The relative price of environmental goods and climate policy evaluation

Moritz A. Drupp [a,*] and Martin C. Hänsel [a,‡]

[a] Department of Economics, University of Kiel, Germany

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Abstract: As environmental goods become relatively scarcer due to climate change, it is increasingly important to consider their relative price changes when evaluating long-term policies. This paper provides a comprehensive analysis of the determinants of the relative price of environmental goods, which amounts to the difference in the good-specific discount rates. Based on the integrated climate-economy model DICE, we show that the relative price effect is substantial compared to the effect of to commonly assumed discount rates. It ranges from 6 percent in 2020 to 3 percent in 2100. In terms of peak temperature stabilization, considering relative prices is equivalent to reducing societal pure time preference by more than 1 percentage point. Neglecting relative prices would lead to an underestimation of the social cost of carbon of more than 30 (130) percent in 2020 (2100). Our findings offer guidance for environmental policy and provide an argument for more stringent climate policies.

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

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[*] Both authors have contributed equally to this work. Correspondence: Department of Economics, University of Kiel, Wilhelm-Seelig-Platz 1, 24118 Kiel, Germany. Email: Drupp@economics.uni-kiel.de, Haensel@economics.uni-kiel.de; Phone: +49-431-880-4986.

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1 Introduction

While the global economy continues to grow, [1] there is a widespread loss of environmental goods or ecosystem services (Millenium Ecosystem Assessment 2005).[2] In light of this development, it becomes increasingly crucial to consider changes in the relative price of environmental goods—capturing at each point in time the scarcity of non-marketed environmental goods relative to marketed consumption goods—when evaluating long-term public policies.

In a prominent article, Sterner and Persson (2008) highlighted the implications of considering relative prices in the integrated assessment of climate change: They assumed that environmental goods are complementary to consumption goods and showed that optimal climate policy—when considering relative price effects—would be more stringent as advocated in the Stern Review (2007), even with the high utility discount rate of Nordhaus (2007). Indeed, a recent survey of experts on intergenerational decision-making has underscored that environmental scarcity, and associated relative price changes, is one of the most important issues missing in discounting guidance (Drupp et al. 2015). In the meantime, the Ministry of Finance of the Netherlands (MFN 2015) has started to consider relative price changes in cost-benefit analysis for policy guidance. It recommends to discount the consumption of environmental goods at a lower rate.

As changes in the relative price of environmental goods may play a substantial role for the appraisal of climate change policies and because of current policy needs for further guidance on dual discounting, it is imperative to scrutinise the relative price of environmental goods, its potential quantitative magnitude and its implications for climate policy more closely. This paper therefore provides a comprehensive, up-to-date analysis of the relative price effect of environmental goods.

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[1] See, e.g., Christensen et al. (2016) and Drupp et al. (2015) for expert predictions on growth rates.

[2] We consider environmental goods at a highly aggregate level to encompass all services provided by the natural environmental that humans 'consume' and value, ranging from clean water to aesthetic beauty. We therefore make no distinction between environmental goods and other commonly used terms, such as environmental quality or ecosystem services, in the remainder of this article.

The literature has developed two approaches to dealing with relative price changes, which are in particular determined by the degree of substitutability between environmental and human-made goods as well as their (weighted) growth rates.[3] In the first approach, we use 'dual discount rates' and explicitly discount consumption streams for human-made goods and for environmental goods separately.[4] In the second, more conventional approach, we compute comprehensive consumption equivalents for each period, by appropriately valuing non-marketed goods, and discount this aggregate bundle of consumption equivalents with a single consumption-equivalent discount rate. In each period, the implicit relative price of environmental goods is given by the marginal utility of consuming a further unit of environmental goods relative to human-made goods. This tells us by how much the consumption of human-made goods would need to increase for a marginal decrease in environmental good consumption in order to hold overall utility constant. The 'relative price effect' is the change of this relative valuation of environmental goods over time. The 'relative price effect' is the relevant measuring rod with which to determine future comprehensive consumption equivalents, and it will be the focus of our paper.

This paper adds to the literature by providing a comprehensive analysis of the fundamental determinants of the relative price effect of environmental goods and by quantitatively exploring their magnitude and importance for climate policy evaluation using the prominent integrated assessment model DICE (Nordhaus, 2014). These drivers include the degree of substitutability between human-made and environmental goods, the magnitude of non-market climate damages on the environmental good and an environmental subsistence requirement. The latter may be thought of as a preference-based measure of a 'planetary boundary' (Rockström et al. 2009) at the level of the representative agent. As the growth rate of consumption goods, which is also an important driver of

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

[4] This is the only viable approach if environmental and human-made consumption goods are perfect complements (Weikard and Zhu 2005). Otherwise, the two approaches are equivalent and, at each point in time, the difference in the good-specific discount rates corresponds to the 'relative price effect'.

relative prices, is endogenous in the DICE model, we also study how the pure rate of time preference, the elasticity of marginal utility of consumption as well as exogenous technological progress impact the relative price effect as well as the social cost of carbon.

We find that the relative price effect of environmental goods is substantial but decreases from around 6 percent in the year 2020 to 3 percent in the year 2100. Considering the different drivers of the relative price effect in the year 2020, we find that these change relative prices along an interval from 0 up to 9 percent along the considered parameter value ranges. Quantitatively, the two most important drivers of relative prices are the degree of substitutability between environmental and human-made goods as well as the economy's productivity growth, which is largely determined by exogenous technological progress. In terms of climate policy evaluation, we find that neglecting relative prices would lead to an underestimation of the social cost of carbon of more than 30 percent in the year 2020 and more than 130 percent in the year 2100. Considering the relative price of environmental goods would lead to a stabilization of the global temperature increase above pre-industrial levels at 0.7°C lower as compared to the optimal baseline policy approach of Nordhaus (2014). Thus, considering relative prices is equivalent to lowering the rate of societal pure time preference by more than 1 percentage point.

The paper is organized as follows. Section 2 provides a general model of the relative price effect of environmental goods in the presence of a subsistence threshold in the consumption of environmental goods. Subsequently, it shows how relative prices are captured in an integrated assessment model of climate change. Section 3 illustrates the impact of considering relative price effects for the evaluation of climate policy. Section 4 then scrutinizes in detail the impact of the fundamental drivers of the relative price effect. Section 5 concludes by discussing limitations of our analysis and offering guidance for discounting policy and climate policy appraisal.

