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Relative Prices and Climate Policy: How the Scarcity of Nonmarket Goods Drives Policy Evaluation†

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Climate change not only impacts production and market consumption but also the relative scarcity of nonmarket 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's Dynamic Integrated Climate-Economy (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* D61, H43, Q51, Q54, Q58)

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 nonmarket 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 nonmarket goods (Millennium Ecosystem Assessment 2005, Intergovernmental Panel on Climate Change 2014),

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it has become more urgent to do so in practice.[1] For illustration, suppose that market goods grow at 2 percent, nonmarket 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 nonmarket goods would increase by more than 600 percent. Ignoring this can lead to large errors.

This paper analyzes the change in the relative price of nonmarket 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 2007a, 2008; Stern 2007), but it quickly shifted to extensions to the standard discounting framework. Besides accounting for uncertainty, considering relative prices has received widespread attention.[2] Yet until today, there exists no systematic examination of how relative price changes of nonmarket 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 nonmarket goods separately. The second approach computes comprehensive consumption equivalents for each period, by appropriately valuing nonmarket goods using relative prices, and discounts this aggregated bundle with a single consumption-equivalent discount rate. The relative price of nonmarket goods is given by the marginal rate of substitution between consuming a further unit of nonmarket 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 nonmarket goods over time.

Relying on constant, exogenous growth rates for environmental goods at the global level and on substitutability estimates derived from nonmarket 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

[1] The Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES) documents that around one 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 ignores the increasing scarcity of such nonmarket goods (Strand et al. 2018). Ito and Zhang (2020) document that revealed willingness to pay (WTP) for clean air in China depends significantly on income and has increased strongly due to rising awareness of the scarcity of clean air.

[2] See, for example, Arrow et al. (2013), Dasgupta (2008), Gollier (2010), Gollier and Hammitt (2014), Hoel and Sterner (2007), Sterner and Persson (2008), Traeger (2011), Nordhaus (2007b), and Weitzman (2009). Limited substitutability features prominently in Heal's (2017) "The Economics of the Climate." Furthermore, environmental scarcity and associated relative price changes have been among the most mentioned issues missing in discounting guidance in a recent expert survey (Drupp et al. 2018).

[3] See, among others, Baumgärtner et al. (2015); Drupp (2018); Gollier (2010); Guéant, Guesnerie, and Lasry (2012); Guesnerie (2004); Hoel and Sterner (2007); Traeger (2011); Weikard and Zhu (2005). Zhu, Smulders, and de Zeeuw (2019) show that this literature implicitly assumes that natural capital is substitutable as a factor of production.

guidance for cost-benefit analysis and to recommend discounting the consumption of environmental goods at a lower rate (Groom and Hepburn 2017, Koetse et al. 2018, Ministry of Finance of the Netherlands 2015). Yet in general, growth rates are nonconstant 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 nonmarket goods. Sterner and Persson (2008) assumed that nonmarket goods are complementary to market goods and argued that optimal climate policy—when introducing relative prices—should be more stringent than as advocated in the *Stern Review*, even when using the higher rate of pure time preference of Nordhaus (2007a). 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 allows studying how a hypothetical global government would optimally balance costs and benefits of the flow of market and nonmarket goods in the context of climate change.[4] Section I defines the relative price effect of nonmarket goods in a stylized model and presents how DICE is adapted to explicitly consider relative prices. In line with previous work, we consider nonmarket 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 nonmarket goods has been a crucial question right from the beginning of integrated assessment modeling. These damages may concern ecosystem impacts on human health, such as 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 nonmarket goods. It was a "surprise" for him (Nordhaus 1994, 50) that the respondents believed that on average "only" between 33 and 38 percent of climate impacts fall on nonmarket goods. More recently, Howard and Sylvan (2015) find that experts expect that around 50 percent of climate impacts fall on nonmarket goods. While there is large heterogeneity in responses, it is clear that a cost-benefit analysis of climate change mitigation policies cannot ignore these substantial expected losses of nonmarket goods.

To study how the scarcity of nonmarket goods affects the evaluation of climate policy, we initially follow Sterner and Persson (2008) in augmenting the standard DICE model to explicitly feature nonmarket goods in Section II as many readers may consider this as a natural benchmark for our paper. It is therefore informative what relative price changes their setting entails. Building on this replication

[4] Dynamic 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, Gerlagh, and Liski 2016; Rezai and Van der Ploeg 2016; Traeger 2015), IAMs still represent a useful tool for such purposes.

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 nonmarket 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 III scrutinizes the impact of determinants of relative price changes. These include the degree of substitutability between market and nonmarket goods, the magnitude of nonmarket climate damages, and a potential subsistence requirement in terms of nonmarket 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 IV, 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 V. In particular, it is important to stress early on that our analysis only focuses on relative prices changes between market and nonmarket goods. Yet, relative price changes are relevant also in other related contexts, such as when considering nonmarket goods as scarce inputs to production (e.g., Zhu, Smulders, and de Zeeuw 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, Gustafson, and Lewis 2019). Despite these caveats, we conclude in Section VI that changes in relative prices of nonmarket 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.

