Relative Price Changes and Climate Policy under Heterogeneous Environmental Goods Dynamics

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Abstract: Climate change impacts human well-being not only through damages to market goods but also by affecting non-market goods such as environmental amenities. Previous analyses that account for how climate change affects environmental goods as a direct source of well-being have typically assumed a homogeneous aggregate environmental good. Here, we investigate how the dynamics of two heterogeneous non-market environmental goods affect relative price changes (RPC) between market and non-market goods, as well as the social cost of carbon (SCC), in a variant of Nordhaus' integrated assessment model, DICE. We examine how results depend on (i) the calibration strategy for climate damages on environmental goods, (ii) the management regime including optimal and suboptimal policy, and (iii) assumptions on the substitutability between market and non-market environmental goods as well as among environmental goods. Based on best available evidence, we use Monte Carlo analyses to suggest plausible ranges and a central calibration for RPCs and the effect on climate policy outcomes. When one of the two environmental goods is managed suboptimally, we show that assuming perfect substitutability between heterogeneous environmental goods underestimates the comprehensive RPC in the year 2025 by about one percentage point in our central calibration. We find that ignoring limited substitutability among heterogeneous environmental goods can lead to a sizable underestimation of the SCC.

Keywords: Climate change, integrated assessment, limited substitutability, relative price changes, non-market goods, social cost of carbon
JEL: D61, H43, Q51, Q54, Q57 Q58

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1 Introduction

Climate change affects not only goods and services traded on markets, but also non-market goods and services, such as those related to ecosystems (Bastien-Olvera et al., 2024) or health (IPCC, 2022). Since the industrial revolution, the supply of market goods has increased steadily, while natural capital, including ecosystems and biodiversity, has been in decline (Dasgupta, 2021).

Considering that both market and non-market environmental goods are important for human well-being and that the willingness to pay (WTP) for environmental goods and services plausibly increases with growing incomes as well as with rising absolute scarcities of nature (Conte et al., 2025), the benefits humans derive from ecosystems increase over time (Drupp et al., 2024). Economists refer to the yearly percentage change in the scarcity of environmental goods vis-a-vis market goods over time as the "relative price effect" (Hoel and Sterner, 2007), or the change in relative prices. Relative scarcity is a crucial concept in economics, as it determines the relative prices of different goods. Previous analyses have shown that the limited substitutability of nature, its increasing scarcity relative to market goods, and the associated changes in relative prices are an important driver of optimal climate policy (Sterner and Persson, 2008; Drupp and Hänsel, 2021). Relative price changes (RPC) between market consumption and environmental goods are determined by the degree of limited substitutability between market and non-market environmental goods as well as the difference between the growth rates of the market and non-market goods (e.g., Weikard and Zhu, 2005; Traeger, 2011). The importance of considering the limited substitutability of scarce nature for estimating the social cost of carbon (SCC) has also recently been documented in an expert survey (Moore et al., 2024), which revealed that this is among the key drivers that have been underappreciated in the SCC literature.

One important aspect neglected in previous analyses of RPCs of environmental goods in the context of estimating the SCC is the heterogeneity that exists within what has hitherto been considered as a composite environmental good. Existing studies have addressed heterogeneous environmental goods in two primary ways. Some estimate the income elasticity of willingness-to-pay (WTP) for air quality when private substitutes, such as air conditioning, are available (He et al., 2024). Others distinguish between use and non-use values across separate natural capital stocks (Bastien-Olvera and Moore, 2021). However, these studies do not explicitly examine how the effects on the SCC are mediated by RPCs, calibration approaches, or management regimes. Indeed, nature is diverse and provides myriad benefits, from mangroves offering storm protection and shelter for valued species and human health, to the existence of heritage landscapes that are threatened by climate change. The suites of benefits that nature provides can differ in material ways and along numerous dimensions. For example, the difference in growth rates across nature's non-market benefits might stem from either different susceptibility to damages from climate change or a differential ability to adapt to the climatic impacts on environmental goods. While it might be possible, for example, to adapt to changes

in recreational ecosystem services, such as those related to ecotourism, by changing the season of visits or turning to alternative forms of entertainment and recreation, it will be more difficult to adapt to changes in life-supporting services provided by biodiversity that support healthy ecosystems. Heterogeneous environmental goods may also be subject to different management regimes, and they may be imperfect substitutes for one another or have different degrees of substitutability or complementarity with market goods. Such heterogeneities among environmental goods may impact how they should be incorporated and treated in integrated assessment models (IAM).