2 Modelling the relative price of environmental goods

2.1 A simple model of the relative price effect

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-marketed environmental good E. Both goods may be interpreted as composites with continuously scalable amounts. The agent furthermore requires an amount $\overline{E}$ of the environmental good to satisfy her subsistence needs (Baumgärtner et al. 2017, Drupp 2016, Heal 2009).[5] The agent's preferences are represented by a utility function

$$U(E,c) = \begin{cases} U_l(E) & \text{for } E \leq \overline{E} \\ U_h(E,c) & \text{else}\,. \end{cases} \tag{1}$$

If the subsistence requirement is met, which we assume throught the remainder of this paper, utility is given by:

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

where θ is the substitutability parameter, and α is a share parameter for the weight of environmental goods in utility.[6] In the constant elasticity of substitution (CES) case without a subsistence requirement ($\overline{E} = 0$) that forms the workhorse of previous research on relative prices, the elasticity of substitution σ is solely determined by the exogenous substitutability parameter θ, with $\sigma = \dfrac{1}{1-\theta}$.[7] In the presence of a subsistence requirement, this direct relationship breaks down and the elasticity of substitution depends also on other model parameters and variables besides θ (Baumgärtner et al. 2017).

For the intertemporal setting, we build on Baumgärtner et al. (2015), Drupp (2016), Gueant et al. (2012), Hoel and Sterner (2007), Traeger (2011) and Weikard and Zhu

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[5] Examples may include food, water and air necessary for survival, but also cultural ecosystem services such as sacred sites that the agent would not be willing to trade-off.

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

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

(2005): A social planner has perfect knowledge about the future and maximizes a constant intertemporal elasticity of substitution (CIES) social welfare function based on the instantaneous utility function U_h (Equation 2). Welfare is given by

$$W = \sum_{t=0}^{T} L_t \frac{1}{(1+\delta)^t} \frac{1}{1-\eta} \left[\alpha(E_t - \overline{E})^\theta + (1-\alpha){c_t}^\theta\right]^{\frac{1-\eta}{\theta}} , \tag{3}$$

where L_t is period $t's$ population size, δ is the utility discount rate and η is the inverse of the CIES with respect to the within-period aggregate consumption bundle $\widetilde{c}(\theta, \overline{E}) = \left[\alpha(E_t - \overline{E})^\theta + (1-\alpha)(c_t)^\theta\right]^{\frac{1}{\theta}}$.

Based on this modelling set-up, we now turn to the focus of our analysis: the 'relative price effect of environmental goods' (hereafter denoted as RPE). It is a measure of the relative scarcity of environmental goods. The value of environmental goods measured in terms of the consumption good numeraire is U_E/U_c, which is the implicit 'price' of environmental goods.[8] This tells us by how much the consumption of human-made goods would need to increase for a marginal decrease in environmental goods in order to hold overall utility constant. The RPE is then defined as the change in this valuation of environmental goods over time and it is given by (Hoel and Sterner 2007, Eq. 7):

$$RPE_t = \frac{\frac{d}{dt}\left(\frac{U_E}{U_c}\right)}{\left(\frac{U_E}{U_c}\right)} . \tag{4}$$

For the utility function with an environmental subsistence requirement (Equation 2), the relative price effect RPE_t reads (see Appendix A.1 for a derivation):

$$RPE_t = (1-\theta)\left[g_{c_t} - \frac{E_t}{E_t - \overline{E}} g_{E_t}\right] .^{9} \tag{5}$$

The RPE depends on the degree of substitutability θ between human-made consumption goods and environmental goods, the growth rates g_{c_t} and g_{E_t} of the two composite goods as well as on the consumption of environmental goods over and above the subsistence requirement $\frac{E_t}{E_t - \overline{E}}$.

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

[9] This 'relative price effect of environmental goods' is the same as the difference in the two good specfic discount rates for man-made goods and environmental goods. This was demonstrated by Weikard and Zhu (2005); See Drupp (2016) for a derivation of Equation 5 based on dual-discount rates.

2.2 Relative prices in integrated assessment

Integrated assessment models (IAM) are a widespread tool for quantitatively analyzing climate-economy feedbacks and are therefore a relevant application for studying the dynamic impacts of considering relative prices in climate policy evaluation.[10]

We use the most prominent IAM, the global Dynamic Integrated Climate-Economy (DICE) model by William Nordhaus (Nordhaus 1992 - Nordhaus 2014). It combines a Ramsey-Economy with a simple climate module through a negative feedback loop of the atmospheric temperature on aggregate economic output. A representative agent maximizes her population-weighted and discounted value of per capita consumption within a finite time horizon of 60 periods.[11] In order to define the relative price effect (RPE) in the DICE setting, we need to specify two crucial functional forms: First, the social welfare function, determining the social intertemporal decision making of the representative agent and, second, the damage function capturing the severity of economic damages from temperature increases on both material consumption goods (market damages) and environmental goods (non-market damages). We want to transparently show the difference between the Nordhaus (2014) model and a DICE model including the relative price effect ßof environmental goods. We proceed in two steps: First we present how Nordhaus (2014) models social welfare and damages and subsequently report the necessary changes to both functional forms to include relative prices.

The social welfare function of the representative agent in Nordhaus (2014) is given by Equation (3), assuming perfect substitutability ($\theta = 1$) and the absence of a subsistence requirement ($\overline{E} = 0$). It reads:

$$W_0(c_0, c_1, c_2, \dots) = \sum_{t=0}^{60} L_t \frac{1}{(1+\delta)^t} \frac{\widetilde{c}_t^{1-\eta}}{1-\eta}. \tag{6}$$

Consumption per-capita $\widetilde{c}_t$ in (6) is here defined as an index of generalized consumption (Nordhaus and Szork 2013), which is meant to also include non-market damages on environmental goods. Total damages from climate change D_ϕ are expressed as a per-

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[10] It should be noted that IAMs are also subject to substantial crtique, see e.g. Pindyck (2015).

[11] One period encompasses 5 years. The planning horizon is therefore 300 years.

centage of the global economy's one-sector aggregate output and are assumed to depend on the squared change in atmospheric temperature T compared to pre-industrial levels.

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

The aggregate scaling parameter for the damages on all generalized consumption goods via production-damages, ϕ (Equation 7), is calibrated such that market plus non-market damages are equal to 2.25 percent of (initial) global output for a temperature increase of 2.9°C.[12] Using this aggregate scaling parameter in Equation (7) implies that the temperature-induced damage from climate change affects both material consumption and environmental goods in the same proportion and, consequently, that the relative price of environmental goods is implicitly assumed to be constant. Sterner and Persson (2008) show that neglecting relative price effects leads to a substantial underestimation of optimal climate change mitigation efforts, and that it is accordingly crucial to explicitly consider changing relative prices.

