\delta_{1.5\%}^{0.02}$ in DICE-2016R2 would be 0.33 percent. Thus, the ‘Nordhaus’ case with higher damages and also the standard DICE-2016R2 model contain sizable implicit relative price effects. This implies that one has to be very careful in interpreting effects when explicitly introducing relative prices to the DICE model. Our analysis thus reveals that explicitly introducing a RPE into DICE may lead to a smaller effect than expected since the standard Nordhaus case already implicitly includes a sizable RPE . In particular, if one considers cases in which market and non-market goods are considered as well substitutable, explicitly introducing a RPE 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” finding. 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) compared to a run with perfect substitutability. 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. Viewed as such, the effect of considering relative prices with the complementarity assumption of Sterner and Persson (2008) may thus be considered as even stronger than has previously been suggested.¹⁹

Third, we address the question of what is the appropriate baseline specification, in terms of social welfare parameters. The analysis depicted in Figures 1 and 2 is built on the baseline specification of the most recent DICE version from Nordhaus (2018), with the exception of the parameters needed to introduce relative prices explicitly as well as higher damages as compared to Nordhaus (2018) to allow for better comparability with Sterner and Persson (2008). Yet, which baseline parameters we choose—for example regarding the welfare parameters δ and η —matters for the effect sizes we obtain when making comparison across model runs. If we use the higher (initial) rate of pure time preference of 3 percent that was, for example, used in earlier DICE versions, we would find that introducing relative prices with the complementarity assumption of Sterner and Persson (2008) is equivalent in terms of peak temperature as reducing the rate of pure time preference from 3 percent by $\Delta\delta_{3\%}^{-1} = 2.5$ 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.

Fourth, it is an open question how comparable the cases considered in Figures 1 and 2 are in terms of their implied savings and investment dynamics. At a fundamental level, these Figures compare different models: a usual DICE model, in which non-market damages are treated as market damages that hit production, and the extended model in

¹⁹Appendix A.6 provides a table with a more systematic exploration of how different degrees of substitutability, θ , translate into values for this equivalent reduction in pure time preference, $\Delta\delta$.

which non-market damages hit a non-market good that is explicitly featured as a source of utility. Although both models are calibrated to entail the same base year welfare costs at $T = 3^{\circ}\text{C}$ warming (cf. Appendix A.2), the explicit introduction of non-market goods in the welfare function (Equation 8) changes the dynamics of the extended model. Specifically, the optimal path of market goods consumption and the associated savings dynamics will be different compared to the standard DICE version where non-market damages are treated as market damages and thus reduce future output of the comprehensive consumption good. In most publications on the DICE model, consumption is introduced as comprehensive consumption that “should be viewed broadly to include not only food and shelter but also nonmarket environmental amenities and services” (Nordhaus 2008: 34). Yet in other publications (Nordhaus 2018), the comprehensive nature is not mentioned. While the calibration of consumption and savings is based on observed market information or forecasts, the dynamics of the model do depend on non-market damages. Specifically, Nordhaus (2018) deals with non-market goods by scaling up the damage coefficient (see Equation 7) and thus implicitly assumes the same savings dynamics for market and non-market goods. It is thus somewhat ambiguous whether savings dynamics in the standard DICE model’s business-as-usual case should be viewed as only pertaining to market good dynamics. Exploring the effects of re-calibrating savings dynamics is thus warranted. The key mechanism behind the different savings dynamics is that the effective elasticity of marginal utility of market consumption or intertemporal elasticity of substitution for the market consumption good changes when the non-market good is introduced explicitly. This complicates comparing results across models as the business as usual paths for market consumption and savings will differ. To ensure that the standard DICE and the extended model yield savings dynamics that are as comparable as possible, we re-calibrate the latter. For this, we adjust the elasticity of marginal utility of comprehensive consumption, η , which concerns the comprehensive consumption bundle of both market and non-market goods, in each period such that the effective elasticity of marginal utility of market consumption takes the value of 1.45, as in DICE. While the analysis so far has not considered how the introduction of non-market goods affects market dynamics, the re-calibration as-

sumes that business-as-usual market consumption and savings dynamics are unaffected by introducing non-market goods. Both approaches are extreme but illuminating cases.

The re-calibration proceeds as follows: From Equation 8 we can derive, following Gerlagh and van der Zwaan (2002), Hoel and Sterner (2007), and Traeger (2011), the effective elasticity of marginal utility of market consumption at each point in time t , hereafter denoted as η_{C_t} , by making use of the value share of the market consumption good $\beta_t^* = \frac{(1-\alpha)c_t^\theta}{\alpha E_t^\theta + (1-\alpha)c_t^\theta}$ (see Appendix A.4 for a derivation):

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

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

By using Equation 12, we can now re-calculate the elasticity of marginal utility of comprehensive consumption such that the initial effective elasticity of marginal utility of market consumption is given as in the DICE model, with $\eta_{C_0} = 1.45$. With $\theta = -1$, $E_0 = c_0$, and $\alpha = 0.1$, the re-calculation yields $\eta = 1.389$ in the initial period. Similarly we can re-calibrate η at each time step such that η_{C_t} remains at 1.45 for all time steps t , yielding a time path of $\eta(t)$ that makes the two models as comparable as possible in terms of their business as usual market dynamics. For this, we fix the time paths of market consumption and investment to be the same as in the standard DICE version to calculate the respective $\eta(t)$ under different degrees of substitutability θ . This allows us to reproduce Figure 2 with the re-calibrated dynamics (see Figure A.2 in the Appendix). The time-path of $\eta(t)$'s that yields $\eta_{C_t} = 1.45 \forall t$ under $\theta = -1$ (i.e. Sterner and Persson (2008) and under $\theta = 1$ (i.e. perfect substitutability) are provided in Appendix A.4.²⁰

²⁰Note that this procedure yields the same business-as-usual market consumption paths in both models, but not exactly the same savings rates. The reason is that output-reducing climate damages are separated into market and non-market damages in the extended model and only market damages reduce output, while non market damages indirectly affect output through the social welfare function. In the standard DICE model both market and non-market damages directly reduce output. Hence, the

We find that the re-calibration has only a minor effect on the model without relative prices, which now features slightly lower peak temperatures for low rates of pure time preference (see Figure A.2 in the Appendix). Specifically, peak temperature for a pure time preference rate of 0.01 is 3.62°C as compared to peak temperature of 3.70°C in the model without re-calibration. Furthermore, the implicit degree of substitutability contained in the ‘Nordhaus’ case is now equivalent to a model without relative prices if we decrease δ by $\Delta\delta_{1.5\%}^N = 0.70$ percentage points. This compares to a value of $\Delta\delta_{1.5\%}^N = 0.78$ percentage points in the comparison without re-calibration.

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

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

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

We now perform a sensitivity analysis for how the *RPE* depends on its drivers at two points in time: the year 2020 as the next ‘short-run’ planning step and the year 2100 for a ‘longer-run’ picture. First, we consider (i) the degree of substitutability between market and non-market goods. Next, we study exogenous drivers that are related to the growth rate of the non-market good: (ii) the magnitude of non-market damages, and

direct effect of climate damages on output in the standard DICE model is different compared to our model and resulting savings rates are not quite be the same.

(iii) the size of the subsistence requirement for non-market goods that we consider from now (cf. Equation 5).²¹ Furthermore, we analyze the main drivers of the growth rate of market goods: (iii) the rate of pure time preference, (iv) the elasticity of the marginal utility of comprehensive consumption and (v) the rate of technological progress.

Substitutability

A key driver of the *RPE* is the degree of substitutability between market and non-market goods. The upper panel of Figure 3 depicts the effects of varying the substitution parameter, θ , along a range of -2.5 to 1. This range encompasses all values used in the literature on relative price changes of non-market goods and ecological discounting. While the applied theory literature relies on expert judgement concerning the degree of substitutability empirical estimates are based on an indirect relationship between the income elasticity of willingness-to-pay (WTP) for non-market goods, ξ , and the degree of substitutability (Baumgärtner et al. 2015, Drupp 2018).²² The applied theory literature assumes a Cobb-Douglas or a complementarity relationship, with $\theta = 0$ (Gollier 2010), $\theta = -0.333$ (Kopp et al. 2012) and $\theta = -1$ (Hoel and Sterner, Sterner and Persson 2008). In contrast, indirect empirical evidence suggests substitutability. While Baumgärtner et al. (2015) rely on a single meta-study estimate on WTP for biodiversity conservation by Jacobsen and Hanley (2009), which indicates a θ of 0.62, Drupp (2018) gathers indirect evidence on substitutability for environmental goods from 18 valuation studies. He finds

²¹The additional determinants of the value share of non-market goods, α and E_0 , do not impact the relative price effect directly (cf. Equation 5). In Appendix A.7 we show that they only have a minor impact on the *RPE*. While the System of Environmental-Economic Accounting (SEEA) strives to include Experimental Ecosystem Accounting (EEA), it is unclear whether its emphasis on exchange values can adequately capture the value (share) of non-market goods (Obst et al. 2016, Droste and Bartkowski 2018). In any case, there is no empirical data yet to inform a parametrization of α or E_0 at the global level (Obst, personal communication). Values of α for non-market environmental goods used in the literature range from 0.1 to 0.29 (Gollier 2010, Hoel and Sterner 2007, Kopp et al. 2012). Sticking to the value of $\alpha = 0.1$ for all non-market goods is therefore a conservative choice.

²²Specifically, with CES preferences, there is a direct inverse relationship between the income elasticity of WTP, the substitutability parameter and the elasticity of substitution: $\xi = 1 - \theta = \frac{1}{\sigma}$. With our subsistence requirement utility setting, $\xi = 1 - \theta$ still holds (Drupp 2018).

a mean estimate [range] for the income elasticity of WTP, ξ of 0.43 [0.14, 1.16], which corresponds to a substitutability parameter, θ , of 0.57 [-0.16 to 0.86].

Here, we not only consider environmental goods, but non-market goods more broadly, which also encompass health-related services, for instance. To gather a more comprehensive empirical evidence base for this broader notion of non-market goods in a replicable fashion, we perform a keywords-based search strategy in SCOPUS. Within the title, abstract and keywords, we search for “income elasticit*” as well as “WTP”, “willingness to pay”, “willingness-to-pay”, “VSL”, “Value of a Statistical Life”, or “Value of a Life”. As of November 5th 2019, this yielded 81 publications.

We then perform a manual relevancy check and exclude papers that do not provide usable additional evidence for the substitutability of non-market goods. Specifically, we exclude studies that (i) value market goods, (ii) are not available in English, (iii) focus on the income elasticity of demand instead of the income elasticity of WTP,²³ and (iv) do not provide estimates themselves. This latter category includes theoretical contributions, literature reviews and studies that apply estimates from the literature, such as for benefit transfer. We thus only include studies that gather their own primary data, conduct a meta-study or use primary data from another source to estimate income elasticities of WTP. This procedure yields 40 relevant and usable studies, with 21 focussing on valuing environmental goods and 19 focussing on health and cultural goods.

Some studies provide multiple income elasticity estimates for diverse reasons.²⁴ As opposed to weighting studies by their number of estimates, we treat all studies equally and consider only one (average) estimate per study.²⁵ Thus, for studies with multiple estimates, we compute the mean of all their reported income elasticities of WTP. We then translate these mean income elasticities into mean substitutability parameters.

²³Flores and Carson (1997) show that these two elasticities are related but distinct and the income elasticity of WTP is the relevant measure for non-market public goods.

²⁴For instance, these studies often use a number of econometric specifications where it remains unclear which of them is superior, they investigate preferences of different groups of respondents, or they study WTP for slightly different goods or different provisioning levels.

²⁵A different weighting scheme would not much affect the mean substitutability parameter. For instance, if we considered each estimate as an independent observation, the mean θ would be 0.28.

Table 2: Estimates of the substitutability parameter θ derived from valuation studies*

Type of good	N**	Substitutability parameter θ			
		Mean	St.Dev.	Min.	Max.
Environmental goods: Nature conservation	6	0.46	0.28	-0.02	0.75
Environmental goods: Water or air quality	9	0.33	0.39	-0.42	0.74
Environmental goods: Climate change mitigation	3	0.46	0.43	0.04	0.90
Environmental goods: All others	3	0.65	0.30	0.32	0.90
Cultural goods	3	-0.18	0.70	-0.98	0.34
Health improvements	5	0.58	0.32	0.10	0.86
Reduction in mortality risk	11	-0.21	1.00	-2.30	0.53
Environmental goods	21	0.43	0.35	-0.42	0.90
Health and cultural goods	19	0.00	0.87	-2.30	0.86
All non-market goods	40	0.23	0.68	-2.30	0.90

* Table A.2 in Appendix A.8 provides an overview of the 40 individual studies.

** N denotes the number of studies included per category. In case a study provides multiple estimates, we use the mean of these individual estimates.

Additionally, we gather key co-variates, including the type of non-market good.

Table 2 reports the resulting estimates for the substitutability parameter θ , including mean, standard deviation as well as the min-max range of the individual study estimates, disaggregated by different types of goods. When first examining disaggregated good types we find that most provide a positive mean substitutability parameter, but also that the majority of min-max ranges contain estimates indicating both substitutes and complements. Distinguishing environmental from other non-market goods, that is those relating to health and cultural goods, yields two striking findings. First, environmental goods are on average less substitutable as compared to the previous estimate by Drupp (2018). Second, health and cultural goods are, on average, considered as Cobb-Douglas vis-a-vis market goods. When we aggregate all non-market goods, we find a considerable min-max range for θ , extending from -2.3 to 0.9. The mean estimate of θ is 0.23, thus indicating a mild substitutive relationship between non-market and market goods. This is in contrast to the mean estimate from expert judgements we derive from the applied theory literature (Gollier 2012, Kopp et al. 2012, Sterner and Persson 2008), which yields $\theta = -0.44$, and a min-max range from -1 to 0.²⁶

²⁶For the computation of the mean value from the applied theory literature, we do not include the

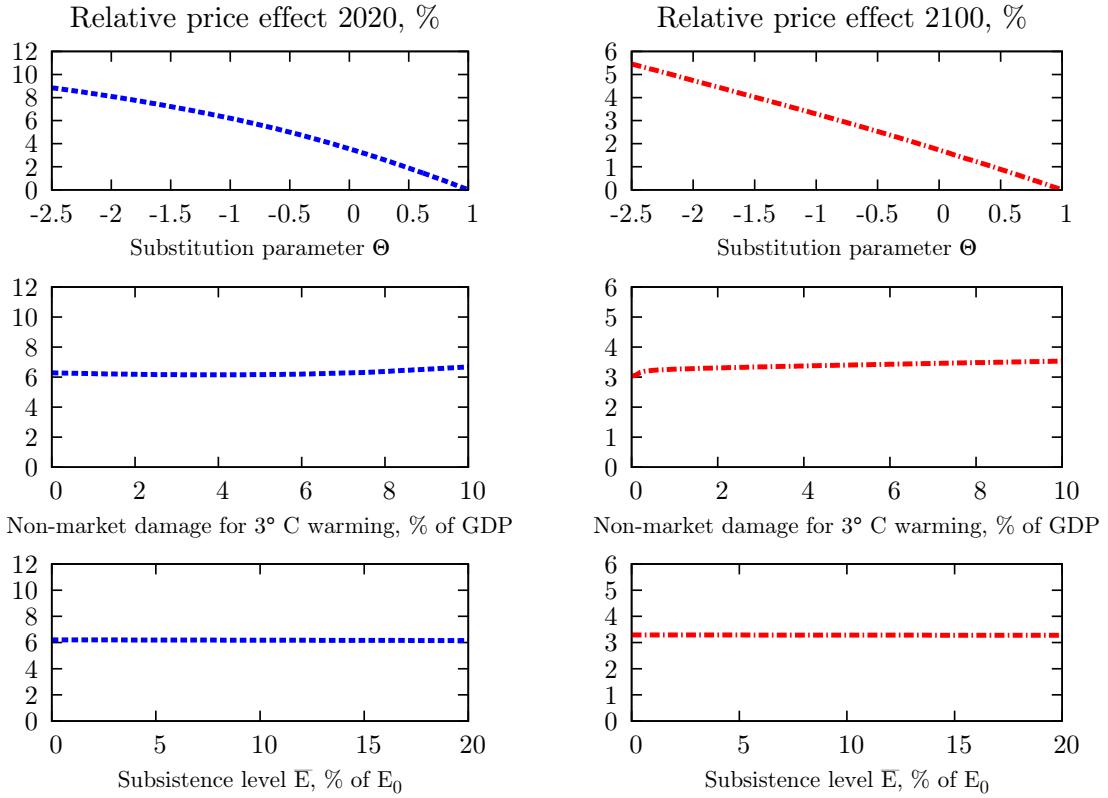


Figure 3: Drivers of the relative price effect (I). Top to bottom: The impact of substitutability, non-market damages and subsistence consumption on the *RPE* in 2020 (left) and in 2100 (right).