I. Modeling Relative Prices

A. *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 nonmarket public good E. Both goods are composites with continuously scalable amounts. The agent may further require an amount $\bar{E}$ of the nonmarket good to satisfy her subsistence needs (Heal 2009a, 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:

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

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

$$u = u^h = \left[\alpha\left(E_t - \bar{E}\right)^\theta + (1-\alpha)c_t^\theta\right]^{1/\theta} \tag{2}$$

$$\text{with} \quad -\infty < \theta \leq +1, \quad \theta \neq 0; \qquad 0 < \alpha < 1,$$

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 $\sigma = 1/(1-\theta)$. Important special cases of substitutability are perfect substitutes ($\theta = 1$; $\sigma \to \infty$), Cobb-Douglas ($\theta = 0$; $\sigma = 1$), and perfect complements ($\theta \to -\infty$; $\sigma = 0$). 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

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

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.

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

We now turn to the focus of our analysis: the "relative price effect" of nonmarket goods (hereafter denoted as *RPE*). The value of nonmarket 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 nonmarket goods.[6] This tells us by how much the consumption of market goods would need to increase for a marginal decrease in nonmarket goods to hold utility constant. The *RPE* measures the change in this valuation of nonmarket goods and thus their relative scarcity over time (Hoel and Sterner 2007):

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

For our utility function (equation (2)), the relative price effect of nonmarket goods, *RPE*, at time t reads (see online Appendix A.1 for a derivation)

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

The *RPE* is equivalent to the difference in the good-specific discount rates for market and nonmarket goods (Weikard and Zhu 2005, Drupp 2018). It depends on the degree of substitutability θ between market and nonmarket goods, their growth rates g_{c_t} and g_{E_t} as well as on the consumption of nonmarket goods over and above the subsistence requirement $E_t/(E_t - \bar{E})$. In the standard CES case, which we consider in Sections IB and II to replicate Sterner and Persson (2008), the subsistence factor simply drops out.

B. *Relative Prices in the DICE Integrated Assessment Model*

Integrated assessment models are a widespread tool for the cost-benefit analysis of climate-economy feedbacks and thus useful for studying the dynamic impacts of considering relative price changes. We use the most recent version of the global Dynamic Integrated Climate-Economy (DICE-2016R2) model by Nordhaus (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

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

and damages and, second, report the changes necessary to explicitly include relative prices. The welfare function in Nordhaus (2018) is given by

$$W_0(\tilde{c}_t, L_t) = \sum_{t=0}^{99} L_t \frac{1}{(1+\delta)^{5t}} \frac{\tilde{c}_t^{1-\eta}}{1-\eta}, \tag{6}$$

where L_t is period t's population size, δ is the rate of pure time preference, and η is the inverse of the CIES for the aggregate consumption bundle, or the elasticity of the marginal utility of comprehensive consumption. Comprehensive consumption per capita $\tilde{c}_t$ is defined as an index of generalized consumption (Nordhaus and Sztorc 2013), which is meant to also include nonmarket goods consumption in most of the papers by Nordhaus (cf. Section IIB). 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 preindustrial levels:

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

Nordhaus (2018) calibrates the aggregate scaling parameter for the damages on all generalized consumption goods via production-damages, ϕ (equation (7)), such that market plus nonmarket damages are equal to 2.12 percent of global output for a temperature increase of 3°C. These total damages include 25 percent nonmarket damages additional to market damages, which amount to 1.63 percent of global output.[7] The DICE model therefore does not properly deal with nonmarket 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 nonmarket damages. One might therefore infer that there is also perfect substitutability between market and nonmarket 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 nonmarket 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, equation A.4; Nordhaus 2018, equation 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 nonmarket damages and is solely driven by temperature change, can thus—in part—be viewed as a form of nonmarket (natural) capital. Since this enters multiplicatively into the net production function, there is Cobb-Douglas-type substitutability between this nonmarket component and the rest of production. This is related to Weitzman's (2010) discussion of an equivalence between what he calls "multiplicative" and "additive" damage functions, where damages either hit consumption multiplicatively or are added additionally as an input to utility as in our

[7] Nordhaus (2018) builds on 36 studies that estimate climate damages and adds 25 percent to each damage estimate to incorporate nonmarket 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 a 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 nonindependent studies and provide an alternative calibration for ϕ based on an updated meta-analysis of the temperature-damage relationship.

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 setup with exogenous consumption streams, including limited substitutability between market and nonmarket 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 nonmarket 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 II.

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 nonmarket good over time and (iii) specifying the initial value of the nonmarket good, (iv) disentangling market and nonmarket damages via appropriate calibration, and finally, (v) raising the level of nonmarket good damages from Nordhaus's 25 percent to 100 percent additional damages to ensure comparability with Sterner and Persson's (2008) analysis. We extend the model such that utility depends not only on market but also on nonmarket goods as in equation (2). However, since a subsistence requirement was absent in the analysis of Sterner and Persson (2008), we set $\bar{E} = 0$ here and for the replication and analysis in Section II.[8] Thus, comprehensive consumption is now given by $\tilde{c}_t = \left[\alpha E_t^\theta + (1-\alpha)c_t^\theta\right]^{1/\theta}$. The initial level of the aggregate nonmarket 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

$$W_0(E_t, c_t, L_t) = \sum_{t=0}^{99} L_t \frac{1}{(1+\delta)^{5t}} \frac{1}{1-\eta} \left[\alpha E_t^\theta + (1-\alpha)c_t^\theta\right]^{\frac{(1-\eta)}{\theta}}. \tag{8}$$