We study the 'relative price effect of environmental goods' in the most recent version of the DICE model (Nordhaus 2014) by considering that utility depends not only on consumption goods but also explicitly on environmental goods. We further consider a subsistence requirement $\overline{E}$ in the consumption of environmental goods, which may be thought of as a 'planetary boundary' for the consumption of environmental goods. Specifically we use the welfare function defined in (3):

$$W_0(E_t, c_t, L_t) = \sum_{t=0}^{60} L_t \frac{1}{(1+\delta)^t} \frac{1}{1-\eta} \left[\alpha[E_t - \overline{E}]^{\theta} + (1-\alpha)c_t^{\theta}\right]^{\frac{1-\eta}{\theta}} . \tag{8}$$

We follow the approach of Sterner and Persson (2008) for extending the DICE framework to a two-good setting. First, we assume that the initial level of the aggregate environmental good E_0 is equal to the initial level of consumption of human-made goods ($C_0 = c_0 \times L_0$). Second, we assume that the evolution of the environmental good is assumed to depend (inversely) on the square of the change in atmospheric temperature

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[12] Nordhaus (2014) builds on the meta-analysis of Tol (2009) and adds 25 percent to each damage estimate to incorporate non-market damages. He then calibrates ϕ by equating it with the coefficient of the impact of squared temperature change on climate damage estimates from an OLS regression.

T compared to pre-industrial levels and the damage parameter ψ:

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

Third, the overall climate damages of 2.25 percent of initial global output for a temperature increase of 2.9°C assumed in Nordhaus (2014) have to be disentangled into damages on human-made marketed consumption goods and damages on non-marketed environmental goods to avoid double counting. The two new damage parameters ψ [κ] now scale up the magnitude of non-market [market] damages, i.e. damages to the environmental good in particular due to climate change [damages to the consumption good via reduced production].

Based on Nordhaus (2014), we re-calibrate the damages on material consumption D_κ, by means of an OLS regression of temperature changes relative to pre-industrial levels on climate damage estimates in Tol (2009), but without adding the 25 percent non-market damage adjustment to each damage estimate from Tol's (2009) meta-analysis.[13] Hence, the new damage function only considers damages on material consumption.

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

To account for the 25 percent non-market damages in DICE, we follow the approach of Sterner and Persson (2008) to calibrate the environmental climate damage parameter ψ by comparing two different model specifications:[14] First, a model in which the non-market damage costs D_ϕ for a given climate sensitivity ν are perfectly substitutable for market goods and consequently are included in consumption directly. Second, a model in which the damages are attributed to both the consumption of market goods D_κ as well as the environmental good D_ψ. The parameter ψ is calibrated as a residual, with $C_0 = E_0$ and $\overline{E} = 0$ (see Appendix A.2), and depends in particular on the non-market damage costs.

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[13] See Howard and Sterner (2014) for a more detailed discussion of calibrating damages.

[14] While Sterner and Persson (2008) assumed that non-market damages amount to an additional 100 percent on top of market damages, we follow the more conservative assumption of Nordhaus (2014) and use a 25 percent non-market damage component for the sake of consistency and comparability.

With the evolution of the environmental good (Equation 9) and the calibrated environmental good climate damage coefficient ψ (see Equation (A.9) in the Appendix), we can specify the equation for the relative price effect in DICE:

$$RPE_t^{DICE} = (1-\theta)\left[g_{c_t}(\delta,\eta,...) + \frac{2\psi T_t \dot{T}_t}{(1+\psi T_t^2)}\left(\frac{E_0}{E_0 - \overline{E}(1+\psi T_t^2)}\right)\right].^{15} \quad (11)$$

Accordingly the RPE in DICE depends on three components: First the growth rate of the material consumption good g_{c_t}, which in DICE is optimally determined by the Ramsey Rule and thus depends on a number of key variables and parameters.[16] It is in particular driven by the exogenously assumed rate of technological progress as well as the distributional parameters of the social welfare function: the pure rate of time preference δ and the elasticity of the marginal utility of consumption η. Second, the growth rate of the environmental good g_{E_t}, which is a function of the assumed degree of non-market damages for a particular temperature increase T summarized in the damage parameter ψ, and is scaled by the size of the subsistence requirement $\overline{E}$. Finally, the difference in the two good-specific growth driver categories are scaled by the degree of substitutability θ between both goods.

In the following we analyze the impact of considering the relative price effect of environmental goods in the current DICE modelling structure and scrutinize the drivers of the relative price effect.

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[15] The growth rate of environmental 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 $T_t^2 - T_{t-1}^2 = \dot{T}_t^2 = 2T_t\dot{T}_t$ this is equivalent to the continuous time version.

[16] The growth rate of the material consumption good is determined by $g_{c_t} = \left[\left(\frac{1}{1+\delta}\right)(1 + Y_{K_t} - \xi\ )\right]^{\frac{1}{\eta}} - 1$, where ξ is the proportional rate of capital depreciation and Y_{K_t} is the marginal productivity of capital, which depends on labour L_t, capital C_t, climate damages $D_\phi(T_t)$ and is in particular driven by total factor productivity $A_t = \frac{A_{t-1}}{1-g_{t-1}^A}$. Total factor productivity A_t grows exogenously at a decreasing rate, with $g_t^A = g_0^A e^{-5t\tau^A}$, where τ^A can be interpreted as the exogenous depreciation of technological progress.

3 Relative prices and climate policy evaluation

In order to evaluate the impact of relative prices on optimal climate policy, we rely in particular on the social cost of carbon (SCC), i.e. the social cost of emitting an extra ton of CO_2 into the atmosphere. The SCC is a summary statistic, which captures the effects of key parameters like CO_2 emissions and the change in the atmospheric temperature relative to pre-industrial levels. It is widely used by governmental bodies to inform carbon pricing (e.g. by the US Interagency Working Group on Social Cost of Carbon (IWG 2010, 2013)). In DICE, the SCC is defined as the ratio of the marginal impact of total CO_{2_t} emissions on welfare to the marginal impact of aggregate consumption C_t on welfare at time t (Nordhaus 2014).[17]

$$SCC_t = -\frac{\partial W_t / \partial CO_{2_t}}{\partial W_t / \partial C_t} \tag{12}$$

We are interested in how optimal climate policy evaluation, as measured by the SCC, is driven by the relative price effect (RPE) in the DICE model.[18] We further consider the impact of considering relative prices in terms of industrial emissions and resulting atmospheric temperature change above pre-industrial levels.

Figure 1 provides an overview on how the baseline relative price effect of environmental goods evolves over time from the year of 2015 to 2100 and how it impacts industrial CO_2 emissions, temperature change and the SCC.[19] This baseline version of the relative price effect draws all parameter inputs from Nordhaus (2014), except for the preference share parameter of environmental goods α as well as the limited degree of substitutability θ, which are based on Sterner and Persson (2008). Furthermore, the climate damage coefficient for environmental goods ψ is calculated based on the approach Sterner and Persson (2008) as described in Section 2.2 (see Table 1 for an overview of the parameter specifications used in the baseline RPE version).

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[17] The negative sign in front of the ratio ensures that the SCC is calculated as a positive number.