Figure 3 confirms that the degree of substitutability is a crucial driver of the *RPE* in both the ‘short-run’ (2020) and ‘longer-run’ (2100). Assuming perfect substitutes eliminates the *RPE*, while the *RPE* in 2020 increases to 6.20 percent for the baseline of $\theta = -1$ (Stern and Persson 2008), and to 8.84 percent for $\theta = -2.5$. The respective *RPE* in 2100 is 3.29 (5.46) percent for $\theta = -1$ ($\theta = -2.5$) and reduces to 1.73 (1.34) percent for a value of θ of 0 (0.23).

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 Stern 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 (2018) considers non-

value from Hoel and Stern (2007) to avoid potential double counting with Stern and Persson (2008).

market damages as an additional damage component, amounting to 0.49 percent of GDP under 3°C warming. As we are not aware of empirical evidence on the climate damages share on non-market goods, we draw on expert survey data. Nordhaus (1994) surveyed 19 experts on the economic impacts of climate change. These experts forecast that 38 percent of damages should be attributed to non-market goods (for a 3°C warming until 2090). More recently, Howard and Sylvain (2015: 34) extended upon this study and surveyed a larger number of experts on their “best guess of the percentage of total impacts (market plus non-market) that will be borne by the market sector”. The best guess of 213 respondents is that 49.76 percent of damages accrue to non-market goods. This would be in line with the doubling of market-damages as assumed by Sterner and Persson (2008). A standard deviation of 28 percent reveals substantial heterogeneity in responses. Figure 3 depicts the effect of non-market damages on the *RPE* for a large range of non-market damages under 3°C warming in the year 2020, spanning from 0 to 10 percent of GDP. In absolute terms the *RPE* remains almost flat at 6 percent. It decreases slightly from 6.28 to 6.15 for non-market damages of up to 4% and increases thereafter reaching 6.67 for non-market damages of 10%. In the year 2100 we find that the *RPE* ranges from 3.03 to 3.53. Why is it—perhaps surprisingly—the case that the non-market damages scaling parameter has such a negligible effect on the *RPE*? In the *RPE* equation (11), the magnitude of non-market damages scales the effect of temperature change to determine the growth rate of non-market goods. Due to the optimal management, the decline of the non-market good through temperature change is dampened, such that the growth rate of the non-market good is close to zero. As a consequence higher non-market damages only marginally change the *RPE*.

Non-market good subsistence consumption

The subsistence requirement for the consumption of non-market goods refers to a distinct amount that the representative agent is not willing to substitute by the consumption of material goods. In our case the subsistence need basically reflects a boundary for the atmospheric temperature, which is the only driving force of the evolution of non-market goods. Figure 3 shows that the *RPE* is not sensitive to changes in the stringency of the subsistence level \bar{E} due to the optimal management that ensures that the non-market

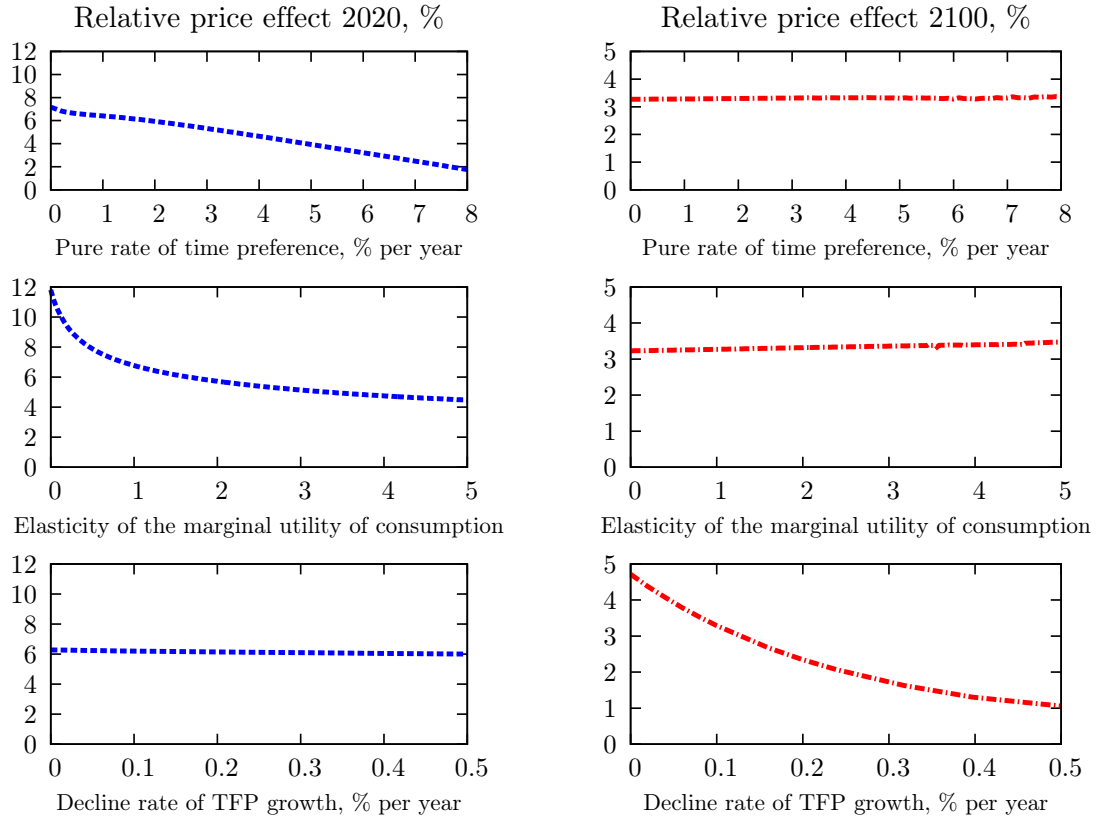


Figure 4: Drivers of the relative price effect (II). Top to bottom: rate of pure time preference, elasticity of the marginal utility of comprehensive consumption, and decline rate of total factor productivity growth—and their impact on the *RPE* in 2020 (left) and in 2100 (right).

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*.²⁷ In the year 2100 we find qualitatively the same as for 2020: the *RPE* declines from 3.29 to 3.28 when increasing the subsistence requirement.

Rate of pure time preference

The rate of pure time preference δ , measures how the utility of the representative agent at different points should be weighted in relative terms. A positive rate implies that the utility of future agents is discounted just because they live in the future. There is considerable disagreement on what constitute plausible and justifiable values for the rate

²⁷Additionally, \bar{E} slightly impacts the *RPE* also indirectly via the calibration of the non-market good climate damage coefficient ψ (Equation A.8), with $\partial\psi/\partial\bar{E} \leq 0$ for $\theta \leq 1$.

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.²⁸ This range is taken from an expert survey on the determinants of the social discount rate by Drupp et al. (2018). Not surprisingly the *RPE* in 2020 falls with the rate of pure time preference from 7.17 percent for $\delta = 0$ percent to 1.76 percent for $\delta = 8$ percent per year. Nordhaus's (2018) assumption of $\delta = 0.015$ corresponds to a *RPE* of 6.20 percent. In the year 2100, the rate of pure time preference has almost no effect on the *RPE*: the corresponding *RPE* range is only 3.27 to 3.37 percent, i.e. the sensitivity is negligible but qualitatively the influence of the rate of pure time preference on the *RPE* reverses.

Elasticity of the marginal utility of comprehensive consumption

The elasticity of the marginal utility of (comprehensive) consumption, η , is a measure of inequality aversion with respect to the intertemporal distribution of inclusive consumption \tilde{c} . Its range from 0 to 5 in Figure 4 considers all views from the expert survey by Drupp et al. (2018). It also encompasses values used in the prominent literature, such as unity (Stern 2007) and 1.45 as used in DICE (Nordhaus 2018). We find that the *RPE* decreases with η over its range from 11.81 to 4.46 percent in 2020. In 2100, the *RPE* increases with η from 3.23 to 3.48 percent. The reversed pattern is thus the same as for the rate of pure time preference, but overall the *RPE* is more sensitive to changes in the elasticity of the marginal utility of comprehensive consumption.

Decline rate of total factor productivity

The growth rate of material consumption is in particular driven by total factor productivity (TFP), $A_t = \frac{A_{t-1}}{1-g_{t-1}^A}$, 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 (2018).²⁹ We find

²⁸Note that for computational reasons we approximate 0 by 0.000001 percent.

²⁹Alternatively, 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.

that the *RPE* in 2020 (2100) decreases from 6.28 (4.72) percent for $\tau^A = 0$ percent to 6.00 (1.02) percent for $\tau^A = 0.5$ percent. The baseline case of Nordhaus (2018) implies a decline rate of TFP growth of around 0.1 percent per year corresponding to a *RPE* in 2020 (2100) of 6.20 (3.29) percent. A lower decline rate of TFP growth τ^A makes non-market goods scarcer relative to human-made consumption goods as global GDP is scaled up by higher exogenous growth in TFP. However, due to the shape of the dynamics of TFP, the effect on relative prices is more pronounced in 2100 and the *RPE* decreases more than linearly in the decline rate of TPF growth per year.

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

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

Based on our systematic study of determinants of relative price changes of non-market goods, this section examines what might be a plausible range and a best-guess central calibration for each determinant of the *RPE* based on available evidence. To compare model runs, and thus the effect of the *RPE* on the cost-benefit analysis of climate policy, we focus on peak temperature as the comparison metric and make comparisons against the case of perfect substitutes, as this causes the *RPE* to vanish.

In contrast to the partial sensitivity analysis in Section 3, we now perform a Monte Carlo analysis with 1000 draws to construct plausible ranges of the determinants

of relative price changes and specify a central calibration as a new baseline. For the lower and upper bounds, we consider 95 and 66 percentile ranges around the mean. For the distribution of the individual determinants, we make the following assumptions: We assume a Normal distribution for the degree of substitutability, for which the mean expert value, $\theta = -0.44$, and the mean empirical estimate from our own data presented in Table 2, as $\theta = 0.23$, encompass the 95 percent confidence interval, with an overall mean of $\theta = -0.11$. For non-market damages, we draw on the expert responses from the survey by Howard and Sylvain (2015) and assume a Normal distribution with mean and standard deviation taken from their expert data.³⁰ For δ and η we use the mean expert recommendations from the survey of Drupp et al. (2018) for the central calibration. To construct plausible range we randomly draw 1000 times from the sample of expert recommendations and use this data for the 1000 Monte Carlo runs (see Appendix A.10.4 for the data). Finally, for the decline rate of TFP, τ^A , we assume a Normal distribution with the mean given by the value from DICE-2016R2. The 95 percent confidence interval is calculated such that it is bounded from below by a zero decline rate.

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

Figure 5 depicts the central calibration run (blue dashed line), the comparison run with perfect substitutability ($\theta = 1$) and thus without relative price changes (black solid line), and the plausible range including both the 95 and the 66 percentile range of the *RPE* (blue-shaded area). These plausible ranges imply different potential worlds, including different savings rates among others. Further, Figure 5 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.

³⁰We truncate the distribution to exclude negative values for non-market damages and τ^A .

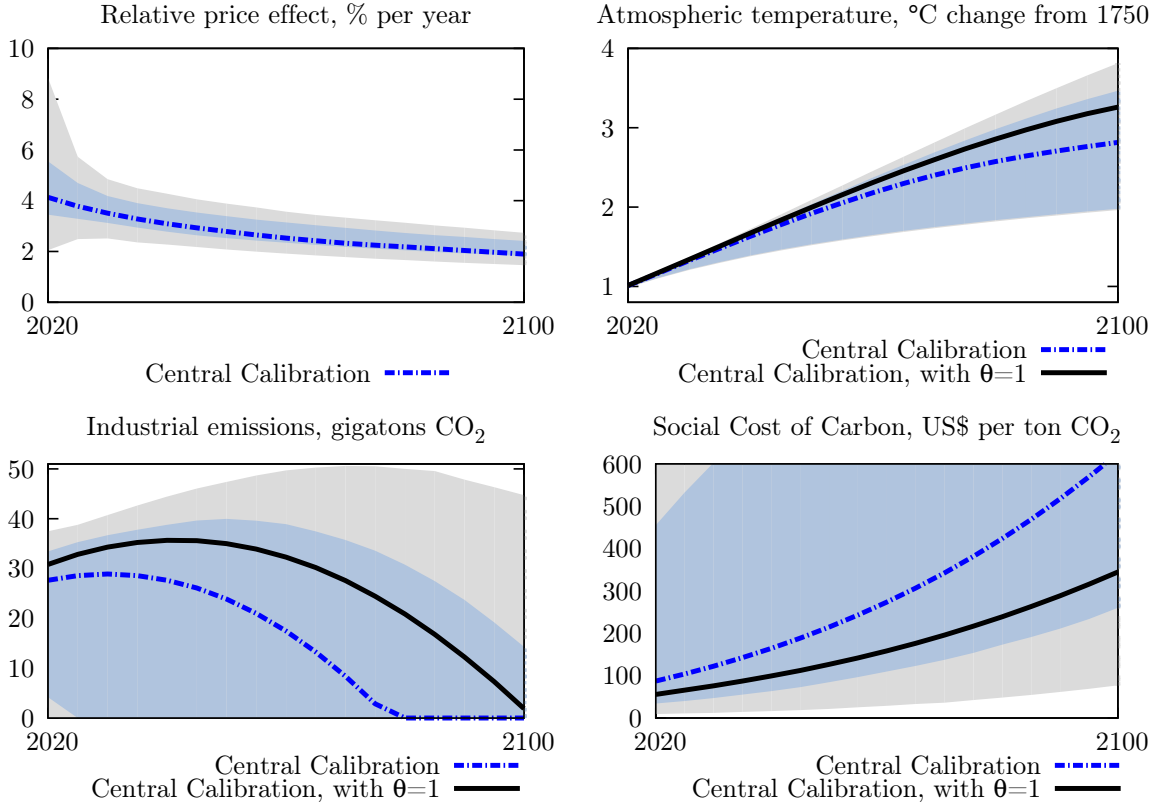


Figure 5: Relative price effect of non-market goods (RPE) and comparison of climate policy paths for plausible ranges and a central calibration of the drivers of relative price changes. The blue line represents the central calibration of the RPE , while the black line depicts the perfect substitutability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

Table 3: Parameter specifications for the range and central calibration of the RPE

Parameter	Source	Distribution*	Central Calibration
θ	Own calculations	Normal; $\mu = -0.11, \chi = 0.17$	-0.11
NMD^{**}	Howard and Sylvain (2015)	Normal; $\mu = 1.65\%, \chi = 4.15\%$	1.65%
\bar{E}/E_0	Assumption	Normal; $\mu = 10\%, \chi = 5.10\%$	10%
δ	Drupp et al. (2018)	Raw expert data	1.10%
η	Drupp et al. (2018)	Raw expert data	1.35
τ^A	Nordhaus (2018)	Normal; $\mu = 0.1\%, \chi = 0.05\%$	0.1%

* We denote the standard deviation with χ as σ is already defined as the elasticity of substitution.