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 nonmarket good depends (inversely) on the square of atmospheric temperature T change compared to preindustrial levels and the damage parameter ψ:

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

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

The nonmarket good thus deteriorates with increasing temperatures due to emissions and may be invested in via negative emission options, such as planting trees or carbon dioxide removal. To ensure comparability with Sterner and Persson (2008), we assume that nonmarket damages double climate damages to recalibrate ϕ. Thus, we include an additional 100 percent nonmarket damages on top of market damages. Hence, for the baseline Nordhaus (2018) model, we assume that market plus nonmarket 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 nonmarket goods. Two new damage parameters ψ [κ] now scale up the magnitude of nonmarket [market] damages. Based on Nordhaus and Moffat (2017), we recalibrate damages on market-good consumption D_t^{κ}. The damage function for market goods becomes

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

To account for the nonmarket damages on top of market damages à la Sterner and Persson (2008), the nonmarket climate damage parameter ψ is calibrated by comparing two different model specifications:[10] On the one hand, a model in which nonmarket damages D_t^{ψ} for a given temperature increase are perfectly substitutable for damages on market goods and are included in consumption directly. On the other hand, a model in which damages are attributed to market goods D_t^{κ} and nonmarket goods D_t^{ψ}. The parameter ψ is calibrated as a residual, with $C_0 = E_0$ (see online Appendix A.2), and depends in particular on nonmarket damage costs but also the degree of substitutability. Given this setup, the *RPE* (cf. equation (5)) in DICE is given by[11]

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

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

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

[10] See Barrage (2018) for an alternative approach to calibrating nonmarket damages.

[11] The growth rate of nonmarket goods in continuous time is given by $g_{E_t} = \dot{E}_t/E_t = -2\psi T_t \dot{T}_t/\left(1+\psi T_t^2\right)$. In discrete time, we have $g_{E_t} = (E_t - E_{t-1})/E_{t-1} = -\psi\left(T_t^2 - T_{t-1}^2\right)/\left(1+\psi T_t^2\right)$. 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.

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 nonmarket good g_{E_t}, which is a function of nonmarket 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 growth rates is scaled by the degree of substitutability, θ.

II. Relative Prices and Climate Policy Evaluation

A. *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 preindustrial 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 nonmarket good—the preference share parameter α, the degree of substitutability θ as well as the magnitude of nonmarket damages—which are based on Sterner and Persson (2008). Table 1 provides an overview of the parameter specifications used in 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 five-year time steps.

The time path of the S&P-*RPE* depicted in Panel A 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 nonmarket 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 nonmarket 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 *RPE*, falls over time.

[12] Total factor productivity $A_t = A_{t-1}/\left(1 - g_{t-1}^A\right)$ 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 III and IV, the *RPE* has an additional term that magnifies the importance of the growth rate of nonmarket goods on the *RPE* (see equation (5)): $RPE_t = (1-\theta)\left[g_{c_t}(\delta, \eta, \dots) + \left(2\psi T_t^2 g_{T_t}/\left(1+\psi T_t^2\right)\right)\left(E_0/\left(E_0 - \bar{E}(1+\psi T_t^2)\right)\right)\right]$.

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

[15] The computations consider the full planning horizon of DICE. Online 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 online Appendix A.10.

Table 1—Parameter Values for Replicating Sterner and Persson (2008) in DICE-2016R2

Parameter	δ	η	MD[b]	NMD[c]	α	θ	$\bar{E}$
Baseline	1.5%	1.45	1.63%	1.63%	0.1	−1	0
Source[a]	N	N	N	S&P	S&P	S&P	N, S&P

Notes:
[a]N denotes values taken from Nordhaus (2018), while S&P denotes Sterner and Persson (2008).
[b]MD denotes market damages under 3°C warming, with $\kappa = 0.0181$.
[c]NMD denotes nonmarket damages under 3°C warming, corresponding to $\psi = 0.01604$, which is calibrated endogenously according to online Appendix equation (A.9).