[18] Note that for calculating the SCC, Nordhaus (2014) uses a discrete approximation to Equation (12) In contrast to Nordhaus (2014), we do not account for a backstop technology when computing the SCC.

[19] Although Figure 1 only presents development paths until 2100 in line with the literature, the computations consider the full planning horizon of DICE.

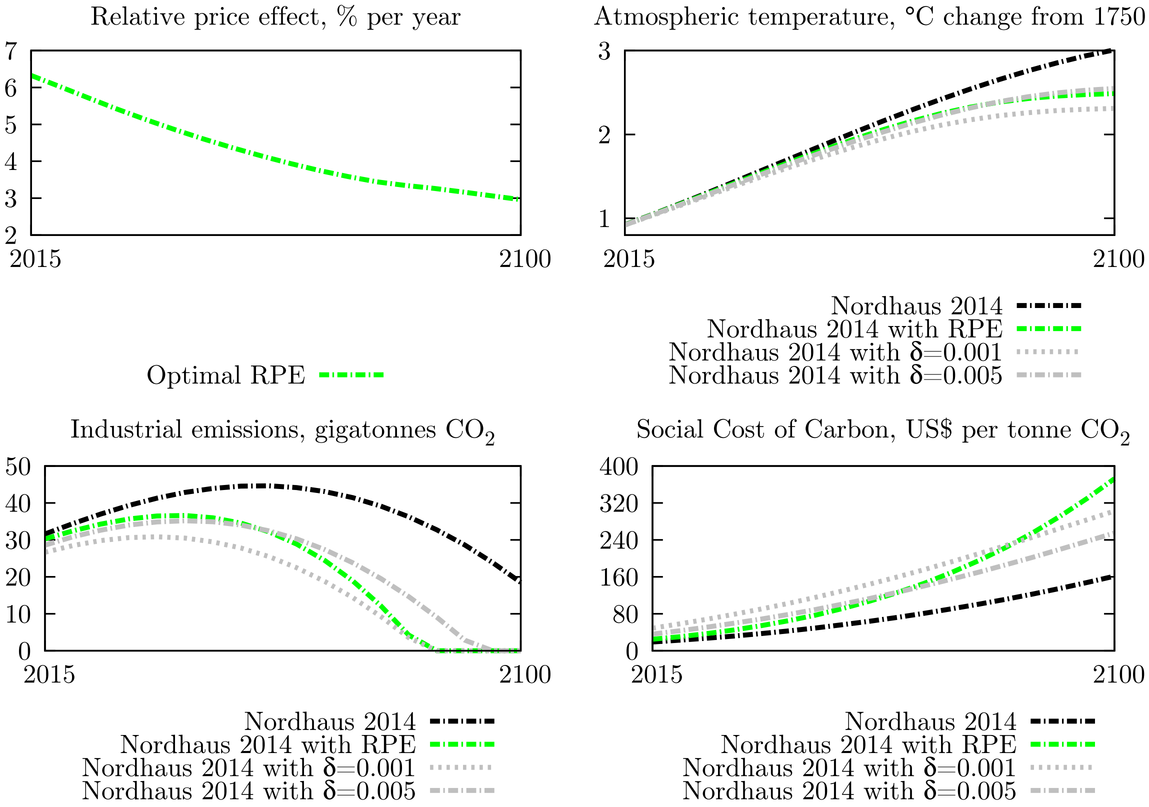

Figure 1: Relative price effect and comparison of climate policy paths. The black line depicts the Nordhaus (2014) baseline case. The green lines considers the relative price effect (*RPE*) based on Sterner and Persson (2008). The grey lines do not consider the *RPE* but instead a lower pure rate of time preference, δ, with dotted [dashed] depicting the case of Stern (2007) [the median expert of the Drupp et al. (2015) survey].

Table 1: Baseline parameter specifications

Parameter	δ	η	ϕ	κ	ψ	α	θ	$\overline{E}$
Baseline	0.015	1.45	0.00267	0.00213	0.00513	0.1	-1	0
Source*	N	N	N	N	N/S&P	S&P	S&P	N, S&P

* N denotes Nordhaus (2014), while S&P denotes Sterner and Persson (2008).
ψ is calibrated endogenously according to Equation A.9 for the baseline case.

Moreover, Figure 1 compares this baseline relative price effect case to three cases that do not consider relative price effects but that differ in their assumptions about the key discounting parameters—the pure rate of time preference, δ, and the elasticity of the marginal utility of consumption, η. First, we compare the baseline *RPE* case to the optimal climate policy trajectories resulting from Nordhaus (2014), thus providing the direct comparison case to the baseline relative price effect. Furthermore, to get an idea of how substantial the *RPE* is compared to commonly assumed discount rates, we consider two further cases with rates of pure time preferences that are lower than the one assumed in Nordhaus (2014): the assumptions of Stern (2007; $\delta = 0.001$) as well as the median response to the expert survey by Drupp et al. (2015; $\delta = 0.005$). We have chosen these cases to capture the findings of Sterner and Persson (2008) within the 2014-DICE modelling framework and to be able to compare the prominent discounting parameter assumptions of Nordhaus and Stern with those of a broader expert population.

The time path of the *RPE* depicted in the upper-left corner of Figure 1 shows that under optimal climate policy in DICE the *RPE* decreases over time from more than 6 percent in 2015 to about 3 percent in 2100. This decrease in the relative price effect is in particular driven by the declining growth rate of material consumption goods due to decreasing productivity growth. Furthermore, the representative agent directly cares for the environment and the social planner thus takes into account the negative effect of climate change on welfare and optimally invests into low-carbon energy technologies to dampen the adverse effects of increasing atmospheric temperature. Hence, the relative scarcity of environmental goods, as measured by the *RPE*, falls over time.[20]

The upper-right panel of Figure 1 shows that atmospheric temperature stabilizes around 2.5°C considering relative prices but continues increasing until 3.2°C in the

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[20] As one may expect the *RPE* to increase over time due to increasing scarcity of the environmental good, among others due to climate change, this decresing *RPE* may not seem intuitive. Indeed, in a second best world without emission abatement, the provision of the environmental good would continuously decline. The relative price-adjusted DICE model, however, calculates an economically optimal time-path of emission abatement, while taking into consideration both impacts of material consumption and environmental goods. It is therefore optimal to invest into slowing down the depletion of the environmental good specifically because relative price effects and damages to the environmental good due to increasing atmospheric temperature are taken into account. Thus, while the growth rate of the environmental good is negative and initially decreases further, it subsequently increases from 2050 onwards. Moreover, the growth rate of the environmental good is not a strong driver of the *RPE*, as it is close to zero in absolute terms throughout the planning horizon. The decreasing shape of the *RPE* is therefore mainly driven by the decreasing growth rate of human-made consumption goods.