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

Figure 5 shows that the 95 percentile plausible range for relative price changes is substantial: The RPE ranges between 2.05 and 8.83 percent in 2020 and between 1.46 and 2.74 percent in 2100. Peak atmospheric temperature ranges from 2.16°C to 5.07°C.

The SCC increase from 9.34 to 77.05 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.³¹ 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 66 percent interval (see the blue-shaded area in Figure 5), we find that the *RPE* ranges from 3.45 to 5.55 percent in 2020 and from 1.82 and 2.42 percent in 2100, and peak atmospheric temperature ranges from 2.17°C to 4.04°C. While there is no run within the 66 percent range with zero emissions in 2020, higher emission runs drop out in comparison to the 95 percent interval. For the SCC the range changes such that the minimum SCC increases to 34.24 (260.11) US\$ in 2020 (2100).

For the central calibration, we find that the *RPE* decreases from 4.13 percent in 2020 to 1.90 percent in 2100. Our central calibration leads to a decarbonization in the year 2080 and a peak temperature of 3.09°C. The SCC in 2020 is 87.18 US\$ per ton of CO_2 and increases up to 624.24 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 56 (81) percent in the year 2020 (2100). Peak temperature in the case without the *RPE* is 3.68°C, that is temperature peaks at 0.58°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 (cf. Section 3.2), we find that introducing relative prices with the degree of substitutability of our central calibration is equivalent to reducing the rate of pure time preference by $\Delta\delta_{1.1\%}^{-0.11} = 0.62$ percentage points in a model without relative prices. Thus, the *RPE* is equivalent to moving from the mean to the median expert view (Drupp et al. 2018).

The central calibration reveals that considering relative prices notably changes the cost-benefit ratio of investing in climate change mitigation, resulting in a decreased decline of non-market goods over time.³² However, a main take-away from Figure 5

³¹At the upper bound of the 95 percentile range the SCC is 1317.93 (4074.14) 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 .

³²We depict the endogenous adjustment of good-specific growth rates in Appendix A.9.

is also that the ‘plausible ranges’ for the *RPE* and the climate policy measures are substantial. But what are the main determinants of this range? Table 4 shows the influence of changing, each time, one parameter to its upper or lower 95 percentile parameter bound, while keeping all other inputs at the central calibration baseline. The 95 percentile ranges for the different determinants are given in column two of Table 4. For the degree of substitutability, θ , for example, we run the central calibration both with a θ of 0.23, indicating a substitutive relationship between market and non-market goods, and with a θ of -0.44, implying a complementary relationship. We consider how these 95 percentile ‘plausible ranges’ for the individual parameters affect the *RPE* and the SCC in 2020 and 2100, and the peak temperature within the whole planning horizon.

Our analysis of the plausible ranges confirms that substitutability is overall the key driver of the *RPE*, driving it from 3.00 to 5.10 percent in 2020 (column 3 of Table 4), and from 1.34 to 2.42 in 2100 (column 4). Most other drivers are negligible for the *RPE* in 2020 except for the rate of pure time preference, δ as well as the elasticity of the marginal utility of comprehensive consumption, η . Indeed, the 95 percentile range for η changes the *RPE* in 2020 from 8.16 to 3.17 and is thus a stronger driver compared to the degree of substitutability. The decline rate of TFP has the second strongest influence on the *RPE* in 2100, altering it by 1.4 percentage points, followed by the influence of non-market damages driving the *RPE* by 0.3 percentage points. For peak temperature (column 5), the strongest effect comes from the standard social welfare parameters, δ and η . These alter peak temperature by 4.95°C and 4.84°C, respectively. The degree of substitutability and the amount of non-market damages also have a considerable influence on peak temperature, driving it by 0.60°C and 1.38°C, respectively. For the 2020-SCC (column 6), the plausible range is substantial and all but subsistence consumption and the decline rate of technological progress are important drivers. Non-market damages and the rate of pure time preference alter the 2020-SCC by 214.83 and 234.07 US\$ per ton of CO_2 , while the elasticity of the marginal utility of comprehensive consumption has about twice their quantitative effect on the SCC, with a range of 499.81 US\$. For the 2100-SCC (column 7), the amount of non-market damages is the the strongest driver, leading to a range in the SCC of 1493.47 US\$.

Table 4: The ‘plausible ranges’ in the *RPE*’s drivers and their influence on the *RPE* and climate policy outcomes

Driver	95%-ile range	RPE 2020 [%]	RPE 2100 [%]	Peak T [°C]	<i>SCC</i> [†] 2020	SCC 2100
θ	-0.44 – 0.23	5.10 – 3.00	2.42 – 1.34	2.78 – 3.39	117 – 70	1035 – 442
<i>NMD</i> [#]	0 – 9.54%	4.08 – 4.45	1.76 – 2.09	3.71 – 2.33	49 – 263	342 – 1836
\bar{E}/E_0	0 – 20%	4.13 – 4.13	1.90 – 1.90	3.10 – 3.09	87-87	621 – 627
δ	0 – 6%	4.45 – 1.93	1.88 – 2.04	2.37 – 7.33	245 – 11	1330 – 70
η	0.1 – 3	8.16 – 3.17	1.87 – 2.01	2.16 – 7.00	521 – 21	1361 – 203
τ^A	0 – 0.2%	4.19 – 4.08	2.76 – 1.34	3.29 – 3.01	73 – 97	600 – 571

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

[†] SCC is measured in US\$ per ton of *CO*₂.

This is followed by the influence of the two welfare parameters, δ and η , at 1259.58 US\$ and 1157.99 US\$, and the degree of substitutability, with 592.90 US\$. 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 estimate the indirect effects of our determinants 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 1.3°C and 0.4°C, corresponding to 27 percent and 9 percent of the overall effect, respectively. The net effect on the SCC in 2020 (2100) is 80.36 (490.05) US\$ and 94.01 (409.17) US\$, respectively. The biggest net effect, though, we find for non-market damages: They alter peak temperature by 1.33°C amounting to 96% of the overall effect and the SCC in 2020 (2100) by 191.19 (1490.14) US\$ corresponding to 89% (99.8%) of the overall effect. While the net effect of the subsistence level of non-market goods is negligible the impact of the RPE via technological progress on the SCC is notable, changing the SCC in 2020 (2100) by 6.49 (11.55) US\$, thus accounting for 26% (40%) of the overall effect.

6 Discussion

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

First, we find that the drivers related to the growth of non-market goods are not of quantitative importance for the *RPE* in the optimal management framework of DICE. We assumed—following the previous literature—that the consumption of non-market goods would stay constant in absence of climate change. Yet, non-market goods could also decline in absence of climate change, for example resulting from biodiversity loss due to land use change, or due to infectious diseases. 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).³³ Conversely, non-market goods may also increase due to technical change that positively affects non-market goods, for example relating to health improvements. Future studies could explore cases in which non-market goods can grow or decline irrespective of the management problem at hand as well as explicitly deal with the heterogeneity contained in the composite non-market good. Introducing drivers of non-market goods growth that are unrelated to climate change also relates to studying non-optimal climate policy, for example in settings with imperfect management control. In such cases that should be explored in future work, 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 technolog-

³³While 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.

ical progress (e.g. Bretschger 1998, Bretschger and Smulders 2012). A crucial related question is also how such technological progress related to the limited substitutability of non-market inputs to production Zhu et al. (2019).

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 (Drupp 2018) to which we add with more recent data in section 4. This indirect empirical evidence suggests weak substitutability at the margin, in contrast to the assumptions made by experts in applied modelling studies, leading overall to the mild complementarity relationship that we use in our central calibration. It is thus imperative to conduct more research to empirically estimate substitutability of non-market goods so as to further increase confidence about the likely magnitude of relative prices. Furthermore, more effort should be put into estimating the magnitude of non-market damages and the channels through which these damages unfold. While damages only affect the level of market and non-market goods in our setting, extensions could also consider damages on the growth rates of these goods (Moore and Diaz 2015).

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 2018, Millner 2019). 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 most fruitful to follow for analyses such as ours.

Fifth, we have abstracted from any behavioral effects related to relative price changes. Dietz and Venmans (2019) 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.³⁴ For example, Jensen and Traeger (2014) analyze long term uncertainty about technological progress as the main driver of growth in the DICE model, Dietz et al. (2017) study the combined effect of uncertainty about baseline growth as well as about the payoff of a mitigation project in DICE, while Gollier (2010) analyzes uncertainty in the growth rates of environmental and consumption goods and Gollier (2019) 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 fundamental drivers, its quantitative magnitude, and its implications for the integrated cost-benefit analysis of climate policy. Our analysis in the most recent version of the widely-used DICE model (Nordhaus 2018) reveals that the relative price effect of non-market goods is substantial in quantitative terms: it amounts to 4.1 (1.9) 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 2.1 to 8.8 percent in 2020 and from 1.5 to 2.7 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.

³⁴See 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.

In terms of climate policy evaluation, we find that neglecting relative price changes would lead to an underestimation of the social cost of carbon of more than 56 (81) percent in the year 2020 (2100) compared to our central calibration that considers relative price effects. Furthermore, atmospheric temperature peaks at 0.6°C lower when considering relative price effects. Introducing relative prices thus has a considerable effect on the cost-benefit analysis of climate change mitigation, providing substantive arguments for recommending more stringent climate policies.

Our study furthermore clarifies how the influence of the relative price effect on climate policy evaluation can be appropriately interpreted. We find that statements such as introducing relative prices leads to an “even Sterner review” (Sterner and Persson 2008) are sensitive to what we choose as comparison metric and variable, how we specify the baseline parameters as well as how savings and investment dynamics are calibrated. As an unambiguous comparison metric across different model runs, we use peak temperature, exploiting the fact that each considered optimization run results in a unique peak temperature in the 500 year time horizon, allowing for comparability across model runs. Introducing relative prices in the spirit of Sterner and Persson (2008) in DICE-2016R2 yields an equivalent reduction in the rate of pure time preference of 1.2 percentage points when compared to the ‘Nordhaus’ run. Yet, since we show that the standard DICE model of Nordhaus (2018) already contains a considerable relative price effect of non-market goods due to a form of Cobb-Douglas substitutability between (non-market) climate damages and production, this value substantially underestimates the impact of introducing relative prices. We show that the cleanest comparison to establish the influence of relative prices on climate policy evaluation is within a model that explicitly models them. This allows us to only vary the degree of substitutability as compared to the case of perfect substitutes, which causes relative prices to vanish, and then compute equivalent changes in the rate of pure time preferences. This direct comparison reveals that there would be no positive pure time preference that is equivalent to considering relative prices with the complementary assumption of Sterner and Persson (2008). In our central calibration that is informed by a systematic study of the determinants of the relative price effect, and features a much milder form of complementarity as com-

pared to Sterner and Persson (2008), we show that considering relative price changes is equivalent to decreasing the rate of pure time preference by 0.6 percentage points. While we believe that relative price effects should be modeled explicitly given their importance for climate policy evaluation, our analysis reveals that the implicit degree of substitutability of non-market goods already contained in the standard DICE model of Nordhaus (2018) is close to our central calibration and thus well contained within the plausible range. Our analysis thus also implies that if market and non-market goods have a somewhat higher substitutability than Cobb-Douglas, explicitly introducing relative prices into DICE may lead to less stringent optimal climate policy as suggested by the standard DICE model.

While relative price changes of non-market goods thus clearly matter considerably for the cost-benefit analysis of climate policy, our results likewise suggest an enduring importance of the key standard discounting parameters. We find that in the short-run, the rate of pure time preference and the elasticity of marginal utility of (comprehensive) consumption indirectly influence the relative price effect, as the growth of consumption is endogenous in DICE. Furthermore, both their direct and indirect effects through relative prices on optimal climate policy outcomes are substantial.

Finally, our analysis provides guidance for the revision of policy guidelines on cost-benefit analysis. Our findings suggest that the relative price effect of non-market goods is likely more substantial than the one percent result presented in the literature for the relative price effect of environmental goods that has informed policy guidance in the Netherlands (Baumgärtner et al. 2015, Drupp 2018, Koetse et al. 2018). Our analysis also points towards the most crucial determinants of relative prices, such as the degree of substitutability, the standard welfare parameters and technological progress. This suggests that it is imperative to obtain better estimates or more agreement on acceptable values for these determinants 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 governmental project appraisal. Such methodological updates can help to reduce the current bias of many cost-benefit analyses, which implicitly tend to undervalue non-market effects.

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.
- Bakkensen, L. and Barrage, L. (2018), Flood Risk Belief Heterogeneity and Coastal Home Price Dynamics: Going Under Water?, *NBER WP* No. 23854.
- Barrage, L. (2018), Be Careful What You Calibrate For: Social Discounting in General Equilibrium, *Journal of Public Economics* **160C**: 33–49.
- Baumgärtner, S., Klein, A.-M., Thiel, D., and K. Winkler (2015), Ramsey Discounting of Ecosystem Services, *Environmental and Resource Economics* **61**(2): 273–296.
- Bernstein, A., Gustafson, M. T., and Lewis, R. (2019), Disaster on the horizon: The price effect of sea level rise, *Journal of Financial Economics* **134**(2): 253–272.
- 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 (2018), Uncertainty in forecasts of long-run economic growth, *Proceedings of the National Academy of Sciences*, **115**(21): 5409–5414.
- Dasgupta, P. (2008), Discounting Climate Change, *Journal of Risk and Uncertainty* **37**(2): 141–169.
- Dietz, S., Gollier, C., and L. Kessler (2018), The climate beta, *Journal of Environmental Economics and Management*, **87**: 258–274.

- Dietz, S., and F. Venmans (2019), The endowment effect, discounting and the environment, *Journal of Environmental Economics and Management*, **97**: 67–91.
- Droste, N., and B. Bartkowski (2018), Ecosystem Service Valuation for National Accounting: A Reply to Obst, Hein and Edens (2016). *Environmental and Resource Economics*, **71**(1): 205–215.
- Drupp, M.A., Freeman, M.C., Groom, B., and F. Nesje (2018), Discounting Disentangled, *American Economic Journal: Economic Policy* **10**(4): 109–134.
- 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.univ-paris1.fr/SURED2016/papers/Zuber_SURED2016.pdf.
- Flores, N.E. and R.T. Carson (1997), The relationship between the income elasticities of demand and willingness to pay, *Journal of Environmental Economics and Management* **33**(3): 287–295.
- Gerlagh, R., and B. van der Zwaan (2002), Long-term substitutability between environmental and man-made goods, *Journal of Environmental Economics and Management* **44**: 329–345.
- Gerlagh, R., and M. Liski (2018), Consistent climate policies, *Journal of the European Economic Association*, **16**(1): 1–44.
- 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. (2019), Valuation of natural capital under uncertain substitutability, *Journal of Environmental Economics and Management* **94**: 54–66.
- 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’veloppement 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.
- Henry, C. (2017), Managing Natural Capital in Line with Malinvaud’s Approach to Efficient Allocation of Capital, *Annals of Economics and Statistics* **125-126**: 165–168.