In this paper, we relax the assumption of perfect substitutability *across* nature's benefits implicit in prior analyses that considered a monolithic environmental good and study implications of accounting for heterogeneous environmental goods on climate policy evaluation. Without this rigid assumption, we are able to more comprehensively incorporate the dynamics of non-market sectors into climate-economic policy evaluation by allowing growth rates to differ among environmental goods as driven by different management regimes. Specifically, we incorporate environmental good heterogeneity into the analysis of how RPCs of non-market environmental goods vis-à-vis market goods drive climate policy evaluation. We implement our numerical analysis in an updated version of Nordhaus' Dynamic Integrated Climate-Economy (DICE) Model (Hänsel et al., 2020), in which both the growth rate of the market good as well as the different growth rates of heterogeneous environmental goods are endogenous and determined by the management regime. This modification to the model allows us to study the impact of heterogeneous management of environmental goods, which might stem from, for example, limits to adaptation across certain goods.

The paper is structured as follows: Starting from the baseline updated DICE model (Hänsel et al., 2020), we first show how RPCs of non-market goods and climate policy are affected when the non-market environmental good is assumed to be homogeneous. This sheds light on how quantitative results differ within this updated modelling structure, which includes updates to earth system modelling, as compared to the previous analysis of Drupp and Hänsel (2021) that is based on the DICE 2016R2 model (Nordhaus, 2018). Next, we explore how relaxing the assumption of perfect substitutability across heterogeneous environmental goods can be incorporated in the IAM structure. We, here, consider one particular type of nesting, in which heterogeneous environmental goods are first nested and aggregated to a composite non-market environmental goods, which is then a substitute or complement to market goods. We show that in particular, the calibration strategy with respect to disentangling the damages that accrue to market versus heterogeneous non-market environmental goods critically determines the qualitative direction and quantification of RPCs and effects on climate policy. Depending on the calibration strategy, we subsequently quantify RPCs and climate policy outcomes, focusing primarily on the SCC, for the cases of optimal-, business-as-usual-, and heterogeneous management. As a last step of our analysis, we gather the best available evidence on the drivers of relative price changes in an IAM and suggest plausible ranges and a central calibration for the RPC and its effect on climate policy outcomes.

2 Relative price changes and climate policy with a homogeneous environmental good

We use the updated DICE version by Hänsel et al. (2020) as our baseline integrated climate-economy model. This model is based on recent updated evidence in climate and economic sciences and includes an updated carbon cycle and energy balance model, updated estimates for the economic damages from climate change, and a wider range of expert views on the determinants of inter-generational fairness incorporated in the measurement of social welfare, among other updates.

Two functional forms are key for the impact of accounting for relative price changes of non-market environmental goods in the evaluation of climate policy: First, the way environmental good consumption is incorporated into the social welfare function, including the assumptions on limited substitutability, and second, how environmental good consumption evolves over time as driven by climate change. In the following, we specify both of these functional forms starting from a model with a homogeneous environmental good and increase complexity by considering two heterogeneous environmental goods with both homogeneous and heterogeneous damages thereafter. We also discuss how the RPC (Hoel and Sterner, 2007; Drupp and Hänsel, 2021) differs when moving from a one-environmental good to a two heterogeneous environmental goods representation. Using an extended version of the DICE model update by Hänsel et al. (2020), we quantify the dynamics of the non-market environmental goods, the RPC, and how key indicators of optimal climate policy are affected. Specifically, we examine effects on industrial emissions, the atmospheric temperature increase compared to 1900 levels, and the SCC.