Nordhaus case. Under Stern and median expert discounting, the atmospheric temperature stabilizes below the relative prices case at around 2°C.

The lower-left panel of Figure 1 depicts the time path for industrial emissions, which corresponds to the key result figure in Sterner and Persson (2008, p. 70). In the new DICE version (Nordhaus 2014), emissions peak shortly after 2050, while they did not peak but continuously increased until 2100 in the older DICE version Sterner and Persson (2008) refer to. When considering the *RPE*, industrial emissions peak in 2040 and become almost zero in 2085, which is both similar to the original finding by Sterner and Persson (2008). Indeed, industrial emissions decrease almost as fast as when using the pure rate of time preference advocated by Stern (2007).

We find that these emission and temperature developments translate into substantil differences between the time paths of the SCC in the depicted policy scenarios (see the lower-right corner of Figure 1). In all four scenarios the SCC increases over time due to increasing marginal impacts of emissions on welfare (see Equation (12)). Comparing the baseline *RPE* to the Nordhaus (2014) comparison case, we find that neglecting the relative price of environmental goods in the DICE model would lead to an underestimation of the SCC of 34 (131) percent in 2020 (2100). When comparing standard discounting and relative prices as two distinct driver categories of the SCC, we find that considering relative prices in the Nordhaus (2014) model becomes roughly equivalent in terms of its impact on the level of the SCC as lowering the rate of societal pure time preference from the one of Nordhaus (2014) to those of the median discounting expert from the survey of Drupp et al. (2015). Initially the SCC is higher with lower pure time preference, but towards the end of the century, the *RPE* has a relatively stringer effect on the SCC.

Overall, our analysis suggests that one needs to distinguish between standard discounting and relative price effects as related but distinct drivers of climate policy evaluation. We have shown that relative price effects can be substantial. With respect to the highly disputed rate of societal pure time preference, our analysis suggests that, in terms of atmospheric peak temperature stabilization, considering relative prices is equivalent to reducing the pure time preference from Nordhaus's (2014) value by 1.1 percentage points.

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

In the following, we explore the main drivers of the *RPE* on relative prices and on the SCC in the year 2020 as the next planning step.[21] First, we consider (i) the degree of substituatability between human-made and environmental goods. Next, we consider (ii) the magnitude of non-market damages and (iii) the size of the subsistence requirement for environmental goods. Finally, we analyze the main drivers of the growth rate of human-made goods: (iv) the rate of pure time preference, (v) the elasticity of the marginal utility of consumption and (vi) the rate of technological progress.

Substitutability

A key driver of the *RPE* is the degree of substitutability between human-made and environmental goods. The upper panel of Figure 4 depicts the effects of varying the substitution parameters θ along a range of -2 to 1. This corresponds to a range of one-third to infinity in terms of the elasticity of substitution σ. It includes the benchmark values of Nordhaus (2014), who assumes perfect substitution possibilities ($\theta = 1$) and of Sterner and Persson (2008), who assume a complementary relationship ($\theta = -1$).[22] Assuming perfect substitutes eliminates the *RPE*, while the *RPE* increases to about 6 percent for the baseline of $\theta = -1$. In a recent study considering ten ecosystem services, Baumgärtner et al. (2015) estimate the global *RPE* to be 0.9 percent for $\theta = 0.62$. Drupp (2016) gathers available indirect evidence on the substitutabiluty parameter from 18 valuation studies and finds a mean estimate for θ of 0.57, with a range of estimates from -0.41 to 0.94. The *RPE* for a value of θ of 0.62 (0.57) would be 1.3 (1.5) percent in DICE. Thus, in DICE it is optimal to apply a larger difference in good-specific discount rates initially. The SCC in 2020 corresponding to $\theta = 0.57$ is 21 US$ per ton of CO_2, but increases more than linearly with the degree of complementary of the two goods. For $\theta = -1$ [-2] the SCC in 2020 become 30 [40] US$ per ton of CO_2, respectively.

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[21] We also consider the effects in year 2100. The corresponding figures are included in Appendix A.3.

[22] Gollier (2012) [Kopp et al. 2012] assumed intermediate 'mean' degrees with $\theta = 0$ [$\theta = -0.333$].

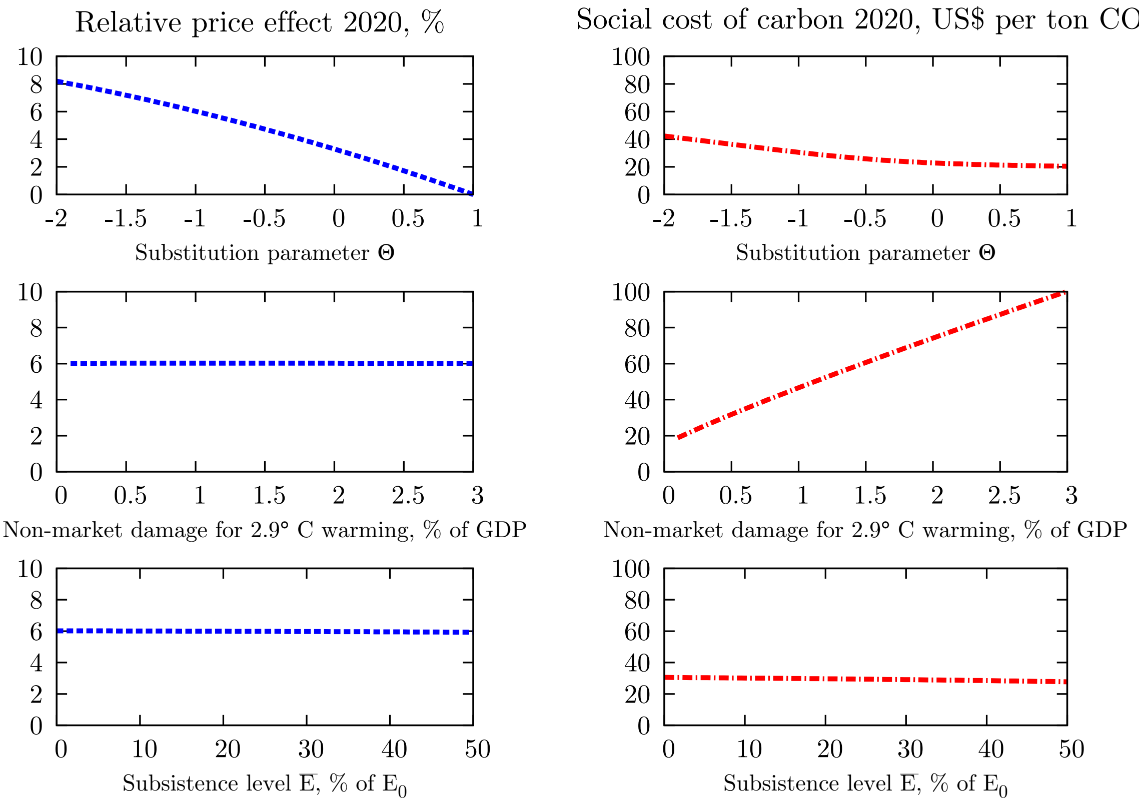

Figure 2: Drivers of the relative price of environmental goods—top to bottom: substitutability, non-market damages and subsistence consumption—and their impact on the relative price effect of environmental goods (left panel) and the social cost of carbon in 2020 (right panel).