- 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.
- Howard, P.H., and T. Sterner (2017), Few and not so far between: a meta-analysis of climate damage estimates, *Environmental and Resource Economics* **68**(1): 197–225.
- 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>.
- Ito, K., and S. Zhang (forthcoming), Willingness to Pay for Clean Air: Evidence from Air Purifier Markets in China, *Journal of Political Economy*, forthcoming.
- 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 (2018), Relative price increase for nature and ecosystem services in cost-benefit analysis. *PBL Netherlands Environmental Assessment Agency, The Hague*.
- Krutilla, J.V. (1967), Conservation reconsidered, *American Economic Review* **57**(4): 777–786.
- Malinvaud, E. (1953), Capital accumulation and the efficient allocation of resources, *Econometrica* **21**(2): 233–268.
- Mendelsohn, R., Prentice, I.C., Schmitz, O., Stocker, B., Buchkowski, R., and B. Dawson (2016), The Ecosystem Impacts of Severe Warming, *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. (2019), Non-dogmatic social discounting, *American Economic Review*, forthcoming.
- [MFN 2015] Ministry of Finance of the Netherlands (2015). Rapport werkgroep discontovoet 2015. Available at: <https://www.rijksoverheid.nl/documenten/rapporten/2015/11/13/rapport-werkgroep-discontovoet-2015-bijlage>
- Moore, F.C., and Diaz, D.B. (2015), Temperature impacts on economic growth warrant stringent mitigation policy, *Nature Climate Change* **5**(2): 127–131.
- 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*, **10**(3): 333–60.
- Nordhaus, W.D., and A. Moffat (2017). A survey of global impacts of climate change: Replication, survey methods, and a statistical analysis *National Bureau of Economic Research Working Paper* No. w23646.

- Obst, C., Hein, L. and B. Edens (2016), National accounting and the valuation of ecosystem assets and their services. *Environmental and Resource Economics*, **64**(1), 1-23.
- 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.
- Strand, J., Soares-Filho, B., Costa, M. H., Oliveira, U., Ribeiro, S. C., Pires, G. F., ... and Siikamäki, J. (2018), Spatially explicit valuation of the Brazilian Amazon Forest’s Ecosystem Services, *Nature Sustainability* **1**(11): 657–664.
- Tollefson, J. (2019), Humans are driving one million species to extinction, *Nature* **569**: 171.
- 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.
- Weitzman, M.L. (2010), What is the damages function for global warming and what difference might it make?, *Climate Change Economics* **1**(1): 57–69.
- Zhu, X., Smulders, S. and A. de Zeeuw (2019), Discounting in the presence of scarce ecosystem services, *Journal of Environmental Economics and Management* **98**, 102272.

ONLINE APPENDIX

A.1 Derivation of the relative price effect

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

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

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

We thus have

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

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

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

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

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

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

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

The relative price effect of non-market goods, i.e. the change in relative prices over time, is thus the same as the difference in the two good-specific discount rates (see Weikard and Zhu (2005) or Drupp (2018) for derivations in continuous time).

A.2 Calibration of non-market damages

A.2.1 Calibration for Section 3

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

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

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

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

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

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

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

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:

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

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

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

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

A.3 Relative prices and comparison of climate policy paths until 2300, with 100% additional non-market damages as in Sterner and Persson (2008)

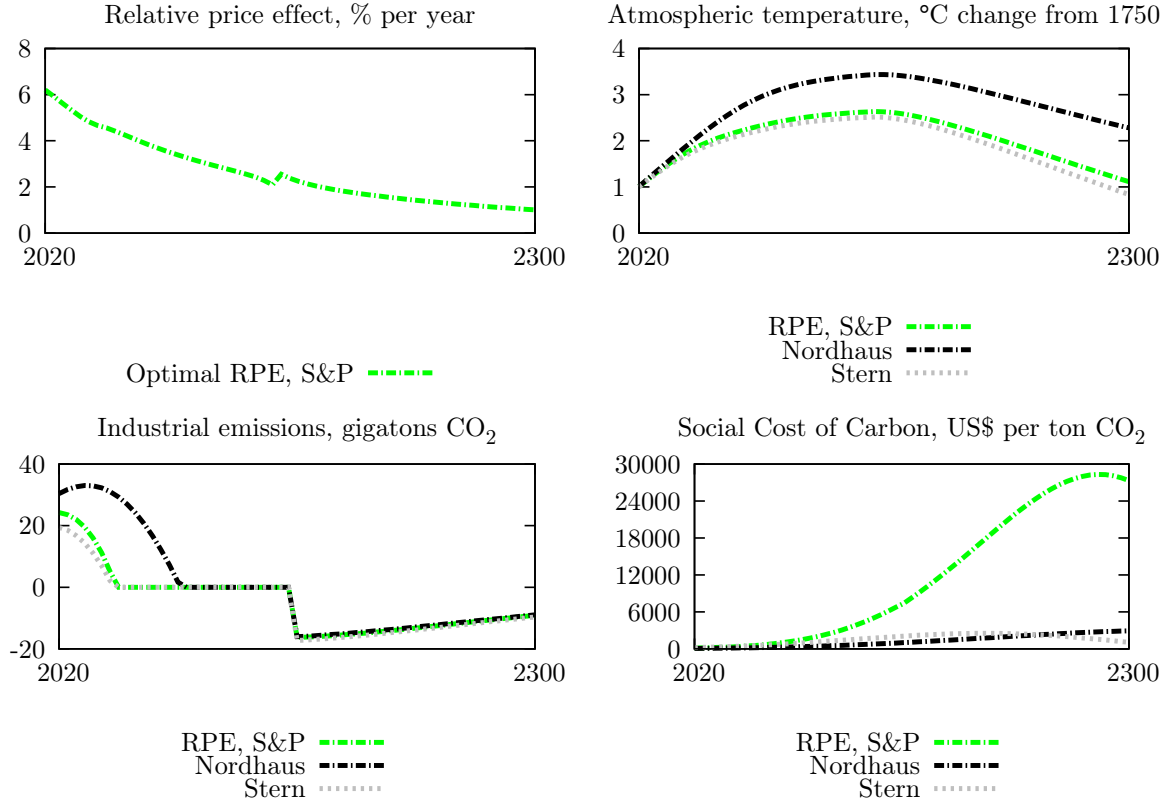


Figure A.1: Relative price effect (*RPE*) and comparison of climate policy paths for a time horizon up to 2300 and 100% additional non-market damages. Otherwise, see description of Figure 1.

A.4 Re-calibration of the model

(1) Derivation of η_C

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

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

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

$$U_{CC} = (1-\alpha) c_t^{\theta-1} \frac{1}{c} (\theta-1) \left[\alpha (E_t - \bar{E})^\theta + (1-\alpha) c_t^\theta \right]^{\frac{1-\eta-\theta}{\theta}} \quad (\text{A.14})$$

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

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

$$\eta_C = -\frac{U_{CC} c}{U_C} = (1-\theta) - (1-\eta-\theta) \frac{(1-\alpha) c_t^\theta}{\alpha (E_t - \bar{E})^\theta + (1-\alpha) c_t^\theta}. \quad (\text{A.16})$$

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

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

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

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

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

34	1.447261	34	1.456910
35	1.447393	35	1.456544
36	1.447515	36	1.456205
37	1.447629	37	1.455891
38	1.447735	38	1.455600
39	1.447833	39	1.455330
40	1.447925	40	1.455078
41	1.448011	41	1.454845
42	1.448091	42	1.454627
43	1.448166	43	1.454424
44	1.448237	44	1.454235
45	1.448303	45	1.454059
46	1.448365	46	1.453894
47	1.448423	47	1.453739
48	1.448478	48	1.453595
49	1.448530	49	1.453459
50	1.448579	50	1.453333
51	1.448625	51	1.453214
52	1.448668	52	1.453102
53	1.448710	53	1.452996
54	1.448749	54	1.452897
55	1.448786	55	1.452804
56	1.448821	56	1.452716
57	1.448855	57	1.452633
58	1.448887	58	1.452555
59	1.448917	59	1.452481
60	1.448946	60	1.452411
61	1.448973	61	1.452345
62	1.449000	62	1.452282
63	1.449025	63	1.452222
64	1.449048	64	1.452166
65	1.449071	65	1.452112
66	1.449093	66	1.452061
67	1.449114	67	1.452013
68	1.449134	68	1.451967
69	1.449153	69	1.451923

70	1.449171	70	1.451881
71	1.449188	71	1.451841
72	1.449205	72	1.451803
73	1.449221	73	1.451767
74	1.449236	74	1.451732
75	1.449251	75	1.451699
76	1.449265	76	1.451668
77	1.449278	77	1.451638
78	1.449291	78	1.451609
79	1.449303	79	1.451581
80	1.449315	80	1.451555
81	1.449327	81	1.451530
82	1.449337	82	1.451505
83	1.449348	83	1.451482
84	1.449358	84	1.451460
85	1.449367	85	1.451439
86	1.449377	86	1.451418
87	1.449386	87	1.451398
88	1.449394	88	1.451379
89	1.449402	89	1.451361
90	1.449410	90	1.451343
91	1.449418	91	1.451325
92	1.449426	92	1.451308
93	1.449435	93	1.451289
94	1.449443	94	1.451270
95	1.449453	95	1.451247
96	1.449466	96	1.451219
97	1.449483	97	1.451181
98	1.449508	98	1.451123
99	1.449552	99	1.451024
100	1.449493;	100	1.451158;

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

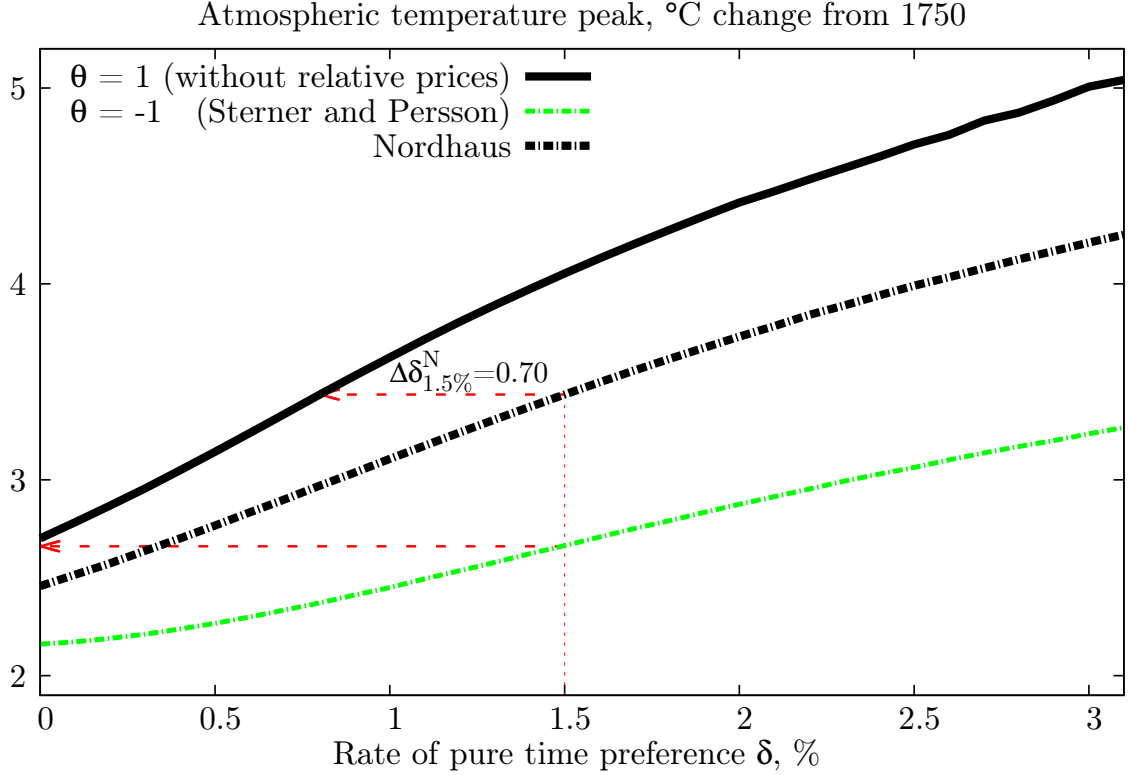


Figure A.2: The comparative influence of introducing relative prices on peak temperature with re-calibrated elasticity of marginal utility. The Figure depicts peak temperature as a function of the rate of pure time preference, δ , for different degrees of substitutability, θ . The solid black line shows the comparison case of perfect substitutability, i.e. without relative prices. The green line depicts the substitutability assumption of Stern and Persson, with $\theta = -1$, and the dashed black line the ‘Nordhaus’ case. A model run with relative prices is compared to a run without but with a higher δ such that peak temperature is the same across both runs.

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

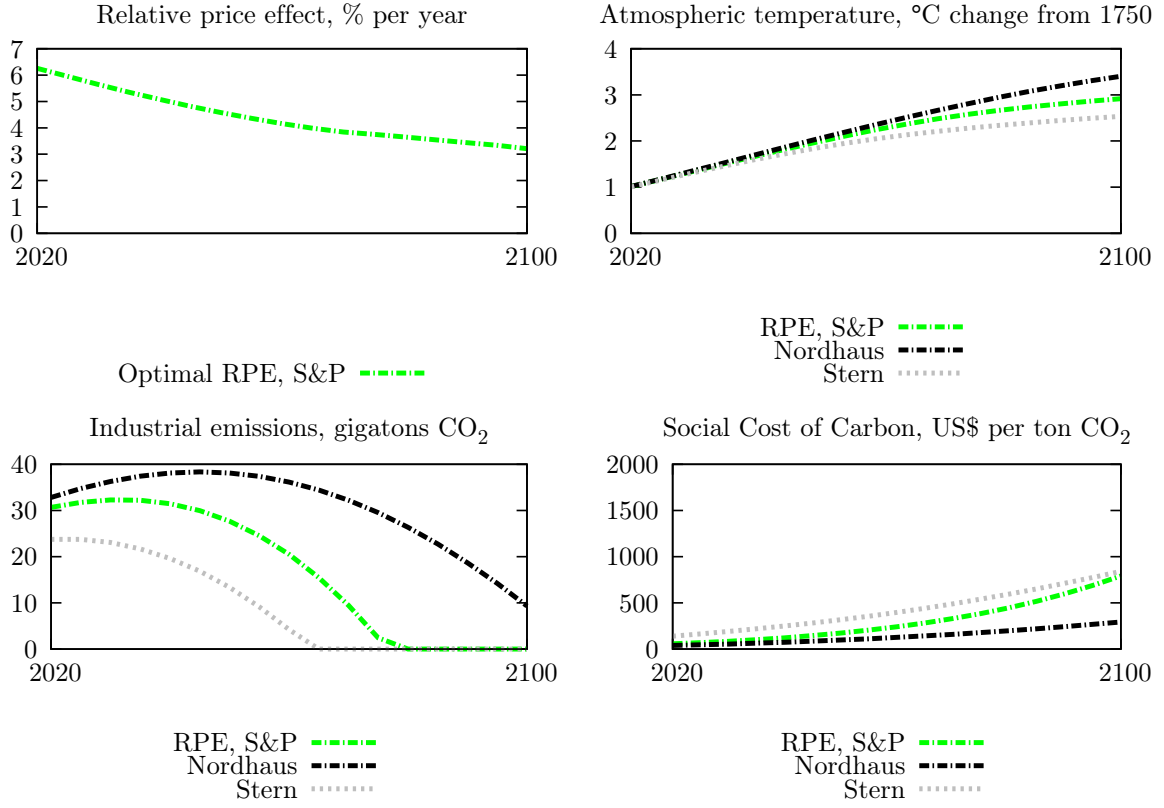


Figure A.3: Relative price effect (RPE) and comparison of climate policy paths for a time horizon up to 2100 and 25% additional non-market damages.

A.6 Relative prices, substitutability and the equivalent reduction in pure time preference

Table A.1: Degree of substitutability (θ) and the corresponding *RPE's* equivalent effect in terms of a reduction of pure time preference ($\Delta\delta$)*

θ_i	$\Delta\delta_{1.5\%}^{\theta_i}$	Reference or relation
1	0	Perfect substitutes
0.8	0.05	
0.6	0.12	Drupp (2018)
0.4	0.18	
0.2	0.4	
0	0.6	Cobb-Douglas, Gollier (2010)
-0.2	0.85	
-0.333	1.01	Kopp et al. (2012)
-0.4	1.09	
-0.66	1.4	Equivalent to Stern's (2007) lower δ
-0.78	1.5	
-1	not defined	Sterner and Persson (2008)
-2.3	not defined	Lowest indirect empirical estimates

* This analysis is conducted without our replication of Sterner and Persson (2008).