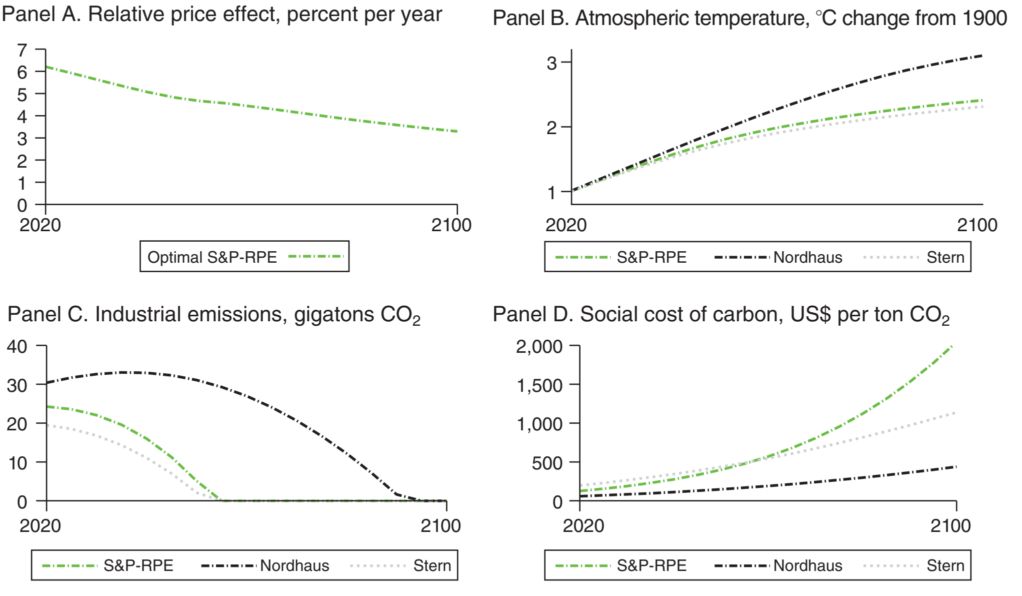

Figure 1. Relative Price Effect of Nonmarket Goods (RPE) and Comparison of Climate Policy Paths

Notes: 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 gray line features another standard comparison case yet with the lower rate of pure time preference, δ, of Stern.

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

[16]Climate damages are higher in the "Nordhaus" run than in Nordhaus (2018) for comparability with Sterner and Persson (2008). In online Appendix A.5, we perform the same analysis with Nordhaus's (2018) estimate of lower nonmarket damages and briefly relate to it in Section IIB.

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

Panel C of Figure 1 depicts the time path for industrial emissions, which corresponds to the results figure in Sterner and Persson (2008, 70).[17] In DICE-2016R2, and with the comparable assumption regarding nonmarket 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. Panel B 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. panel D of Figure 1). Comparing the S&P-*RPE* to the "Nordhaus" case, we find that the SCC is 112 (365) percent higher in 2020 (2100) in the S&P-*RPE* case. Comparing "Nordhaus" and "Stern," we find that the latter leads to an SCC that is 229 (159) percent higher in 2020 (2100). Overall, Figure 1 underscores the need to distinguish between standard discounting and relative price changes as related but distinct drivers of climate policy evaluation.

B. *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 nonmarket 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

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

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 preindustrial 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 *RPE*s. 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

[18] When market and nonmarket 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.

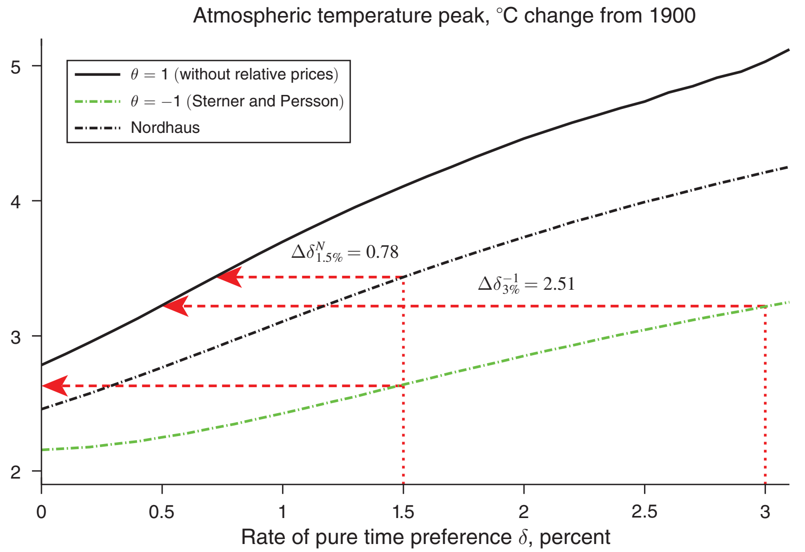

Figure 2. The Comparative Influence of Introducing Relative Prices on Peak Temperature

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

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

In the same fashion, we can compare the black dashed line of the "Nordhaus" case to the bold black line of perfect substitutes to back out the implicit degree of relative prices contained in the "Nordhaus" case. We find that a simple comparison of these two lines reveals that the "Nordhaus" case is equivalent to a model without relative prices if we decrease δ by about $\Delta\delta^N_{1.5\%} = 0.78$ percentage points. We can also reestimate 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 nonconstant: 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 reestimate the black dashed line, we find that the resulting $\Delta\delta^{-0.13}_{1.5\%}$ would be 0.77 percentage points and thus very close to that of the "Nordhaus" case. This analysis of the

"Nordhaus" case does not reveal the implicit degree of substitutability and relative prices contained in the standard DICE-2016R2 model as our analysis considers higher damages for comparability with Sterner and Persson (2008). In online Appendix A.5, we rerun 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 percentage points. 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 an *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 nonmarket goods are considered easily substitutable, explicitly introducing an *RPE* will lead to less stringent optimal climate policy as compared to the Nordhaus case.

Figure 2 also allows us to reexamine 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

[19] Online Appendix 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, $\Delta\delta$.