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 2.9 °C on the environmental good measured in percent of (initial) GDP. The baseline specification depicted in Figure 1 assumes that all non-market damages from Nordhaus (2014) are damages on the environmental good.[23] These amount to 0.46 percent of initial GDP. In contrast to this baseline following Nordhaus (2014), Sterner and Persson (2008) assume that non-market impacts double the total loss in consumption. In their earlier version of the DICE model, this amounted to damages on the environmental good of 1.05 percent

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[23] As these non-market damages include damages e.g. to human health, attributing all of them to environmental goods is an over-estimation of the true damage in terms of Nordhaus's specification.

of initial GDP. In the current DICE version, environmental damages would increase up to 1.79 percent. Figure 4 depicts the effect of higher non-market damages on the *RPE* for the whole range of 0 to 3 percent non-market damages under 2.9 °C warming. In absolute terms the *RPE* remains almost flat at 6 percent. The SCC in 2020 increase with the depicted range of non-market damages from 19 to 150 US$ per ton of CO_2. Assuming higher damages from an increasing atmospheric temperature caused by the anthropogenic emission of CO_2 clearly increases the marginal impact of those emissions on the global economy's welfare, increasing the numerator in Equation (12).

Environmental subsistence consumption

The subsistence requirement for the consumption of environmental goods refers to a distinct amount of environmental goods, which are essential for human survival and cannot be substituted 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 environmental goods. Figure 4 reveals that the *RPE* decreases with the subsistence level $\overline{E}$, although the range of changes in the *RPE* is relatively small, i.e. 5.95-6.02 percent for a range of the subsistence level of 0-50 percent of the initial environmental good E_0. Under optimal climate policy a higher subsistence level $\overline{E}$ requires the social planner to slow down the depletion of the environmental good even faster compared to considering lower or no subsistence needs. Thus, the difference between the goods specific growth rates and hence, the relative price effect, will become smaller with increasing $\overline{E}$.[24] Also the SCC in 2020 decrease with the size of the subsistence need as a higher subsistence requirement reduces the optimal amount of CO_2 emissions in 2020, because higher emissions would not be compatible with keeping the required subsistence needs. Consequently the numerator in equation (12) will fall with rising $\overline{E}$ and hence, the SCC in 2020 decrease.

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[24] Additionally, $\overline{E}$ slightly impacts the *RPE* also indirectly via the calibration of the environmental good climate damage coefficent ψ (Equation A.8), with $\partial\psi/\partial\overline{E} \leq 0 \quad \text{for} \quad \theta \leq 1$.

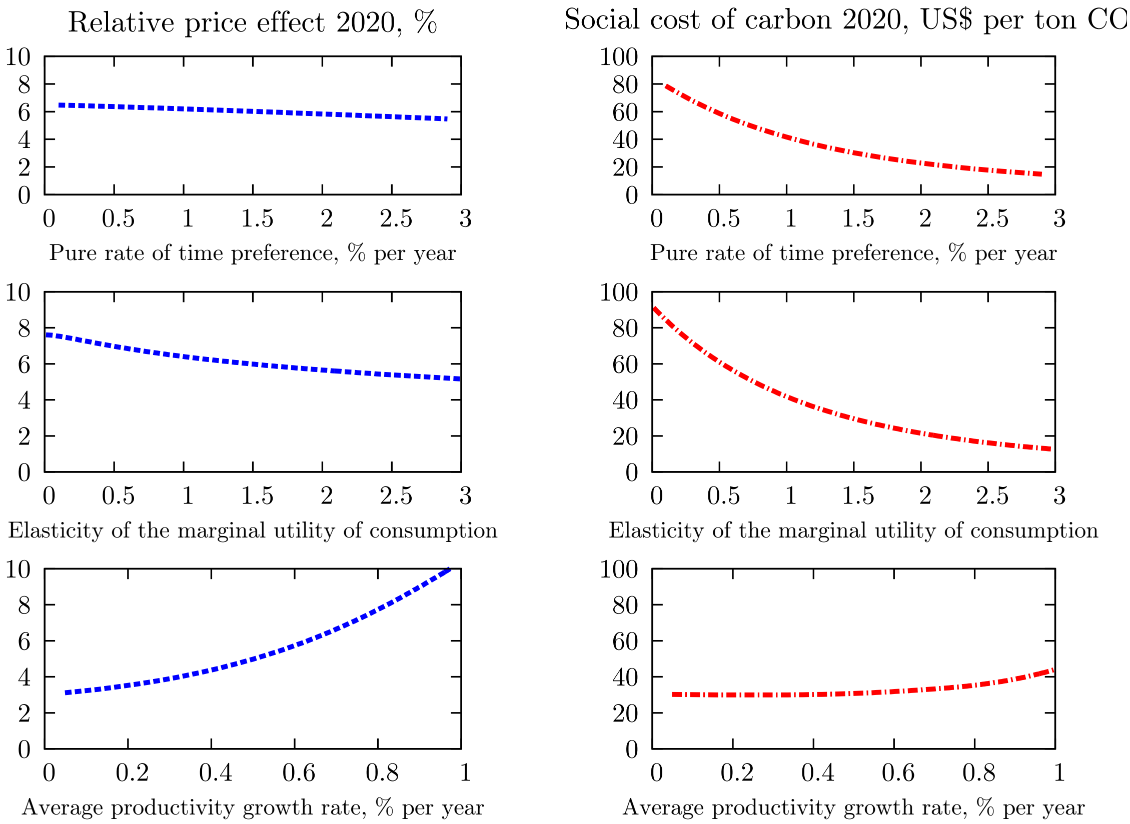

Figure 3: Drivers of the growth rate of consumption goods—top to bottom: pure rate of time preference, elasticity of the marginal utility of consumption, and average productivity growth rate—and their their impact on the relative price effect of environmental goods (left panel) and the social cost of carbon in 2020 (right panel).