A.7 Additional drivers of the relative price effect: Initial value of non-market goods and share of non-market goods in utility

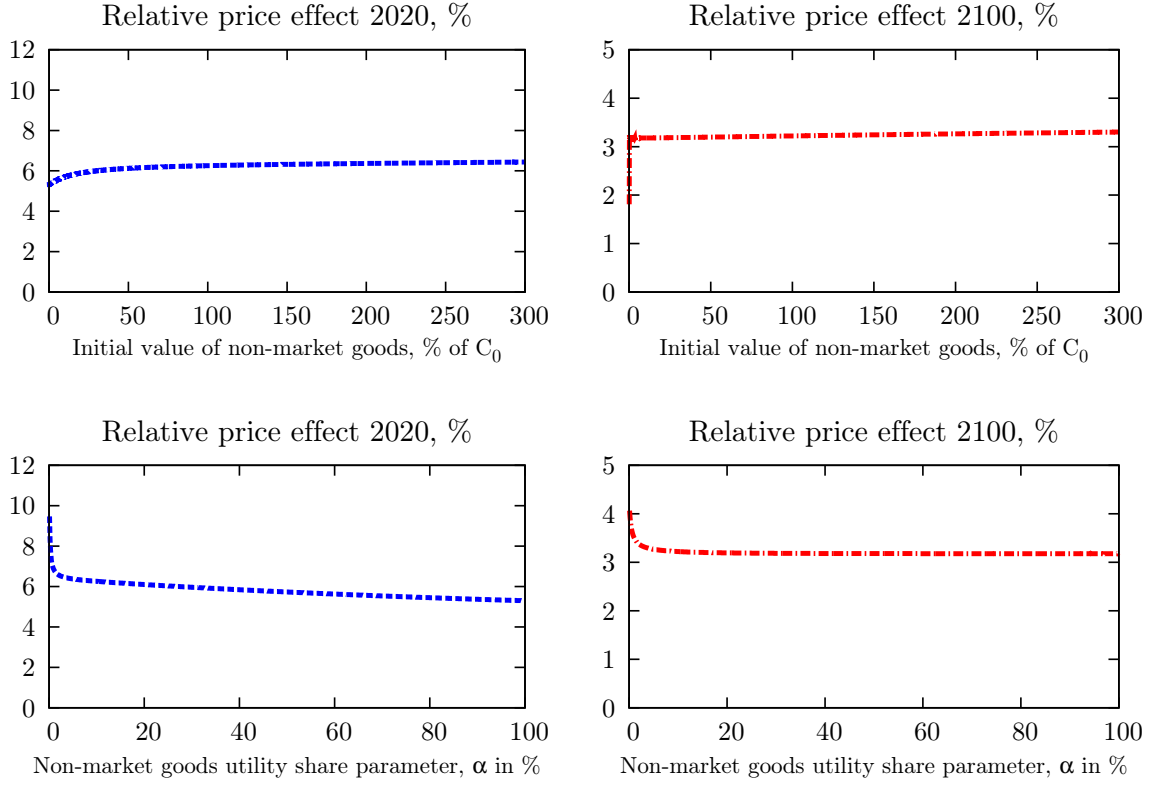


Figure A.4: Additional drivers of the relative price effect (I). Top to bottom: The impact of the initial value of non-market goods and the share of non-market goods in utility on the *RPE* in 2020 (left) and in 2100 (right).

A.8 Empirical estimates of the substitutability parameter

Table A.2: Indirect empirical estimates of the substitutability parameter*

Study	Mean θ	Type of good
Alberini et al. (2018)	0.46	Environmental goods: Climate change mitigation
Alberini et al. (2006)	0.53	Reduction in mortality risk
Aldy et al. (1999)	0.58	Environmental goods: Nature conservation
Ara and Tekesin (2016)	0.43	Health improvements
Ara and Tekesin (2017)	0.10	Health improvements
Barbier et al. (2017)	0.74	Environmental goods: Water or air quality
Basili et al. (2006)	0.58	Environmental goods: Water or air quality
Broberg (2010)	0.75	Environmental goods: Nature conservation
Clark and Kahn (1988)	0.10	Cultural goods
Cuevas-Alvarado et al. (2016)	0.73	Environmental goods: All others
Czajkowski et al. (2017)	0.72	Environmental goods: Water or air quality
Czajkowski and Scasny (2010)	0.36	Environmental goods: Water or air quality
Dickie (2005)	0.86	Health improvements
Doucouliafos et al. (2014)	0.48	Reduction in mortality risk
Francisco (2015)	0.52	Environmental goods: Water or air quality
Hammit et al. (2019)	-2.00	Reduction in mortality risk
Hammit and Herrera-Araujo (2018)	0.11	Reduction in mortality risk
Hökby and Söderqvist (2003)	0.32	Environmental goods: All others
Huhtala and Pouta (2008)	0.90	Environmental goods: All others
Jacobsen and Hanley (2009)	0.62	Environmental goods: Nature conservation
Johannesson et al. (1993)	0.82	Health improvements
Li et al. (2016)	0.90	Environmental goods: Climate change mitigation
Lindhjem et al. (2011)	0.20	Reduction in mortality risk
Lindhjem and Tuan (2012)	0.27	Environmental goods: Nature conservation
Martini and Tiezzi (2014)	-0.16	Environmental goods: Water or air quality
Masiye and Rehnberg (2005)	0.71	Health improvements
Masterman and Viscusi (2018)	0.18	Reduction in mortality risk
McLeod (1984)	0.34	Cultural goods
Milligan et al. (2014)	0.45	Reduction in mortality risk
Nastis and Mattas (2018)	0.04	Environmental goods: Climate change mitigation
Navrud and Strand (2018)	-0.02	Environmental goods: Nature conservation
Ready et al. (2002)	0.41	Environmental goods: Water or air quality
Riera et al. (2006)	0.01	Reduction in mortality risk
Robinson et al. (2019)	-0.50	Reduction in mortality risk
Scandizzo and Ventura (2010)	0.55	Environmental goods: Nature conservation
Tuan et al. (2009)	-0.98	Cultural goods
Tyllianakis and Skuras (2016)	0.26	Environmental goods: Water or air quality
Viscusi and Aldy (2003)	0.50	Reduction in mortality risk
Wang and Mullahy (2006)	-0.42	Environmental goods: Water or air quality
Zan and Scharff (2017)	-2.30	Reduction in mortality risk

* A separate data file contains more details on these 40 as well as the 41 non-relevant studies.

References of the relevant studies:

- Alberini, A., Bigano, A., Scasny, M., & Zverinova, I. (2018). Preferences for energy efficiency vs. renewables: what is the willingness to pay to reduce CO2 emissions?. *Ecological Economics*, 144, 171-185.
- Alberini, A., Hunt, A., & Markandya, A. (2006). Willingness to pay to reduce mortality risks: evidence from a three-country contingent valuation study. *Environmental and Resource Economics*, 33(2), 251-264.
- Aldy, J. E., Kramer, R. A., & Holmes, T. P. (1999). Environmental equity and the conservation of unique ecosystems: an analysis of the distribution of benefits for protecting southern Appalachian spruce-fir forests. *Society & natural resources*, 12(2), 93-106.
- Ara, S., & Tekesin, C. (2016). The monetary valuation of acute respiratory illness from air pollution in Turkey. *Atmospheric Pollution Research*, 7(1), 82-91.
- Ara, S., & Teke?in, C. (2017). The Monetary Valuation of Lifetime Health Improvement and Life Expectancy Gains in Turkey. *International journal of environmental research and public health*, 14(10), 1151.
- Barbier, E. B., Czajkowski, M., & Hanley, N. (2017). Is the income elasticity of the willingness to pay for pollution control constant?. *Environmental and resource economics*, 68(3), 663-682.
- Basili, M., Di Matteo, M., & Ferrini, S. (2006). Analysing demand for environmental quality: A willingness to pay/accept study in the province of Siena (Italy). *Waste Management*, 26(3), 209-219.
- Broberg, T. (2010). Income treatment effects in contingent valuation: the case of the Swedish predator policy. *Environmental and Resource Economics*, 46(1), 1-17.
- Clark, D. E., & Kahn, J. R. (1988). The social benefits of urban cultural amenities. *Journal of regional science*, 28(3), 363-377.

- Cuevas-Alvarado, C. M., Sandoval-Romero, F., Valdivia-Alcala, R., Ramírez-Espinosa, J. M., & Borja-de la Rosa, A. M. (2016). Econometric estimation of the income elasticity of consumer demand for environmental services. *Revista Chapingo. Serie Ciencias Forestales y del Ambiente*, 22(3), 369-377.
- Czajkowski, M., Ahtiainen, H., Artell, J., & Meyerhoff, J. (2017). Choosing a functional form for an international benefit transfer: Evidence from a nine-country valuation experiment. *Ecological Economics*, 134, 104-113.
- Czajkowski, M., & Scasny, M. (2010). Study on benefit transfer in an international setting. How to improve welfare estimates in the case of the countries' income heterogeneity?. *Ecological Economics*, 69(12), 2409-2416.
- Dickie, M. (2005). Parental behavior and the value of children's health: A health production approach. *Southern Economic Journal*, 855-872.
- Doucouliagos, H., Stanley, T. D., & Viscusi, W. K. (2014). Publication selection and the income elasticity of the value of a statistical life. *Journal of Health Economics*, 33, 67-75.
- Francisco, J. P. S. (2015). Willingness To Pay For Air Quality Improvements From Using Electric Jeepneys In Metro Manila. *The Singapore Economic Review*, 60(04), 1550073.
- Hammitt, J. K., Geng, F., Guo, X., & Nielsen, C. P. (2019). Valuing mortality risk in China: Comparing stated-preference estimates from 2005 and 2016. *Journal of Risk and Uncertainty*, 1-20.
- Hammitt, J. K., & Herrera-Araujo, D. (2018). Peeling back the onion: Using latent class analysis to uncover heterogeneous responses to stated preference surveys. *Journal of Environmental Economics and Management*, 87, 165-189.
- Hökby, S., & Söderqvist, T. (2003). Elasticities of demand and willingness to pay for environmental services in Sweden. *Environmental and resource economics*, 26(3), 361-383.

- Huhtala, A., & Pouta, E. (2008). User fees, equity and the benefits of public outdoor recreation services. *Journal of Forest Economics*, 14(2), 117-132.
- Jacobsen, J. B., & Hanley, N. (2009). Are there income effects on global willingness to pay for biodiversity conservation?. *Environmental and Resource Economics*, 43(2), 137-160.
- Johannesson, M., Johannsson, P. O., Kriström, B., Borgquist, L., & Jonsson, B. (1993). Willingness to pay for lipid lowering: a health production function approach. *Applied Economics*, 25(8), 1023-1031.
- Li, Y., Mu, X., Schiller, A., & Zheng, B. (2016). Willingness to pay for climate change mitigation: evidence from China. *The Energy Journal*, 37(China Special Issue).
- Lindhjem, H., Navrud, S., Braathen, N. A., & Biaisque, V. (2011). Valuing mortality risk reductions from environmental, transport, and health policies: A global meta-analysis of stated preference studies. *Risk Analysis: An International Journal*, 31(9), 1381-1407.
- Lindhjem, H., & Tuan, T. H. (2012). Valuation of species and nature conservation in Asia and Oceania: a meta-analysis. *Environmental Economics and Policy Studies*, 14(1), 1-22.
- Martini, C., & Tiezzi, S. (2014). Is the environment a luxury? An empirical investigation using revealed preferences and household production. *Resource and Energy Economics*, 37, 147-167.
- Masiye, F., & Rehnberg, C. (2005). The economic value of an improved malaria treatment programme in Zambia: results from a contingent valuation survey. *Malaria journal*, 4(1), 60.
- Masterman, C. J., & Viscusi, W. K. (2018). The income elasticity of global values of a statistical life: Stated preference evidence. *Journal of Benefit-Cost Analysis*, 9(3), 407-434.

- McLeod, P. B. (1984). The demand for local amenity: an hedonic price analysis. *Environment and Planning A*, 16(3), 389-400.
- Milligan, C., Kopp, A., Dahdah, S., & Montufar, J. (2014). Value of a statistical life in road safety: a benefit-transfer function with risk-analysis guidance based on developing country data. *Accident Analysis & Prevention*, 71, 236-247.
- Nastis, S. A., & Mattas, K. (2018). Income elasticity of willingness-to-pay for a carbon tax in Greece. *International Journal of Global Warming*, 14(4), 510-524.
- Navrud, S., & Strand, J. (2018). Valuing global ecosystem services: what do European experts say? Applying the delphi method to contingent valuation of the Amazon rainforest. *Environmental and resource economics*, 70(1), 249-269.
- Ready, R. C., Malzubris, J., & Senkane, S. (2002). The relationship between environmental values and income in a transition economy: surface water quality in Latvia. *Environment and Development Economics*, 7(1), 147-156.
- Riera, P., Mhawej, A., Mavsar, R., & Brey, R. (2006). Fixed-effects Hedonic Price Model for Statistical Value of Life Estimations. *Transport reviews*, 26(4), 487-500.
- Robinson, L. A., Hammitt, J. K., & O’Keeffe, L. (2019). Valuing mortality risk reductions in global benefit-cost analysis. *Journal of Benefit-Cost Analysis*, 10(S1), 15-50.
- Scandizzo, P. L., & Ventura, M. (2010). Estimating the value of natural resources under legal constraints: an application to marine resources in Sicily. *Applied Economics Letters*, 17(4), 317-323.
- Tuan, T. H., Seenprachawong, U., & Navrud, S. (2009). Comparing cultural heritage values in South East Asia—Possibilities and difficulties in cross-country transfers of economic values. *Journal of cultural heritage*, 10(1), 9-21.

- Tyllianakis, E., & Skuras, D. (2016). The income elasticity of Willingness-To-Pay (WTP) revisited: A meta-analysis of studies for restoring Good Ecological Status (GES) of water bodies under the Water Framework Directive (WFD). *Journal of environmental management*, 182, 531-541.
- Viscusi, W. K., & Aldy, J. E. (2003). The value of a statistical life: a critical review of market estimates throughout the world. *Journal of risk and uncertainty*, 27(1), 5-76.
- Wang, H., & Mullahy, J. (2006). Willingness to pay for reducing fatal risk by improving air quality: a contingent valuation study in Chongqing, China. *Science of the Total Environment*, 367(1), 50-57.
- Zan, H., & Scharff, R. L. (2017). Regional Differences in the Value of Statistical Life. *Journal of consumer policy*, 40(2), 157-176.

A.9 Optimal versus business as usual growth rates of the market and non-market good

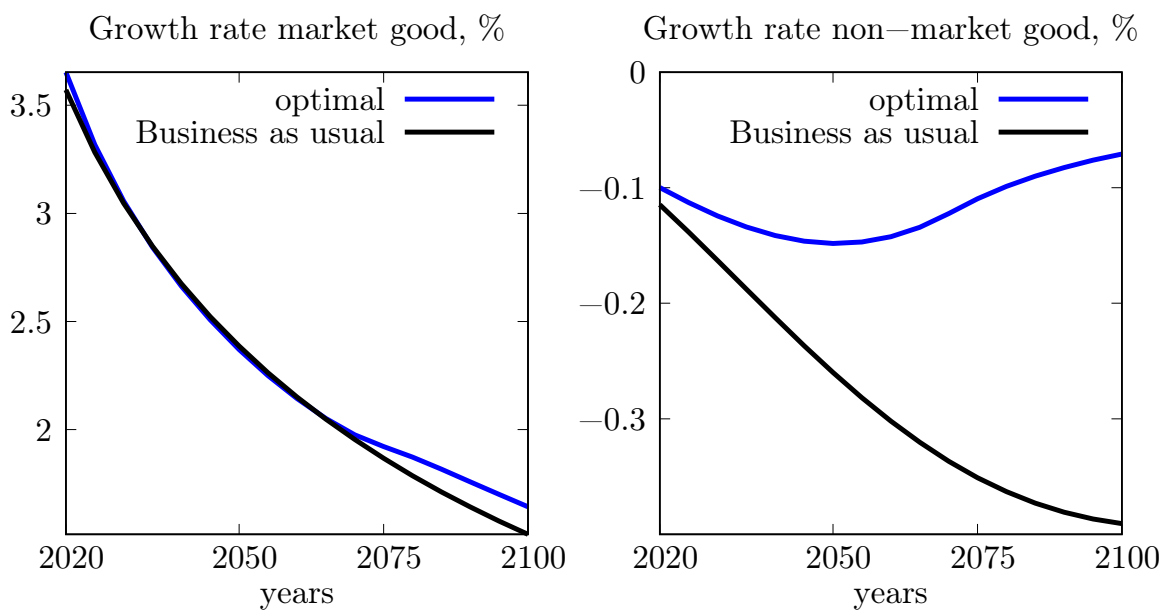


Figure A.5: Optimal versus business as usual growth rates of the market good (left) and non-market good (right) using the central calibration of our plausible ranges model.