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 nonmarket damages are treated as market damages that hit production, and the extended model in which nonmarket damages hit a nonmarket good that is explicitly featured as a source of utility. Although both models are calibrated to entail the same base year welfare costs at $T = 3°\text{C}$ warming (cf. online Appendix A.2), the explicit introduction of nonmarket 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 nonmarket 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 nonmarket damages. Specifically, Nordhaus (2018) deals with nonmarket goods by scaling up the damage coefficient (see equation (7)) and thus implicitly assumes the same savings dynamics for market and nonmarket 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 recalibrating 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 nonmarket 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 recalibrate 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 nonmarket 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 nonmarket goods affects market dynamics, the recalibration assumes that business-as-usual market consumption and savings dynamics are unaffected by introducing nonmarket goods. Both approaches are extreme but illuminating cases.

The recalibration 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 $\beta_t^* = (1-\alpha)c_t^\theta / \left(\alpha E_t^\theta + (1-\alpha)c_t^\theta\right)$ (see online Appendix A.4 for a derivation):

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

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

By using equation (12), we can now recalculate 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 recalculation yields $\eta = 1.389$ in the initial period. Similarly, we can recalibrate 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 recalibrated dynamics (see Figure A.2 in the online 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) is provided in online Appendix A.4.[20]

We find that the recalibration 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 online Appendix). Specifically, peak temperature for a pure time preference rate of 1 percent is 3.62°C as compared to peak temperature of 3.70°C in the model without recalibration. 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 recalibration.

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 $\delta = 1.5$ percent to $\delta = 0$ percent in a model without relative

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

prices ($\theta = 1$) is now almost equivalent to the recalibrated 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 recalibration).

Overall, this means that introducing relative prices in the fashion of Sterner and Persson (2008) into DICE-2016R2 under a recalibrated 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 nonmarket goods affect cost-benefit dynamics in integrated climate-economy models.

III. 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 nonmarket goods. Next, we study exogenous drivers that are related to the growth rate of the nonmarket good: (ii) the magnitude of nonmarket damages and (iii) the size of the subsistence requirement for nonmarket goods that we consider from now (cf. equation (5)).[21] Furthermore, we analyze the main drivers of the growth rate of market goods: (iv) the rate of pure time preference, (v) the elasticity of the marginal utility of comprehensive consumption, and (vi) the rate of technological progress.

Substitutability.—A key driver of the *RPE* is the degree of substitutability between market and nonmarket goods. The upper panels of Figure 3 depict 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 nonmarket goods and ecological discounting. While the applied theory literature relies on expert judgment concerning the degree of substitutability, empirical estimates are based on an indirect relationship between the income elasticity of willingness to pay (WTP) for nonmarket 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 2007, 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

[21] The additional determinants of the value share of nonmarket goods, α and E_0, do not impact the relative price effect directly (cf. equation (5)). In online 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 nonmarket goods (Obst, Hein, and Edens 2016; Droste and Bartkowski 2018). In any case, there are no empirical data yet to inform a parameterization of α or E_0 at the global level (Obst, personal communication). Values of α for nonmarket 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 nonmarket goods is therefore a conservative choice.

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

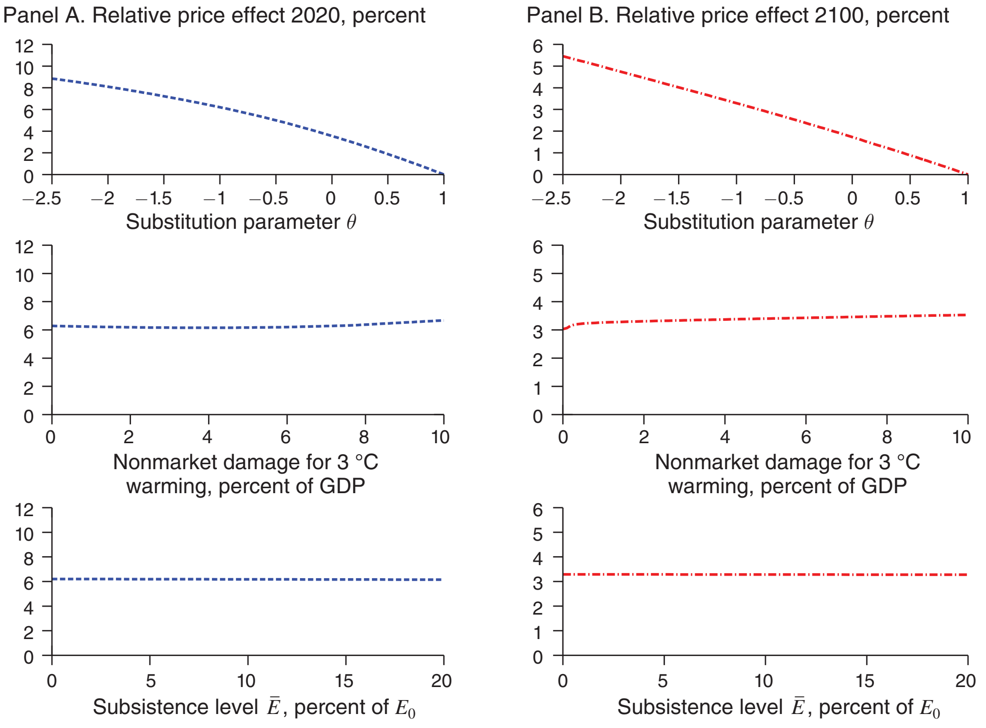

Figure 3. Drivers of the Relative Price Effect (I)

Note: Top to bottom: The impact of substitutability, nonmarket damages, and subsistence consumption on the RPE in 2020 (left) and in 2100 (right).