Pure rate of time preference

The pure rate of 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 generations of agents is discounted just because they live in the more distant future. There is large heterogeneity among economists and philosophers on what constitute reasonable and justifiable values for the pure rate of time preference. Figure 5 depicts the effects of the pure rate of time preference on the *RPE* and the SCC over an interval of 0 to 3 percent. This range includes recommendations by 94 percent of respondents to an expert survey on the determinants of the social discount rate (Drupp et al. 2015). Not surprisingly the *RPE* falls with the rate of pure time preference from 6.5 percent for $\delta = 0.001$ as advocated by Stern (2007) to about 5.5 percent for $\delta = 0.03$

per year. The middle of the range captures Nordhaus's (2014) assumption of $\delta = 0.015$ corresponding to a *RPE* of about 6 percent. The SCC in 2020 decrease with δ from about 80 to 15 US$ per ton of CO_2 over the parameter range. As it is well known in the literature, higher societal impatience towards the utility of future generations tends to decrease today's optimal cost of emitting CO_2.

Elasticity of the marginal utility of consumption

The elasticity of the marginal utility of consumption η is a measure of inequality aversion with respect to the intertemporal distribution of inclusive consumption $\widetilde{c}$. The range for η from 0 to 3 provided in Figure 5 includes the recommendations by 97 percent of respondents to an expert survey on the determinants of the social discount rate (Drupp et al. 2015), and encompasses prominent parameter values used in the literature, such as unity (Stern 2007) and, roughly in the middle of the range, the 1.45 used in Nordhaus (2014). We find that the *RPE* decreases with η over this range of parameter values from 7.6 to 5.2 percent. Hence, the *RPE* is more sensitive to changes in η as compared to the rate of pure time preference. The SCC in 2020 in turn decrease with η on comparable magnitudes as the pure rate of time preference.

Average productivity growth rate

The average productivity growth rate measures the average rate of exogenous technological progress over the DICE planning horizon of 300 years. For determining the sensitivity of the *RPE* with respect to average productivity growth we do not change the shape of the time profile of technological progress imposed by Nordhaus (2014), who assumes increasing productivity growth at a decreasing rate. The exogenous productivity parameter directly scales up the production of material consumption goods, whose growth rate predominately determines the *RPE*. Hence, the *RPE* increases more than linearly in the average productivity growth rate per year, ranging from about 3 to 9 percent for an average annual productivity growth between zero and one percent. The baseline case of Nordhaus (2014) implies an average annual productivity growth of 0.76 percent for the 300-year time horizon. The SCC in 2020 rises convexly from 30 to 40 US$ per ton of CO_2.

5 Conclusions

This paper has studied the relative price of environmental goods and its fundamental drivers in the integrated assessment of climate change. We thereby extend the analysis of Sterner and Persson (2008) in the setting of the most recent version of the DICE model (Nordhaus 2014).

We find that the relative price effect of environmental goods is of substantial magnitude and amounts to 6 percent in the year 2020, implying that discount rates for environmental goods would be negative for most conventionally adopted discount rate specifications. Largely due to expected decreasing productivity growth, the relative price effect of environmental goods decreases to 3 percent in the year 2100. In terms of climate policy evaluation, we find that neglecting relative prices would lead to an underestimation of the social cost of carbon in 2020 (2100) of more than 30 (130) percent. While considering relative price effects would lead to a phase-out of industrial emissions until 2080, it would not succeed in keeping the global temperature increase below the 2°C goal. It would stabilize the global temperature increase at around 2.5°C in contrast to 3.2°C in the Nordhaus (2014) baseline specification without relative prices. The effect of considering the relative price of environmental goods is of comparable magnitude for climate policy evaluation as decreasing a key parameter of intertemporal welfare economics that many experts disagree about—the pure rate of time preference—from Nordhaus's (2014) 1.5 percent to the 0.4 percent, which is even lower than the median recommendation of the expert discounting survey of Drupp et al. (2015).

Exploring different drivers of the relative price effect in the year 2020, we find that these change relative prices along an interval from 0 up to 9 percent for the considered parameter value ranges. The two most important drivers of relative prices are the degree of substitutability between environmental and human-made goods as well as the economy's productivity growth, which is predominantly determined by exogenous technological progress.

The importance of substitutability as a driver of the relative price effect is well-known (Baumgärtner et al. 2015, Sterner and Persson 2008, Traeger 2010). Yet, there is only scarce empirical evidence on its potential magnitude, which suggests substitutability at the margin (Drupp 2016) in contrast to the complementary relationship assumed in our baseline specification following Sterner and Persson (2008). These assumptions of substitutability and complementarity would imply relative price effects of 1.5 and 6 percent, respectively. It is therefore imperative to conduct more research to empirically estimate substitutability of environmental goods so as to increase confidence about the likely magnitude of relative price effect. Nevertheless, our analysis suggests that the relative price of environmental goods in integrated assessment is more substantial in the near future than the 1 percent results presented in the literature (Baumgärtner et al. 2015, Drupp 2016).

Due to optimal management of the environmental good through abatement activities but more importantly due to declining productivity growth, the relative price decreases from 6 percent in 2010 to around 3 percent in the year 2100. As productivity growth is not only the most important driver of relative prices over time but also changes relative prices in the year 2020 from around 3 to 9 percent along the considered parameter range, it is crucial to study technological progress in more detail. This includes in particular to also consider the possibility of endogenous technological progress (e.g. Hübler et al. 2012, Popp 2004). As the growth rate of human-made consumption goods is endogenous in integrated assessment, the relative price also depends indirectly on the two key ‘normative’ parameters determining the intertemporal distribution of well-being: the pure rate of time preference and the elasticity of marginal utility of consumption. These two parameters simply canceled out in previous analyses that assumed constant growth rates (e.g. Baumgärtner et al. 2015), but they turn out to have a non-negligible impact on relative prices. Specifically, they each drive the relative price of environmental goods in DICE from around 7.5 to 5 percent in the year 2020 along a parameter range that captures around 95 percent of recommendations for these two key parameters in a recent expert survey on social discounting (Drupp et al. 2015).

In the optimal management framework of DICE, the two drivers related to the growth of the environmental good – the magnitude of non-market climate damages scaling the effect of temperature increases on the environmental good as well as environmental subsistence consumption – are not of quantitative importance for the relative price effect. This would be different for non-optimal climate policy or if the aggregate environmental good would be driven by other factors, such as biodiversity loss. Indeed, empirical evidence suggests that environmental good growth is not close to zero, as under optimal management of the environmental good in DICE: Baumgärtner et al. (2015) estimate that the growth rates of environmental goods was negative over recent decades.

Overall, our findings suggest that the relative price of environmental goods is of considerable magnitude across relevant parameter ranges compared to commonly adopted discount rates. These results support recent initiatives, such as by the Dutch government, to consider relative price effects in guidance for project appraisal. Furthermore, our results support calls for more stringent climate policies due to relative environmental scarcity, as neglecting relative price effects would lead to substantial underestimates of the social cost of carbon and would allow a stabilization of global temperatures at 0.7°C higher than as would optimally be suggested when appropriately accounting for the relative scarcity of environmental goods.