A.10 Code

A.10.1 AMPL code to produce Figure 1

(1) AMPL mod-file Nordhaus

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

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

# for sensitivity analysis and figure 2 use: param R {t in 0..T}:= 1*exp(-rho*5*t);

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

# Technology and its dynamics
param gamma:=0.3; #capital elasticity in production function
param deltaK:=0.100; #depreciation rate on capital (per year)
param Qgross0:=105.5; #Initial world gross output 2015 (trill 2010 USD)
param K0:=223; #initial capital value 2015 (trillions 2010 USD)
param A0:=5.115; #initial level of total factor productivity
param gA0:=0.076; #initial growth rate for TFP per 5 years
param deltaA:=0.005; #decline rate of TFP per 5 years
```

```

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

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

# Emission parameters, where sigma is the carbon intensity or CO2-output ratio
param gsigma0:=-0.0152; #initial growth of sigma (coninuous per year ),
param deltasigma:=-0.001; #decline rate of decarbonization per period
param ELand0:=2.6; #initial Carbon emissions from land 2015 (GtCO2 per period)
param deltaLand:=0.115; #decline rate of land emissions (per period)
param EInd0:=35.85; #Industrial emissions 2015 (GtCO2 per year)
param Ecum0:=400; #Initial cumulative emissions (GtCO2)
param mu0:=.03; #Initial emissions control rate; under BAU: 0.00
param Lambda0:=0; #Initial abatement costs
param sigma0:=EInd0/(Qgross0*(1-mu0));
#initial sigma (kgCO2 per output 2005 USD in 2010)

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

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

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

# Carbon cycle
param MAT0=851; # Initial Concentration in atmosphere 2015 (GtC)
param MUP0=460; # Initial Concentration in upper strata 2015 (GtC)
param MLO0=1740; # Initial Concentration in lower strata 2015 (GtC)
param MATEQ=588; # Equilibrium concentration in atmosphere (GtC)
param MUPEQ=360; # Equilibrium concentration in upper strata (GtC)
param MLOEQ=1720; # Equilibrium concentration in lower strata (GtC)

```



```

# Flow parameters (carbon cycle transition matrix)
# correspond to the bXX parameters in Nordhaus)
param phi12:=0.12;
param phi23:=0.007;
param phi11=1-phi12;
param phi21=phi12*MATEQ/MUPEQ;
param phi22=1-phi21-phi23;
param phi32=phi23*MUPEQ/MLOEQ;
param phi33=1-phi32;

# Climate model parameters
param nu:=3.1; # Equilibrium temperature impact (°C per doubling CO2)
param Fex0:=0.5; # 2015 forcings of non-CO2 GHG (Wm-2)
param Fex1:=1.0; # 2100 forcings of non-CO2 GHG (Wm-2)
param TL00:=0.0068; # Initial lower stratum temperature change (°C from 1900)
param TAT0:=0.85; # Initial atmospheric temp change (°C from 1900)
param xi1:=0.1005; # Speed of adjustment parameter for atmospheric temperature
param xi3:=0.088; # Coefficient of heat loss from atmosphere to oceans
param xi4:=0.025; # Coefficient of heat gain by deep oceans
param kappa:=3.6813; # Forcings of equilibrium CO2 doubling (Wm-2)
param xi2=kappa/nu; # climate model parameter
param Fex {t in 0..T}>=0;
let {t in 0..17} Fex[t]:=Fex0+1/17*(Fex1-Fex0)*(t); # external forcing (Wm-2)
let {t in 18..T} Fex[t]:=Fex1;
# external forcing (Wm-2)
# is assumed to be constant and equal to Fex1 from 2100 onward
# see e.g. Traeger (2014, Fig.1)

# climate damage parameters
param Psi:=0.003622;
# 0.00236 damage quadratic term for 25% add on NMD; for 100% add on: 0.003622
param TATlim default 12; # upper bound on atm. temperature change

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

```

```

param cprice0:=2; # Initial base carbon price (2010$ per tCO2)

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

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

# VARIABLES

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

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

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

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

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

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

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

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

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

# damages (trillions 2010 USD)

```

```

var damage {t in 0..T}=Omega[t]*Qgross[t];

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

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

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

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

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

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

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

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

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

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

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

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

```

```

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

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

# Initial conditions
subject to initial_capital: K[0] = K0;
subject to initial_Ecum: Ecum[0]=Ecum0;
subject to initial_MAT: MAT[0]=MAT0;
subject to initial_MUP: MUP[0]=MUP0;
subject to initial_MLO: MLO[0]=MLO0;
subject to initial_TLO: TLO[0]=TLO0;
subject to initial_TAT: TAT[0]=TAT0;
subject to initial_control: mu[0]=mu0;
subject to control1 {t in 1..28}: mu[t]<=1;
subject to control2 {t in 29..T}: mu[t]<=1.2; # from 2150
#subject to control_BAU {t in 1..T}: mu[t]=0;

```

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

```
# DICE 2016R2 with Relative Prices
# To work with the run-file, this mod-file should be named: DICE_2016_RPE.mod
# for central calibration for Section 5 change parameters according to table 3
# PARAMETERS
#Time horizon
param T default 100;

# Preferences
param eta default 1.45; #I-EMUC central calibration: 1.35
param rho default 0.015; #time preference rate; central calibration: 0.011

# relative prices additions
param zeta default -1; #substitution parameter S\&P 2008

#central calibration: -0.11
#for a model run without relative prices:1

param beta default 0.1; #share of non-market good in utility function
param EQbar default 0; #subsistence level of non-market good
#central calibration: 7.77

param cbar default 0; #subsistence level of consumption per capita

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

#for sensitivity analysis and figure 2/5: 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
#central calibration: 0.005

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

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

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

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

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

param ELand {t in 0..T}>=0;
let ELand[0]:=ELand0;

```

```

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

# Carbon cycle
param MAT0=851; # Initial Concentration in atmosphere 2015 (GtC)
param MUP0:=460; # Initial Concentration in upper strata 2015 (GtC)
param 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; # market damage term without 25% adjustment
# damage quadratic term with 25% adjustment is 0.00236
param MD default 0.0163;
# market damages for 3°C warming above preindustrial according to Nordhaus (2017)
param NMD default 0.0163;
# corresponds to 100% NMD add on; with 25% add on 0.00494
# central calibration: 0.0165
param TD=MD+NMD; # total climate damages

param TATlim default 12; # upper bound on atm. temperature change

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

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

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

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

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

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

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

# carbon reservoir lower ocean (GtC)

```



```

var MLO {t in 0..T}>=1000;

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

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

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

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

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

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

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

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

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

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

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

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

```

```

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

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

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

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

# Non-market damages scaling parameter including subsistence requirement

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

# growth rate of market good

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

# growth rate of non market good

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

# relative price effect

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

# utility

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

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

```

```

maximize objective_function: W;
subject to initial_consumption: c[0]=10.4893;
subject to constr_accounting {t in 0..T}:
C[t]=Q[t]-I[t];
subject to constr_emissions {t in 0..T}:
E[t]=EInd[t]+ELand[t];
subject to constr_capital_dynamics {t in 1..T}:
K[t]=(1-deltaK)^5*K[t-1]+5*I[t-1];
subject to constr_cumulativeemissions {t in 1..T}:
Ecum[t]=Ecum[t-1]+(EInd[t-1]*5/3.666);
subject to constr_atmosphere {t in 1..T}:
MAT[t]=E[t]*(5/3.666)+phi11*MAT[t-1]+phi21*MUP[t-1];
subject to constr_upper_ocean {t in 1..T}:
MUP[t]=phi12*MAT[t-1]+phi22*MUP[t-1]+phi32*MLO[t-1];
subject to constr_lower_ocean {t in 1..T}:
MLO[t]=phi23*MUP[t-1]+phi33*MLO[t-1];
subject to constr_atmospheric_temp {t in 1..T}:
TAT[t]=TAT[t-1]+xi1*((F[t]-xi2*TAT[t-1])-(xi3*(TAT[t-1]-TLO[t-1])));
subject to constr_ocean_temp {t in 1..T}:
TLO[t]=TLO[t-1]+xi4*(TAT[t-1]-TLO[t-1]);

# Initial conditions
subject to initial_capital: K[0] = K0;
subject to initial_Ecum: Ecum[0]=Ecum0;
subject to initial_MAT: MAT[0]=MAT0;
subject to initial_MUP: MUP[0]=MUP0;
subject to initial_MLO: MLO[0]=MLO0;
subject to initial_TLO: TLO[0]=TLO0;
subject to initial_TAT: TAT[0]=TAT0;
subject to initial_control: mu[0]=mu0;
subject to control1 {t in 1..28}: mu[t]<=1;
subject to control2 {t in 29..T}: mu[t]<=1.2; # from 2150
subject to initial_EQ: EQ[0]=C[0];
subject to constr_EQ {t in 1..T}: EQ[t]=(EQ[0]/(1+a[t]*(TAT[t]^2)));

```

(3) AMPL run-file

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

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

A.10.2 AMPL code to produce Figure 2

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

A.10.3 AMPL code for Figure 3 and Figure 4

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

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

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

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

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

```

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

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

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

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

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

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

```

A.10.4 AMPL code for figure 5

(1) AMPL dat-file, Plausible Ranges

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