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 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 nonmarket goods more broadly, which also encompass health-related services, for instance. To gather a more comprehensive empirical evidence base for this broader notion of nonmarket 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 5, 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 nonmarket 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

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

TABLE 2—ESTIMATES OF THE SUBSTITUTABILITY PARAMETER θ DERIVED FROM VALUATION STUDIES[a]

		Substitutability parameter θ			
Type of good	Observations[b]	Mean	SD	Minimum	Maximum
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 nonmarket goods	40	0.23	0.68	−2.30	0.90

Notes:
[a]Table A.2 in online Appendix A.8 provides an overview of the 40 individual studies.
[b]Denotes the number of studies included per category. In case a study provides multiple estimates, we use the mean of these individual estimates.

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 focusing on valuing environmental goods and 19 focusing 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. Additionally, we gather key covariates, including the type of nonmarket 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 nonmarket 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-à-vis market goods. When we aggregate all nonmarket 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 nonmarket and market goods. This is in contrast to the mean

[24]For 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.
[25]A 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.

estimate from expert judgments we derive from the applied theory literature (Gollier 2010, Kopp et al. 2012, Sterner and Persson 2008), which yields $\theta = -0.44$ and a min-max range from -1 to 0.[26]

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 $\theta = -1$ (Sterner 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 Nonmarket Damages.—In our model, the magnitude of nonmarket damages refers to the hypothetical monetary damages from a climate change-induced temperature increase to 3°C on the nonmarket good measured in percent of GDP. The baseline specification depicted in Figure 1 assumes, following Sterner and Persson (2008), that nonmarket 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 nonmarket 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 nonmarket 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 nonmarket goods (for a 3°C warming until 2090). More recently, Howard and Sylvan (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 nonmarket) that will be borne by the market sector." The best guess of 213 respondents is that 50.24 percent of damages accrue to nonmarket 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 nonmarket damages on the *RPE* for a large range of nonmarket 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 nonmarket damages of up to 4 percent and increases thereafter, reaching 6.67 for nonmarket damages of 10 percent. 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 nonmarket damages scaling parameter has such a negligible effect on the *RPE*? In the *RPE* equation (11), the magnitude of nonmarket damages scales the effect of temperature change to determine the growth rate of nonmarket goods. Due to the optimal management, the decline of the nonmarket good through temperature change is dampened such that the growth rate of the nonmarket good is close to zero. As a consequence, higher nonmarket damages only marginally change the *RPE*.

[26] For the computation of the mean value from the applied theory literature, we do not include the value from Hoel and Sterner (2007) to avoid potential double counting with Sterner and Persson (2008).

Nonmarket Good Subsistence Consumption.—The subsistence requirement for the consumption of nonmarket 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 nonmarket 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 nonmarket 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 nonmarket 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 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 an *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 zero to five 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), $A_t = A_{t-1}/\left(1 - g_{t-1}^A\right)$,

[27] Additionally, $\bar{E}$ slightly impacts the *RPE* also indirectly via the calibration of the nonmarket good climate damage coefficient ψ (online Appendix equation A.8), with $\partial\psi/\partial\bar{E} \leq 0$ for $\theta \leq 1$.

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

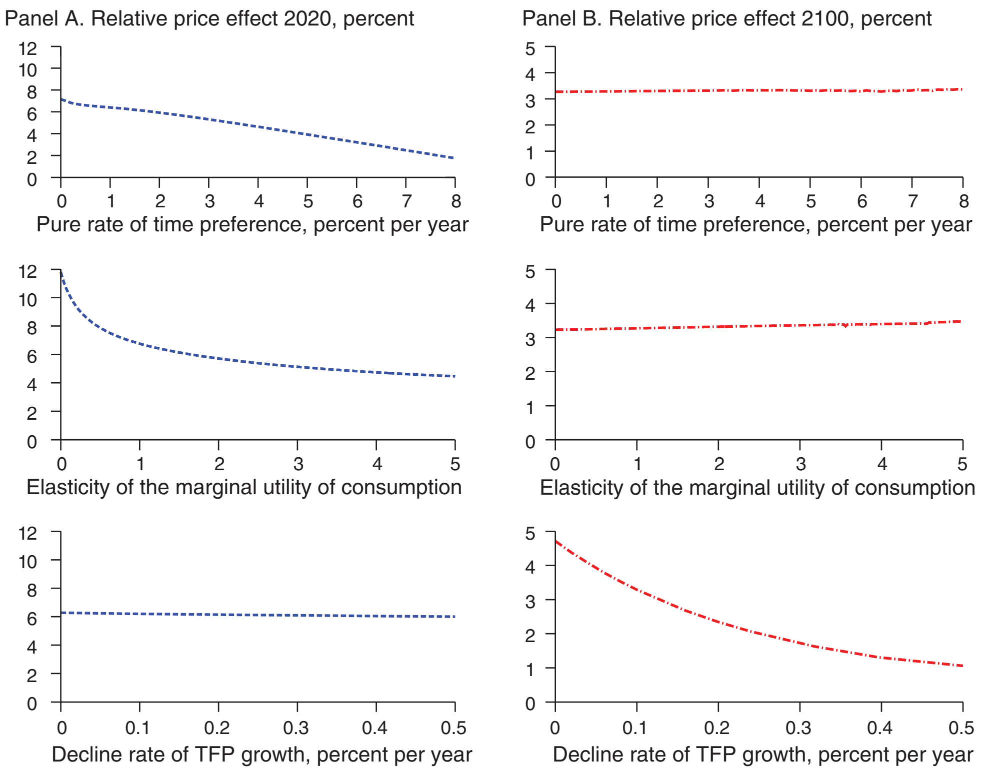

Figure 4. Drivers of the Relative Price Effect (II)

Note: 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).