In a first step, following Sterner and Persson (2008) and Drupp and Hänsel (2021), we explicitly consider imperfect substitutability between the market composite, C, and a non-market good, $\tilde{E}$, using a constant elasticity of substitution (CES) framework. Given the DICE time horizon of $t = 100$ periods, each comprising 5 years, social welfare in $t = 0$, i.e., W_0 is given by

$$W_0(C_t, \tilde{E}_t, L_t) = \sum_{t=0}^{99} L_t \frac{(1+\delta)^{-5t}}{1-\eta} \left[s_c c_t^{\theta} + (1-s_c)\tilde{e}_t^{\theta} \right]^{\frac{1-\eta}{\theta}} , \tag{1}$$

where L_t is period $t's$ population size such that per capita consumption of the two goods is given by $c = {}^{C}/_{L}$ and $\tilde{e} = {}^{\tilde{E}}/_{L}$. Further, δ denotes the rate of pure time preference, η is the inverse of the elasticity of the marginal utility of comprehensive consumption, s_c is the share parameter for the weight of the market good in utility and θ is an exogenous substitutability parameter that determines the elasticity of substitution, $\sigma = \frac{1}{1-\theta}$.

Again following Sterner and Persson (2008) and Drupp and Hänsel (2021), we assume that the dynamics of $\tilde{E}$ can be represented by a power function of the increase in atmospheric temperature T compared to pre-industrial levels with damage parameters

$\psi_{\tilde{E}}$ and damage exponent $\phi_{\tilde{E}}$.

$$\tilde{E}_t = \frac{\tilde{E}_0}{[1 + \psi_{\tilde{E}} T_t^{\phi_{\tilde{E}}}]} \tag{2}$$

The RPC over time in the single non-market good framework (Drupp and Hänsel (2021)) is then given by

$$RPC_t = (1-\theta) \left[g_{C_t}(\delta, \eta, \tau^A, ...) + \underbrace{\frac{2\,\psi_{\tilde{E}}\, T_t^2\, g_{T_t}}{(1 + \psi_{\tilde{E}}\, T_t^2)}}_{-g_{\tilde{E}_t}} \right] . \tag{3}$$

It depends on the difference between the growth rates of the market good g_C and the aggregate non-market environmental good $g_{\tilde{E}}$, scaled by the degree of substitutability between the market and the non-market good θ. Importantly, in the setting of an IAM, both growth rates are endogenous and depend on the management regime, for example, optimal management versus business-as-usual. Accordingly, the growth rate of the market goods depends on the parameters of the social welfare function δ and η, or the assumption on technical progress τ^A, while the growth rate of the non-market goods depends on the temperature trajectory T_t and g_{T_t}, and assumptions on the expected magnitude of non-market damages captured by $\psi_{\tilde{E}}$. The social cost of carbon (SCC) is then computed as the welfare impact of emitting an additional ton of CO_2 into the atmosphere, evaluated in units of market consumption (Nordhaus, 2007):

$$SC\text{-}CO_2(t) = -\frac{\partial W(t)\left(c_t, \tilde{E}_t, L_t\right)/\partial CO_2(t)}{\partial W(t)\left(c_t, \tilde{E}_t, L_t\right)/\partial C(t)} \tag{4}$$

Figures 1 and 2 compare the central calibration in terms of the main determinants of the RPC on climate policy evaluation in Drupp and Hänsel (2021) (DICE-DH21-RPC curves) to the outcomes within the updated climate-economic modelling structure in Hänsel et al. (2020) (DICE-Update-RPC curves). The central calibration in Drupp and Hänsel (2021) parametrizes the rate of pure time preference, the elasticity of the marginal utility of comprehensive consumption, the growth rate of total factor productivity, the assumption of non-market climate damages for a 3°C increase in atmospheric temperatures, and the substitutability parameter determining the elasticity of substitution between the aggregate market and non-market goods. One key difference between both models is the magnitude of climate damages. While Drupp and Hänsel (2021) incorporate the market damages in Nordhaus (2019), which amount to 1.6% of global output for a 3°C increase in atmospheric temperature, and roughly double those damages to account for non-market damages based on an expert survey by Howard and Sylvan (2015), Hänsel et al. (2020) use the market damages from the meta-analysis by Howard and Sterner (2017), which amount to about 5% of global output for a 3°C increase in atmospheric temperature and also double these to capture non-market effects.