Appendix

A.1 Derivation of the relative price effect

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

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

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

We thus have

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

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

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

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

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

The relative price effect of environmental goods is therefore given by

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

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

A.2 Calibration of non-market damages

The environmental good climate damage coefficient ψ is calibrated as follows:

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

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

We can solve this for the environmental climate damage parameter ψ as follows:

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

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

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

A.3 Drivers of the relative price effect in 2100

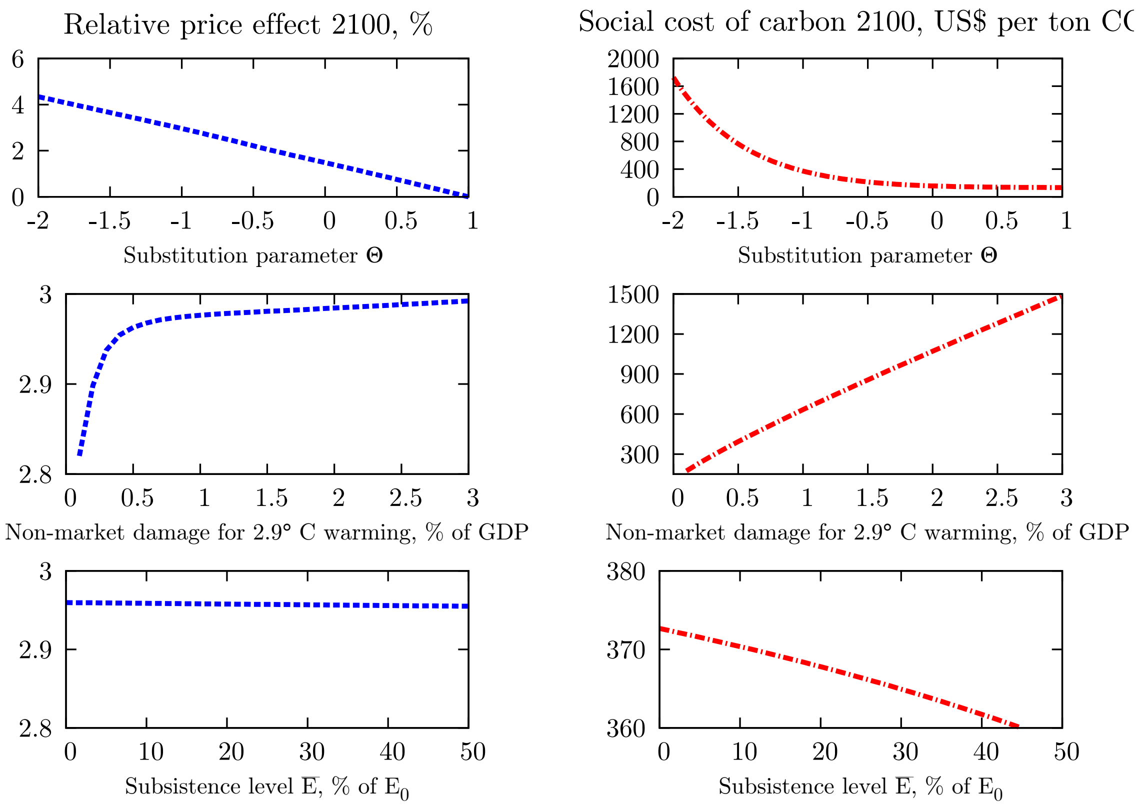

Figure 4: Drivers of the relative price of environmental goods and their impact on the relative price effect and the social cost of carbon in 2100

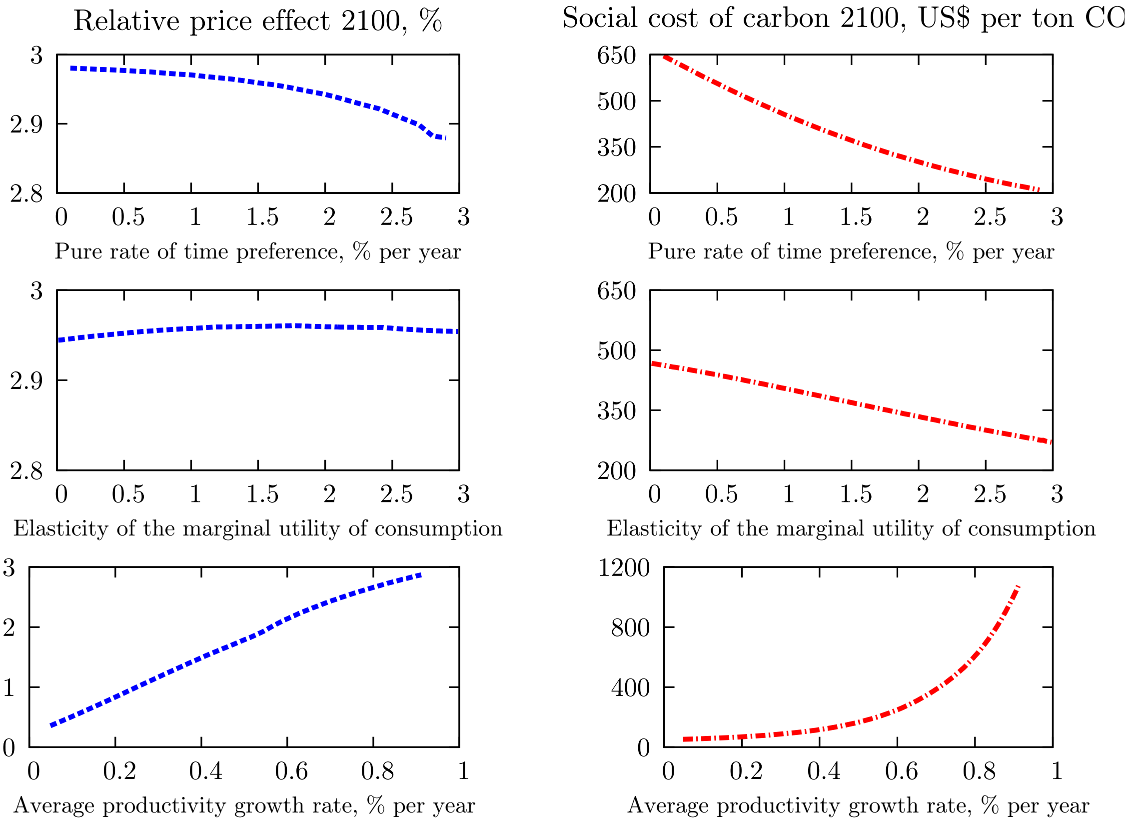

Figure 5: Drivers of the growth rate of consumption goods and their effect on the relative price of environmental goods and the social cost of carbon in 2100

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