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 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 an *RPE* in 2020 (2100) of 6.20 (3.29) percent. A lower decline rate of TFP growth τ^A makes nonmarket 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 TFP growth per year.

This sensitivity analysis reveals that exogenous drivers have very heterogenous effects on the *RPE*. The degree of substitutability between market and nonmarket

[29] Alternatively, 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.

goods is the key driver of relative price changes. The magnitude of nonmarket 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.

IV. 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 nonmarket 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 II, we now perform a Monte Carlo analysis with 1,000 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 nonmarket damages, we draw on the expert responses from the survey by Howard and Sylvan (2015) and assume a Normal distribution with mean and standard deviation taken from their expert data.[30] For the Nonmarket Good Subsistence Consumption, $\bar{E}/E_0$, we use a middle value of 10 percent. The 95 percent interval is calculated such that it is bounded below by zero. 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 1,000 times from the sample of expert recommendations and use these data for the 1,000 Monte Carlo runs (see online 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 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 nonnegligible fraction of experts may advocate employing them. For instance, with

[30] We truncate the distribution to exclude negative values for nonmarket damages, the decline rate of TFP and the subsistence requirement for the nonmarket good.

TABLE 3—PARAMETER SPECIFICATIONS FOR THE RANGE AND CENTRAL CALIBRATION OF THE *RPE*

Parameter	Source	Distribution[a]	Central calibration
θ	Own calculations	Normal; $\mu = -0.11$, $\chi = 0.17$	-0.11
NMD[b]	Howard and Sylvan (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%

Notes:
[a] We truncate the Normal distributions for NMD, $\bar{E}/E_0$ and τ^{A}, and we denote the standard deviation with χ, as σ is already defined as the elasticity of substitution.
[b] NMD denotes nonmarket damages under 3°C warming. NMD of 1.65 percent (4.15 percent) correspond to a ψ of 0.0162414 (0.0419335).

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 (gray-shaded area) and the 66 (blue-shaded area) percentile range of the *RPE*. 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.

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. Atmospheric temperature in 2100 ranges from 1.96°C to 3.81°C. The SCC increases from US$9.34 to US$77.05 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 midcentury.

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 US$34.24 (260.11) 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 US$87.18

[31] At the upper bound of the 95 percentile range, the SCC is US$1,317.93 (4,074.14) per ton of CO_2 in 2020 (2100). For better visibility, we only show the range up to US$600 per ton of CO_2.

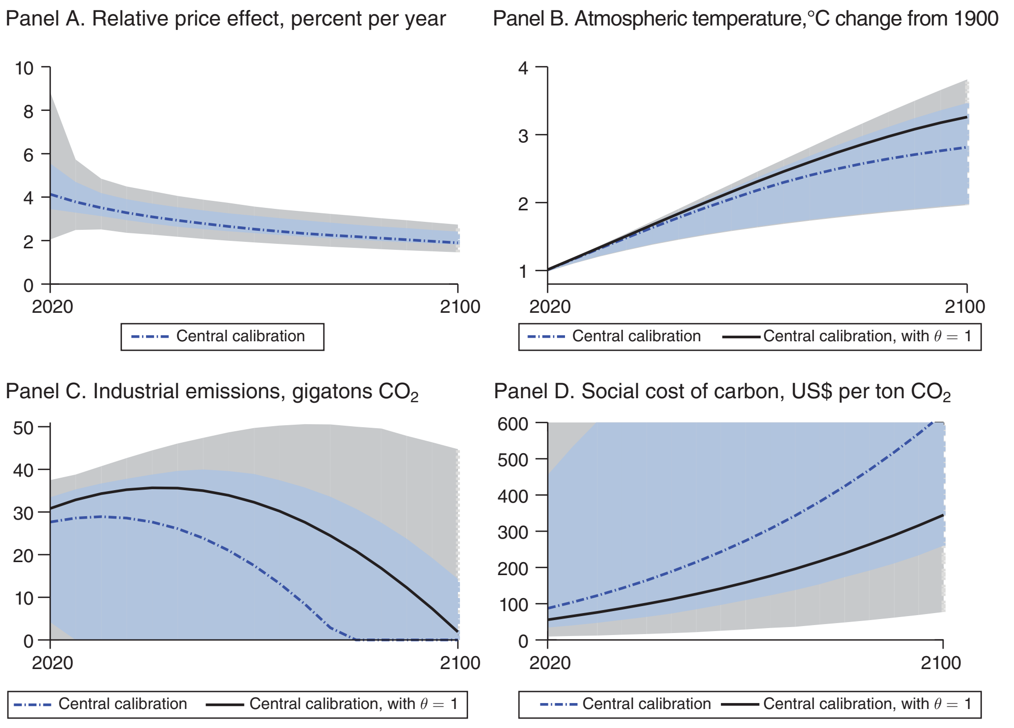

Figure 5. Relative Price Effect of Nonmarket Goods (*RPE*) and Comparison of Climate Policy Paths for Plausible Ranges and a Central Calibration of the Drivers of Relative Price Changes