```
param nruns:=1000;
```

```
param rhos:=
```

```
1 0.015
```

```
2 0.00000001
```

```
3 0.02
```

```
4 0.01
```

```
5 0.03
```

```
6 0.03
```

```
7 0.001
```

```
8 0.005
```

```
9 0.00000001
```

```
10 0.00000001
```

```
11 0.01
```

```
12 0.00000001
```

```
13 0.001
```

```
14 0.001
```

```
15 0.005
```

```
16 0.01
```

```
17 0.00000001
```

```
18 0.02
```

```
19 0.015
```

```
20 0.00000001
```

```
21 0.04
```

```
22 0.00000001
```

```
23 0.00000001
```

```
24 0.00000001
```

```
25 0.03
```

```
26 0.00000001
```

```
27 0.00000001
```

```
28 0.001
```

```
29 0.02
```


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

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

106 0.00000001
107 0.02
108 0.005
109 0.02
110 0.00000001
111 0.00000001
112 0.00000001
113 0.00000001
114 0.008
115 0.00001
116 0.06
117 0.00000001
118 0.02
119 0.015
120 0.02
121 0.005
122 0.005
123 0.005
124 0.00000001
125 0.01
126 0.001
127 0.00001
128 0.01
129 0.01
130 0.005
131 0.00000001
132 0.01
133 0.005
134 0.08
135 0.001
136 0.00000001
137 0.00000001
138 0.00000001
139 0.00000001
140 0.00000001
141 0.001
142 0.025
143 0.00000001

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

182 0.03
183 0.001
184 0.00000001
185 0.02
186 0.0001
187 0.00000001
188 0.005
189 0.00000001
190 0.00000001
191 0.00000001
192 0.01
193 0.00001
194 0.005
195 0.01
196 0.00000001
197 0.00000001
198 0.04
199 0.01
200 0.015
201 0.01
202 0.005
203 0.002
204 0.00000001
205 0.001
206 0.02
207 0.00000001
208 0.005
209 0.02
210 0.005
211 0.001
212 0.02
213 0.00000001
214 0.02
215 0.01
216 0.001
217 0.00000001
218 0.08
219 0.00000001

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

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

296 0.00000001
297 0.001
298 0.012
299 0.01
300 0.00000001
301 0.00000001
302 0.00000001
303 0.005
304 0.00000001
305 0.02
306 0.01
307 0.00000001
308 0.005
309 0.00000001
310 0.00000001
311 0.00000001
312 0.001
313 0.005
314 0.02
315 0.03
316 0.02
317 0.00000001
318 0.03
319 0.01
320 0.03
321 0.025
322 0.02
323 0.00000001
324 0.005
325 0.01
326 0.005
327 0.005
328 0.01
329 0.00000001
330 0.00000001
331 0.00000001
332 0.02
333 0.01

334 0.005
335 0.03
336 0.00000001
337 0.00000001
338 0.005
339 0.00000001
340 0.01
341 0.001
342 0.005
343 0.00000001
344 0.02
345 0.03
346 0.00000001
347 0.005
348 0.01
349 0.001
350 0.02
351 0.00000001
352 0.03
353 0.01
354 0.01
355 0.00000001
356 0.01
357 0.05
358 0.02
359 0.008
360 0.008
361 0.005
362 0.02
363 0.03
364 0.03
365 0.001
366 0.02
367 0.02
368 0.00000001
369 0.02
370 0.00000001
371 0.02

372 0.003
373 0.001
374 0.00000001
375 0.00001
376 0.02
377 0.0001
378 0.00000001
379 0.06
380 0.01
381 0.00000001
382 0.005
383 0.00000001
384 0.002
385 0.01
386 0.03
387 0.02
388 0.01
389 0.01
390 0.08
391 0.00000001
392 0.001
393 0.00000001
394 0.00000001
395 0.01
396 0.005
397 0.025
398 0.00000001
399 0.00000001
400 0.001
401 0.00000001
402 0.00000001
403 0.00000001
404 0.06
405 0.00000001
406 0.003
407 0.00000001
408 0.005
409 0.02

410 0.00000001
411 0.005
412 0.02
413 0.00001
414 0.00000001
415 0.001
416 0.00000001
417 0.001
418 0.01
419 0.00000001
420 0.01
421 0.005
422 0.00000001
423 0.015
424 0.01
425 0.01
426 0.02
427 0.00000001
428 0.001
429 0.005
430 0.02
431 0.01
432 0.003
433 0.002
434 0.01
435 0.00000001
436 0.01
437 0.01
438 0.01
439 0.06
440 0.01
441 0.001
442 0.01
443 0.012
444 0.002
445 0.03
446 0.00000001
447 0.00000001

448 0.00001
449 0.001
450 0.02
451 0.03
452 0.02
453 0.008
454 0.04
455 0.00000001
456 0.01
457 0.01
458 0.01
459 0.01
460 0.001
461 0.001
462 0.00000001
463 0.01
464 0.01
465 0.02
466 0.00000001
467 0.00000001
468 0.01
469 0.001
470 0.015
471 0.00000001
472 0.005
473 0.001
474 0.00000001
475 0.001
476 0.00000001
477 0.001
478 0.00000001
479 0.002
480 0.0001
481 0.005
482 0.04
483 0.001
484 0.003
485 0.002

486 0.001
487 0.01
488 0.005
489 0.01
490 0.00000001
491 0.03
492 0.02
493 0.025
494 0.005
495 0.01
496 0.005
497 0.02
498 0.0001
499 0.00000001
500 0.025
501 0.00000001
502 0.02
503 0.005
504 0.005
505 0.025
506 0.001
507 0.02
508 0.02
509 0.005
510 0.001
511 0.02
512 0.02
513 0.0005
514 0.00000001
515 0.005
516 0.015
517 0.002
518 0.02
519 0.01
520 0.00000001
521 0.00000001
522 0.01
523 0.03

524 0.00000001
525 0.01
526 0.001
527 0.02
528 0.01
529 0.07
530 0.01
531 0.00000001
532 0.00000001
533 0.00000001
534 0.07
535 0.05
536 0.025
537 0.02
538 0.01
539 0.00000001
540 0.02
541 0.005
542 0.005
543 0.03
544 0.00001
545 0.00000001
546 0.00000001
547 0.00000001
548 0.02
549 0.00000001
550 0.025
551 0.001
552 0.00000001
553 0.001
554 0.00000001
555 0.00000001
556 0.001
557 0.01
558 0.01
559 0.001
560 0.00000001
561 0.005

562 0.01
563 0.02
564 0.03
565 0.00000001
566 0.00000001
567 0.03
568 0.00000001
569 0.001
570 0.0001
571 0.00000001
572 0.001
573 0.0005
574 0.00000001
575 0.00000001
576 0.005
577 0.008
578 0.001
579 0.01
580 0.001
581 0.02
582 0.02
583 0.00005
584 0.00000001
585 0.001
586 0.005
587 0.001
588 0.01
589 0.001
590 0.00000001
591 0.02
592 0.005
593 0.02
594 0.005
595 0.00000001
596 0.01
597 0.005
598 0.01
599 0.0005

600 0.015
601 0.025
602 0.00000001
603 0.02
604 0.01
605 0.025
606 0.00000001
607 0.02
608 0.02
609 0.02
610 0.00000001
611 0.01
612 0.025
613 0.001
614 0.00001
615 0.01
616 0.02
617 0.02
618 0.00000001
619 0.02
620 0.01
621 0.00000001
622 0.03
623 0.01
624 0.008
625 0.001
626 0.015
627 0.001
628 0.00000001
629 0.00000001
630 0.00000001
631 0.00000001
632 0.02
633 0.001
634 0.02
635 0.03
636 0.005
637 0.005

638 0.00000001
639 0.001
640 0.08
641 0.0005
642 0.00000001
643 0.005
644 0.02
645 0.001
646 0.00000001
647 0.02
648 0.01
649 0.00000001
650 0.01
651 0.00000001
652 0.03
653 0.06
654 0.01
655 0.00005
656 0.005
657 0.00000001
658 0.002
659 0.01
660 0.025
661 0.00005
662 0.015
663 0.00000001
664 0.02
665 0.015
666 0.0025
667 0.01
668 0.002
669 0.001
670 0.015
671 0.02
672 0.01
673 0.01
674 0.01
675 0.001

676 0.00000001
677 0.01
678 0.02
679 0.00000001
680 0.02
681 0.005
682 0.07
683 0.002
684 0.07
685 0.005
686 0.015
687 0.00001
688 0.05
689 0.03
690 0.00000001
691 0.00000001
692 0.00000001
693 0.01
694 0.005
695 0.0005
696 0.03
697 0.001
698 0.01
699 0.00000001
700 0.005
701 0.01
702 0.00000001
703 0.01
704 0.005
705 0.00000001
706 0.02
707 0.01
708 0.00000001
709 0.001
710 0.01
711 0.00000001
712 0.00000001
713 0.01

714 0.01
715 0.01
716 0.001
717 0.02
718 0.0025
719 0.025
720 0.00000001
721 0.02
722 0.001
723 0.001
724 0.001
725 0.00000001
726 0.02
727 0.00001
728 0.003
729 0.01
730 0.03
731 0.06
732 0.01
733 0.00000001
734 0.03
735 0.001
736 0.00000001
737 0.00000001
738 0.00000001
739 0.01
740 0.005
741 0.025
742 0.00000001
743 0.01
744 0.05
745 0.02
746 0.01
747 0.01
748 0.005
749 0.01
750 0.002
751 0.00001

752 0.005
753 0.005
754 0.05
755 0.00000001
756 0.00000001
757 0.00000001
758 0.02
759 0.001
760 0.01
761 0.025
762 0.025
763 0.005
764 0.00000001
765 0.02
766 0.00000001
767 0.00000001
768 0.02
769 0.00000001
770 0.00000001
771 0.00000001
772 0.01
773 0.025
774 0.001
775 0.01
776 0.00000001
777 0.00000001
778 0.01
779 0.01
780 0.08
781 0.005
782 0.04
783 0.08
784 0.00000001
785 0.02
786 0.01
787 0.00000001
788 0.01
789 0.00000001

790 0.015
791 0.008
792 0.015
793 0.008
794 0.02
795 0.001
796 0.00000001
797 0.00000001
798 0.03
799 0.03
800 0.02
801 0.00001
802 0.00000001
803 0.001
804 0.005
805 0.01
806 0.001
807 0.05
808 0.001
809 0.01
810 0.00000001
811 0.01
812 0.01
813 0.001
814 0.00000001
815 0.015
816 0.001
817 0.005
818 0.00000001
819 0.03
820 0.001
821 0.00000001
822 0.03
823 0.01
824 0.005
825 0.02
826 0.00000001
827 0.00000001

828 0.02
829 0.00000001
830 0.02
831 0.00000001
832 0.001
833 0.08
834 0.003
835 0.03
836 0.07
837 0.001
838 0.03
839 0.02
840 0.01
841 0.01
842 0.00000001
843 0.00000001
844 0.04
845 0.02
846 0.00001
847 0.005
848 0.00000001
849 0.005
850 0.0001
851 0.0001
852 0.03
853 0.00001
854 0.02
855 0.01
856 0.001
857 0.00000001
858 0.005
859 0.06
860 0.01
861 0.02
862 0.00000001
863 0.001
864 0.00000001
865 0.00000001

866 0.02
867 0.03
868 0.001
869 0.00000001
870 0.01
871 0.00000001
872 0.005
873 0.02
874 0.00000001
875 0.08
876 0.005
877 0.005
878 0.01
879 0.001
880 0.003
881 0.02
882 0.012
883 0.02
884 0.01
885 0.01
886 0.00000001
887 0.03
888 0.00000001
889 0.001
890 0.03
891 0.02
892 0.00000001
893 0.03
894 0.02
895 0.00000001
896 0.005
897 0.001
898 0.01
899 0.00000001
900 0.01
901 0.015
902 0.00000001
903 0.01

904 0.00000001
905 0.00000001
906 0.00000001
907 0.08
908 0.00000001
909 0.001
910 0.01
911 0.00001
912 0.001
913 0.001
914 0.01
915 0.005
916 0.008
917 0.03
918 0.00000001
919 0.005
920 0.00000001
921 0.00000001
922 0.00000001
923 0.005
924 0.001
925 0.02
926 0.02
927 0.01
928 0.00001
929 0.00000001
930 0.02
931 0.01
932 0.00000001
933 0.001
934 0.02
935 0.005
936 0.00000001
937 0.001
938 0.005
939 0.01
940 0.005
941 0.01

942 0.01
943 0.015
944 0.05
945 0.03
946 0.002
947 0.001
948 0.0001
949 0.02
950 0.002
951 0.02
952 0.02
953 0.00000001
954 0.001
955 0.00000001
956 0.06
957 0.02
958 0.01
959 0.005
960 0.00000001
961 0.00000001
962 0.05
963 0.0005
964 0.02
965 0.02
966 0.01
967 0.01
968 0.05
969 0.001
970 0.02
971 0.01
972 0.00000001
973 0.00000001
974 0.00000001
975 0.008
976 0.005
977 0.00000001
978 0.02
979 0.01

```
980 0.08
981 0.005
982 0.0025
983 0.02
984 0.06
985 0.0005
986 0.005
987 0.025
988 0.02
989 0.00000001
990 0.00000001
991 0.01
992 0.008
993 0.00000001
994 0.001
995 0.01
996 0.00000001
997 0.005
998 0.00000001
999 0.00000001
1000 0.00000001;
```