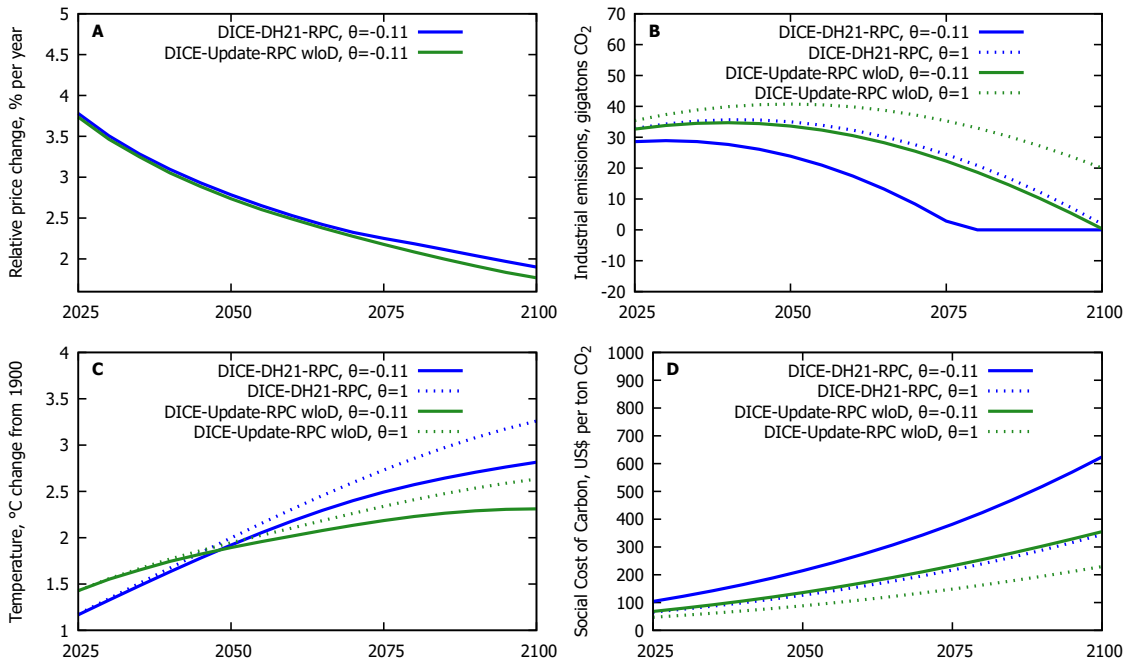


Figure 1: **Relative price changes (RPC) and climate policy with a homogeneous environmental good and low climate damages.** Central calibration in terms of the main determinants of the RPC on climate policy evaluation in Drupp and Hänsel (2021) versus within the updated DICE model by Hänsel et al. (2020) with low climate damages (wloD). Compared to the model by Hänsel et al. (2020), the central calibration in Drupp and Hänsel (2021) includes lower market (non-market) damages equal to 1.63% (1.65%) of global output for a 3°C increase in atmospheric temperature, i.e. the "DICE-Update-RPC wloD" DICE model includes all updates from Hänsel et al. (2020) except for the updated damage function.