Notes: The blue-dashed 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 (gray-shaded) area represents the 66 (95) percentile range around the mean of the individual drivers.

per ton of CO_2 and increases up to US\$624.24 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 IIB), 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 nonmarket goods over time.[32] However, a main takeaway from Figure 5

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

Table 4—The "Plausible Ranges" in the *RPE*'s Drivers and Their Influence on the *RPE* and Climate Policy Outcomes

Driver	95 percentile range	RPE 2020 (percent)	RPE 2100 (percent)	Peak T [°C]	SCC^{b} 2020	SCC 2100
θ	-0.44–0.23	5.10–3.00	2.42–1.34	2.78–3.39	117–70	1,035–442
NMD[a]	0–9.54%	4.08–4.45	1.76–2.09	3.71–2.33	49–263	342–1,836
$\bar{E}/E_0$	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	1,330–70
η	0.1–3	8.16–3.17	1.87–2.01	2.16–7.00	521–21	1,361–203
τ^{A}	0–0.2%	4.19–4.08	2.76–1.34	3.29–3.01	73–97	600–571

Notes:
[a]NMD denotes nonmarket damages under 3°C warming.
[b]SCC is measured in US$ per ton of CO_2.

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 2 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 nonmarket 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 nonmarket 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 nonmarket 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. Nonmarket damages and the rate of pure time preference alter the 2020-SCC by US$214.83 and US$234.07 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 US$499.81. For the 2100-SCC (column 7), the amount of nonmarket damages is the strongest driver, leading to a range in the SCC of US$1,493.47. This is followed by the influence of the two welfare parameters, δ and η, at US$1,259.58 and

US$1,157.99 and the degree of substitutability, with US$592.90. 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 US$80.36 (490.05) and US$94.01 (409.17), respectively. The biggest net effect, though, we find for nonmarket damages. They alter peak temperature by 1.33°C, amounting to 96 percent of the overall effect, and the SCC in 2020 (2100) by US$191.19 (1,490.14), corresponding to 89 percent (99.8 percent) of the overall effect. While the net effect of the subsistence level of nonmarket goods is negligible, the impact of the RPE via technological progress on the SCC is notable, changing the SCC in 2020 (2100) by US$6.49 (11.55), thus accounting for 26 percent (40 percent) of the overall effect.

V. 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 nonmarket goods, (ii) technological progress, (iii) data availability on substitutability and nonmarket damages, (iv) preference change, (v) behavioral influences as well as (vi) uncertainty.

First, we find that the drivers related to the growth of nonmarket 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 nonmarket goods would stay constant in absence of climate change. Yet nonmarket 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, nonmarket goods may also increase due to technical change that positively affects nonmarket goods, for example relating to health improvements. Future studies could explore cases in which nonmarket goods can grow or decline irrespective of the management problem at hand as well as explicitly deal with the heterogeneity contained in the composite nonmarket good. Introducing drivers of nonmarket goods growth that are unrelated to climate change also relates to studying nonoptimal climate policy, for example in settings with imperfect management

[33] While much of the literature suggests that climate change leads to a loss of ecosystem services (e.g., Millennium Ecosystem Assessment 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.

control. In such cases that should be explored in future work, drivers of nonmarket goods may play a larger role for relative prices as in the optimal management considered here.

Second, the DICE model considers a specific kind of exogenous technological progress. We have shown that it has a considerable impact on the *RPE*. It is thus crucial to study technological progress in more detail, also considering the possibility of endogenous technological progress (e.g., Hübler et al. 2012, Popp 2004) as well as how substitutability of environmental goods and natural capital interact with technological progress (e.g., Bretschger 1998, Bretschger and Smulders 2012). A crucial related question is also how such technological progress related to the limited substitutability of nonmarket inputs to production (Zhu, Smulders, and de Zeeuw 2019).

Third, the availability of reliable data on the magnitude of nonmarket damages and the degree of substitutability of nonmarket 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 III. This indirect empirical evidence suggests weak substitutability at the margin, in contrast to the assumptions made by experts in applied modeling 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 nonmarket 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 nonmarket damages and the channels through which these damages unfold. While damages only affect the level of market and nonmarket 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, assume 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 2020). Zuber and Fleurbaey (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 agents' 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. (2018) 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.

VI. Conclusion

This paper provides a comprehensive analysis of the change in the relative price of nonmarket 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 nonmarket 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 nonmarket goods, the elasticity of the marginal utility, pure time preference, and the development of technological progress.

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)

[34] See Heal and Millner (2014) for an overview of decision-making under uncertainty in climate economics. Traeger (2014) adapts the 2007-DICE version to analyze effects of uncertainty quantitatively.

already contains a considerable relative price effect of nonmarket goods due to a form of Cobb-Douglas substitutability between (nonmarket) 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 compared 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 nonmarket 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 nonmarket 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 nonmarket 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 nonmarket goods is likely more substantial than the 1 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 toward 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 nonmarket effects.

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