```
param etas:=
1 1.00000010
2 1.00000010
3 1.00000010
4 0.50000000
5 1.00000010
6 2.00000000
7 1.50000000
8 2.50000000
9 1.00000010
10 0.70000000
11 1.00000010
12 0.50000000
13 0.50000000
14 0.50000000
15 2.00000000
```

16 2.00000000
17 1.00000010
18 1.00000010
19 2.00000000
20 1.00000010
21 1.30000000
22 0.70000000
23 1.00000010
24 1.00000010
25 0.50000000
26 2.50000000
27 2.00000000
28 0.50000000
29 1.00000010
30 1.00000010
31 1.00000010
32 1.00000010
33 2.00000000
34 0.50000000
35 2.00000000
36 2.00000000
37 1.20000000
38 0.50000000
39 1.50000000
40 2.00000000
41 1.00000010
42 1.50000000
43 1.50000000
44 0.20000000
45 1.00000010
46 1.50000000
47 1.25000000
48 1.00000010
49 1.00000010
50 1.00000010
51 2.00000000
52 1.00000010
53 0.20000000

54 1.50000000
55 2.50000000
56 1.50000000
57 2.00000000
58 0.20000000
59 1.00000010
60 1.00000010
61 3.00000000
62 1.00000010
63 0.20000000
64 1.50000000
65 1.00000010
66 1.00000010
67 3.00000000
68 1.50000000
69 2.00000000
70 0.50000000
71 1.40000000
72 2.00000000
73 0.50000000
74 4.00000000
75 0.25000000
76 0.80000000
77 1.00000010
78 1.00000010
79 1.00000010
80 1.00000010
81 3.00000000
82 1.00000010
83 1.50000000
84 2.00000000
85 0.50000000
86 0.50000000
87 0.20000000
88 1.00000010
89 1.50000000
90 2.00000000
91 1.00000010

92 1.00000010
93 1.00000010
94 1.00000010
95 2.00000000
96 0.50000000
97 0.50000000
98 0.20000000
99 1.00000010
100 4.00000000
101 0.50000000
102 2.00000000
103 1.50000000
104 1.00000010
105 1.00000010
106 1.20000000
107 1.00000010
108 1.50000000
109 2.50000000
110 1.00000010
111 1.30000000
112 1.00000010
113 1.50000000
114 2.00000000
115 2.00000000
116 0.00000100
117 1.50000000
118 0.25000000
119 1.00000010
120 2.50000000
121 0.20000000
122 2.00000000
123 1.50000000
124 0.00000100
125 1.00000010
126 1.00000010
127 1.50000000
128 1.50000000
129 1.50000000

130 1.00000010
131 1.50000000
132 1.40000000
133 0.00000100
134 0.50000000
135 2.00000000
136 0.50000000
137 0.50000000
138 1.00000010
139 1.00000010
140 1.50000000
141 2.00000000
142 3.00000000
143 1.00000010
144 1.00000010
145 1.80000000
146 2.00000000
147 5.00000000
148 1.00000010
149 1.00000010
150 0.60000000
151 1.00000010
152 2.00000000
153 1.50000000
154 1.00000010
155 1.50000000
156 1.00000010
157 0.20000000
158 0.90000000
159 1.50000000
160 1.00000010
161 1.00000010
162 1.00000010
163 1.00000010
164 1.00000010
165 1.00000010
166 3.00000000
167 1.40000000

168 1.00000010
169 1.00000010
170 2.00000000
171 1.00000010
172 1.00000010
173 1.00000010
174 1.20000000
175 2.00000000
176 4.00000000
177 2.00000000
178 4.00000000
179 0.50000000
180 0.90000000
181 2.00000000
182 3.00000000
183 2.00000000
184 1.00000010
185 1.20000000
186 1.50000000
187 3.00000000
188 3.00000000
189 0.80000000
190 1.00000010
191 1.30000000
192 1.00000010
193 0.20000000
194 0.90000000
195 1.00000010
196 0.20000000
197 1.50000000
198 1.00000010
199 1.25000000
200 0.90000000
201 3.00000000
202 1.30000000
203 1.50000000
204 0.00000100
205 1.00000010

206 1.00000010
207 1.50000000
208 0.50000000
209 0.10000000
210 1.10000000
211 1.00000010
212 1.50000000
213 4.00000000
214 1.00000010
215 1.00000010
216 2.00000000
217 2.00000000
218 4.00000000
219 1.00000010
220 1.20000000
221 2.00000000
222 0.50000000
223 0.50000000
224 2.00000000
225 1.00000010
226 1.00000010
227 2.00000000
228 1.00000010
229 1.00000010
230 0.10000000
231 0.00000100
232 0.25000000
233 0.20000000
234 1.00000010
235 1.00000010
236 1.00000010
237 2.00000000
238 2.00000000
239 3.00000000
240 0.00000100
241 2.50000000
242 1.00000010
243 0.50000000

244 2.00000000
245 1.50000000
246 1.30000000
247 0.00000100
248 1.00000010
249 2.00000000
250 1.00000010
251 1.00000010
252 2.00000000
253 0.50000000
254 1.30000000
255 1.50000000
256 0.20000000
257 0.50000000
258 0.50000000
259 2.00000000
260 2.00000000
261 1.00000010
262 1.00000010
263 1.00000010
264 1.00000010
265 0.80000000
266 1.00000010
267 2.00000000
268 0.25000000
269 1.50000000
270 2.00000000
271 2.00000000
272 1.00000010
273 1.50000000
274 1.00000010
275 2.50000000
276 1.00000010
277 1.00000010
278 0.50000000
279 2.00000000
280 2.00000000
281 1.00000010

282 1.00000010
283 1.50000000
284 3.00000000
285 1.50000000
286 0.20000000
287 2.00000000
288 1.50000000
289 1.00000010
290 1.00000010
291 1.00000010
292 2.00000000
293 1.00000010
294 2.00000000
295 1.50000000
296 1.00000010
297 1.30000000
298 1.40000000
299 1.50000000
300 0.50000000
301 1.00000010
302 2.00000000
303 0.70000000
304 1.00000010
305 2.00000000
306 1.00000010
307 1.00000010
308 2.00000000
309 0.25000000
310 2.00000000
311 1.00000010
312 2.00000000
313 1.00000010
314 2.00000000
315 1.00000010
316 2.00000000
317 1.00000010
318 0.90000000
319 1.50000000

320 0.90000000
321 1.00000010
322 1.00000010
323 0.50000000
324 1.00000010
325 1.50000000
326 2.00000000
327 1.00000010
328 0.20000000
329 2.00000000
330 1.00000010
331 1.00000010
332 0.80000000
333 1.80000000
334 1.10000000
335 2.00000000
336 0.50000000
337 1.00000010
338 1.00000010
339 1.00000010
340 0.50000000
341 0.50000000
342 0.50000000
343 3.00000000
344 1.00000010
345 0.20000000
346 1.00000010
347 4.00000000
348 1.00000010
349 0.00000100
350 1.50000000
351 1.00000010
352 1.30000000
353 2.00000000
354 0.50000000
355 3.00000000
356 1.00000010
357 0.20000000

358 1.00000010
359 2.00000000
360 0.20000000
361 0.20000000
362 1.00000010
363 1.00000010
364 1.00000010
365 1.00000010
366 0.70000000
367 0.20000000
368 1.50000000
369 2.00000000
370 1.25000000
371 1.80000000
372 1.00000010
373 0.33300000
374 1.00000010
375 1.00000010
376 1.00000010
377 0.50000000
378 1.20000000
379 1.00000010
380 1.00000010
381 1.50000000
382 1.00000010
383 1.00000010
384 0.50000000
385 0.50000000
386 1.00000010
387 1.80000000
388 2.00000000
389 2.00000000
390 0.20000000
391 0.50000000
392 5.00000000
393 2.00000000
394 2.00000000
395 1.00000010

396 5.00000000
397 1.00000010
398 1.50000000
399 2.00000000
400 1.00000010
401 1.30000000
402 1.00000010
403 1.00000010
404 2.00000000
405 1.00000010
406 1.00000010
407 2.00000000
408 1.00000010
409 0.25000000
410 1.00000010
411 1.25000000
412 0.50000000
413 1.30000000
414 0.50000000
415 2.00000000
416 1.50000000
417 2.00000000
418 0.50000000
419 0.70000000
420 2.50000000
421 1.00000010
422 2.00000000
423 1.50000000
424 0.33300000
425 2.00000000
426 2.00000000
427 1.30000000
428 0.10000000
429 2.00000000
430 3.00000000
431 2.00000000
432 1.00000010
433 2.00000000

434 5.00000000
435 0.70000000
436 0.70000000
437 1.00000010
438 0.20000000
439 1.00000010
440 1.00000010
441 1.30000000
442 1.00000010
443 1.50000000
444 1.00000010
445 3.00000000
446 1.00000010
447 2.00000000
448 0.50000000
449 1.00000010
450 2.00000000
451 2.00000000
452 3.00000000
453 0.25000000
454 2.00000000
455 1.50000000
456 1.00000010
457 2.00000000
458 1.00000010
459 0.50000000
460 1.40000000
461 2.00000000
462 1.00000010
463 1.00000010
464 1.30000000
465 4.00000000
466 2.50000000
467 2.00000000
468 0.80000000
469 1.20000000
470 1.00000010
471 1.50000000

472 2.00000000
473 1.00000010
474 1.00000010
475 0.50000000
476 2.00000000
477 1.50000000
478 0.50000000
479 0.90000000
480 2.00000000
481 0.50000000
482 1.00000010
483 2.00000000
484 2.00000000
485 1.00000010
486 0.33300000
487 1.00000010
488 1.50000000
489 1.00000010
490 2.00000000
491 0.20000000
492 1.00000010
493 0.00000100
494 2.00000000
495 2.00000000
496 3.00000000
497 1.00000010
498 2.00000000
499 1.50000000
500 1.50000000
501 0.50000000
502 2.00000000
503 2.00000000
504 1.00000010
505 0.50000000
506 2.00000000
507 2.00000000
508 1.50000000
509 1.00000010

510 2.00000000
511 1.30000000
512 0.90000000
513 1.00000010
514 0.20000000
515 1.00000010
516 1.50000000
517 2.00000000
518 0.50000000
519 0.50000000
520 2.00000000
521 2.00000000
522 2.00000000
523 1.00000010
524 1.50000000
525 2.00000000
526 2.00000000
527 0.90000000
528 1.00000010
529 2.50000000
530 1.50000000
531 1.00000010
532 3.00000000
533 1.00000010
534 1.00000010
535 1.00000010
536 1.50000000
537 0.50000000
538 0.20000000
539 1.00000010
540 2.00000000
541 0.50000000
542 2.00000000
543 2.00000000
544 0.50000000
545 1.00000010
546 0.50000000
547 2.00000000

548 1.00000010
549 1.70000000
550 1.00000010
551 1.00000010
552 1.50000000
553 1.50000000
554 2.00000000
555 1.50000000
556 1.50000000
557 0.50000000
558 3.00000000
559 1.50000000
560 1.00000010
561 0.90000000
562 4.00000000
563 2.00000000
564 1.00000010
565 1.50000000
566 0.90000000
567 3.00000000
568 1.00000010
569 5.00000000
570 2.00000000
571 1.40000000
572 2.00000000
573 1.00000010
574 1.00000010
575 0.50000000
576 1.50000000
577 1.50000000
578 1.00000010
579 1.00000010
580 1.50000000
581 0.50000000
582 1.00000010
583 1.00000010
584 1.00000010
585 1.00000010

586 0.50000000
587 1.00000010
588 0.50000000
589 1.00000010
590 0.50000000
591 1.00000010
592 1.00000010
593 1.00000010
594 1.00000010
595 2.00000000
596 0.50000000
597 2.00000000
598 1.40000000
599 1.00000010
600 0.33300000
601 1.50000000
602 0.33300000
603 0.50000000
604 2.00000000
605 1.00000010
606 0.20000000
607 1.50000000
608 0.20000000
609 2.00000000
610 1.50000000
611 1.00000010
612 0.50000000
613 1.50000000
614 2.00000000
615 0.50000000
616 2.00000000
617 0.90000000
618 1.50000000
619 1.50000000
620 0.80000000
621 1.20000000
622 1.00000010
623 1.50000000

624 0.70000000
625 2.00000000
626 1.00000010
627 0.50000000
628 1.50000000
629 1.00000010
630 2.00000000
631 3.00000000
632 2.00000000
633 1.20000000
634 2.00000000
635 2.00000000
636 1.00000010
637 1.30000000
638 2.00000000
639 0.20000000
640 0.50000000
641 0.50000000
642 1.00000010
643 2.00000000
644 2.00000000
645 1.50000000
646 5.00000000
647 2.00000000
648 0.25000000
649 0.60000000
650 2.00000000
651 0.00000100
652 2.00000000
653 1.80000000
654 1.00000010
655 4.00000000
656 1.50000000
657 1.00000010
658 2.00000000
659 1.00000010
660 0.90000000
661 1.00000010

662 1.50000000
663 1.50000000
664 1.00000010
665 0.10000000
666 1.50000000
667 1.30000000
668 0.50000000
669 3.00000000
670 2.00000000
671 0.20000000
672 3.00000000
673 1.50000000
674 1.00000010
675 1.00000010
676 3.00000000
677 3.00000000
678 2.00000000
679 0.20000000
680 1.00000010
681 1.30000000
682 2.00000000
683 2.00000000
684 1.50000000
685 1.00000010
686 1.00000010
687 0.20000000
688 1.00000010
689 0.80000000
690 2.00000000
691 0.60000000
692 1.00000010
693 1.00000010
694 0.10000000
695 1.30000000
696 1.00000010
697 1.50000000
698 0.20000000
699 0.50000000

700 1.10000000
701 1.50000000
702 1.20000000
703 0.33300000
704 0.50000000
705 2.00000000
706 1.00000010
707 0.70000000
708 0.70000000
709 0.66660000
710 2.00000000
711 1.00000010
712 2.00000000
713 1.00000010
714 2.00000000
715 3.00000000
716 1.00000010
717 1.00000010
718 1.00000010
719 1.00000010
720 1.50000000
721 3.00000000
722 2.00000000
723 1.40000000
724 4.00000000
725 1.20000000
726 2.00000000
727 1.00000010
728 2.00000000
729 1.50000000
730 1.00000010
731 1.00000010
732 0.70000000
733 2.00000000
734 0.50000000
735 2.00000000
736 0.00000100
737 0.50000000

738 0.50000000
739 3.00000000
740 2.00000000
741 1.20000000
742 2.00000000
743 1.30000000
744 2.00000000
745 2.00000000
746 2.00000000
747 0.80000000
748 1.50000000
749 0.33300000
750 2.00000000
751 1.50000000
752 0.80000000
753 1.50000000
754 0.10000000
755 2.00000000
756 0.10000000
757 2.00000000
758 0.50000000
759 2.00000000
760 1.00000010
761 1.30000000
762 3.00000000
763 1.50000000
764 0.25000000
765 0.80000000
766 0.33300000
767 0.10000000
768 1.20000000
769 2.00000000
770 2.00000000
771 1.00000010
772 0.50000000
773 1.00000010
774 1.00000010
775 1.50000000

776 1.30000000
777 0.70000000
778 1.50000000
779 1.00000010
780 2.00000000
781 2.00000000
782 2.00000000
783 1.20000000
784 1.20000000
785 0.50000000
786 1.00000010
787 1.50000000
788 1.00000010
789 0.50000000
790 1.50000000
791 1.20000000
792 0.50000000
793 1.50000000
794 1.00000010
795 2.00000000
796 2.00000000
797 1.20000000
798 1.00000010
799 2.00000000
800 0.50000000
801 2.00000000
802 1.00000010
803 1.00000010
804 1.00000010
805 1.00000010
806 2.00000000
807 2.00000000
808 1.00000010
809 0.50000000
810 1.50000000
811 1.30000000
812 0.00000100
813 1.00000010

814 1.00000010
815 1.00000010
816 0.90000000
817 2.00000000
818 0.80000000
819 1.50000000
820 0.90000000
821 1.50000000
822 1.00000010
823 1.00000010
824 4.00000000
825 0.50000000
826 2.00000000
827 3.00000000
828 0.50000000
829 1.50000000
830 1.50000000
831 1.00000010
832 1.50000000
833 1.50000000
834 1.00000010
835 1.50000000
836 1.00000010
837 2.50000000
838 1.80000000
839 1.00000010
840 1.00000010
841 2.00000000
842 1.00000010
843 3.00000000
844 1.00000010
845 1.50000000
846 1.00000010
847 1.00000010
848 1.00000010
849 0.50000000
850 1.00000010
851 1.00000010

852 2.00000000
853 3.00000000
854 1.00000010
855 3.00000000
856 1.00000010
857 0.90000000
858 1.00000010
859 0.20000000
860 2.00000000
861 0.00000100
862 1.30000000
863 1.00000010
864 1.00000010
865 2.00000000
866 2.00000000
867 3.00000000
868 1.20000000
869 1.00000010
870 0.10000000
871 1.00000010
872 1.00000010
873 1.00000010
874 0.10000000
875 1.50000000
876 1.00000010
877 2.00000000
878 2.00000000
879 1.00000010
880 0.90000000
881 1.20000000
882 1.50000000
883 2.00000000
884 1.00000010
885 1.50000000
886 0.70000000
887 1.00000010
888 1.50000000
889 1.50000000

890 1.20000000
891 1.00000010
892 2.00000000
893 1.00000010
894 0.50000000
895 0.50000000
896 0.20000000
897 2.00000000
898 1.50000000
899 0.25000000
900 0.50000000
901 2.00000000
902 1.00000010
903 1.00000010
904 2.00000000
905 2.00000000
906 1.00000010
907 1.00000010
908 1.00000010
909 1.00000010
910 1.00000010
911 2.50000000
912 1.00000010
913 3.00000000
914 1.00000010
915 1.00000010
916 1.00000010
917 2.00000000
918 2.00000000
919 0.50000000
920 2.50000000
921 2.00000000
922 1.30000000
923 0.33300000
924 1.50000000
925 0.60000000
926 0.60000000
927 1.00000010

928 0.80000000
929 2.00000000
930 2.00000000
931 1.00000010
932 2.00000000
933 2.00000000
934 1.20000000
935 0.90000000
936 1.25000000
937 0.50000000
938 3.00000000
939 2.00000000
940 1.00000010
941 1.00000010
942 1.00000010
943 0.00000100
944 2.00000000
945 2.00000000
946 2.00000000
947 0.20000000
948 1.50000000
949 1.30000000
950 0.00000100
951 5.00000000
952 2.50000000
953 2.00000000
954 2.00000000
955 1.00000010
956 0.20000000
957 2.00000000
958 1.00000010
959 1.00000010
960 1.00000010
961 0.10000000
962 1.50000000
963 1.00000010
964 1.00000010
965 0.80000000

966 2.00000000
967 1.80000000
968 0.50000000
969 2.00000000
970 1.00000010
971 0.20000000
972 1.00000010
973 2.00000000
974 1.00000010
975 1.50000000
976 1.80000000
977 1.00000010
978 1.00000010
979 5.00000000
980 2.00000000
981 0.50000000
982 2.00000000
983 1.50000000
984 3.00000000
985 1.00000010
986 1.00000010
987 2.00000000
988 2.00000000
989 1.00000010
990 1.00000010
991 1.00000010
992 1.00000010
993 0.50000000
994 0.20000000
995 2.00000000
996 0.50000000
997 0.70000000
998 1.50000000
999 1.00000010
1000 2.00000000;

(2) AMPL mod-file, Plausible Ranges

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

PARAMETERS

#Time horizon

param T default 100;

number of runs for Monte Carlo analysis

param nruns;

Preferences

param etas {1..nruns}; #I-EMUC consumption

param eta;

param rhos {1..nruns}; #time preference rate

param rho;

relative prices additions

param zeta=min(Normal(-0.11,0.17),1);

#substitution parameter, first value is central calibration

param beta default 0.1; #share of non-market good in utility function

param EQbar=max(Normal(7.77,3.96),0); #subsistence level of non-market good

param cbar default 0; #subsistence level of consumption per capita

Discount factor

param R {t in 0..T} = 1*exp(-rho*5*t);

Population and its dynamics

param L0:=7403; #initial world population 2015 (millions)

param gL0:=0.134; #growthrate to calibrate to 2050 pop projection

param L {t in 0..T}>=0;

let L[0]:=L0;

let {t in 1..T} L[t]:=L[t-1]*((11500/L[t-1])^gL0);

Technology and its dynamics

param gamma:=0.3; #capital elasticity in production function

param deltaK:=0.1; #depreciation rate on capital (per year)

```

param Qgross0:=105.5; #Initial world gross output 2015 (trill 2010 USD)
param K0:=223; #initial capital value 2015 (trillions 2010 USD)
param A0:=5.115; #initial level of total factor productivity
param gA0 :=0.076; #initial growth rate for TFP per 5 years
param deltaA=max(Normal(0.005,0.00255),0); #decline rate of TFP per 5 years

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

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

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

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

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

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

# Carbon cycle
param MAT0=851; # Initial Concentration in atmosphere 2015 (GtC)

```

```

param MUP0:=460; # Initial Concentration in upper strata 2015 (GtC)
param ML00:=1740; # Initial Concentration in lower strata 2015 (GtC)
param MATEQ:=588; # Equilibrium concentration in atmosphere (GtC)
param MUPEQ:=360; # Equilibrium concentration in upper strata (GtC)
param MLOEQ:=1720; # Equilibrium concentration in lower strata (GtC)

# Flow parameters (carbon cycle transition matrix)

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

# Climate model parameters
param nu:=3.1; # Equilibrium temperature impact (°C per doubling CO2)
param Fex0:=0.5; # 2015 forcings of non-CO2 GHG (Wm-2)
param Fex1:=1.0; # 2100 forcings of non-CO2 GHG (Wm-2)
param TL00:=0.0068; # Initial lower stratum temperature change (°C from 1900)
param TAT0:=0.85; # Initial atmospheric temp change (°C from 1900)
param xi1:=0.1005; # Speed of adjustment parameter for atmospheric temperature
param xi3:=0.088; # Coefficient of heat loss from atmosphere to oceans
param xi4:=0.025; # Coefficient of heat gain by deep oceans
param kappa:=3.6813; # Forcings of equilibrium CO2 doubling (Wm-2)
param xi2=kappa/nu; # climate model parameter

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

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

```

```

param MD default 0.0163; # market damages for 3°C warming (Nordhaus (2017))
param NMD=max(Normal(0.01646,0.0415),0);# non-market damages for 3°C warming
param TD=MD+NMD; # total damages
param TATlim default 12; # upper bound on atm. temperature change

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

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

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

# VARIABLES

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

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

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

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

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

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

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

```



```

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

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

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

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

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

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

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

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

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

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

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

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

# Investment(trillions 2005 USD)

```

```

var I {t in 0..T}>=0;

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

# Non-market damages scaling parameter including subsistence requirement

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

# growth rate of market good

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

# growth rate of non-market good

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

# relative price effect

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

# utility

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

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

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

```

```

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

# Initial conditions
subject to initial_capital: K[0] = K0;
subject to initial_Ecum: Ecum[0]=Ecum0;
subject to initial_MAT: MAT[0]=MAT0;
subject to initial_MUP: MUP[0]=MUP0;
subject to initial_MLO: MLO[0]=MLO0;
subject to initial_TLO: TLO[0]=TLO0;
subject to initial_TAT: TAT[0]=TAT0;
subject to initial_control: mu[0]=mu0;
subject to control1 {t in 1..28}: mu[t]<=1;
subject to control2 {t in 29..T}: mu[t]<=1.2; # from 2150

subject to initial_EQ: EQ[0]=C[0];
subject to constr_EQ {t in 1..T}: EQ[t]=(EQ[0]/(1+a[t]*(TAT[t]^2)));

```

AMPL-run file, Plausible Ranges

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