Figure 1 mirrors the updates to the DICE model in Hänsel et al. (2020) that go beyond the parametrization of the central calibration in Drupp and Hänsel (2021), i.e., structural changes of the climate system, assumptions regarding negative emission technologies (NETs) and the path of non-CO2 emissions from land-use changes. Specifically, the updates of the carbon cycle based on Millar et al. (2017) and Smith et al. (2018) consider the non-linearity of the carbon cycle, i.e., that the fraction of carbon in the atmosphere is higher for higher cumulative emissions, resulting in a later decarbonization for the same atmospheric temperature increase as compared to DICE 2016R2 Nordhaus (2019). Similarly, and ceteris paribus, the updates to the energy balance model based on Geoffroy et al. (2013) lower the pressure on decarbonization. Further, the updated DICE model by Hänsel et al. (2020) assumes availability of NETs by 2050 (IPCC, 2018) and accounts for an exogenous path of non-CO_2 emissions in line with the temperature targets of the Paris Agreement. Thus, the same RPC would lead to different optimal climate policy paths across the two model versions. In particular, accounting for the changing scarcity of non-market goods implies less pressure on the speed of decarbonization in the "DICE-Update-RPC wloD" model, such that even if industrial emissions stay positive until the end of century (green line in Panel 1B), the optimal temperature increase and the social cost of carbon are lower, as compared to the "DICE-DH21-RPC" model, i.e. the DICE 2016R2 model extended for RPC effects by Drupp and Hänsel (2021).

When we instead consider the assumption on market damages in line with Hänsel

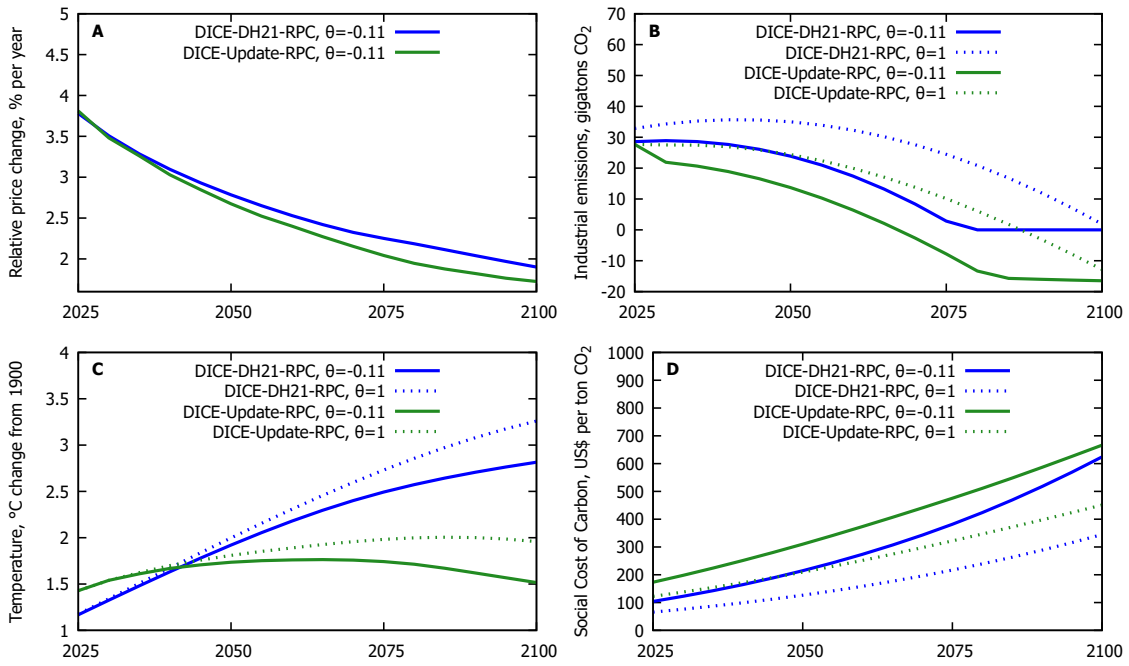


Figure 2: **Relative price changes and climate policy with a homogeneous environmental good and high climate damages.** Central calibration in terms of the main determinants of the RPC on climate policy evaluation in Drupp and Hänsel (2021) versus within the updated DICE model by Hänsel et al. (2020), but with higher market damages of 5.02% output for a 3°increase in atmospheric temperature as in Hänsel et al. (2020). In line with Howard and Sylvan (2015) and Drupp and Hänsel (2021) non-market damages have roughly the same size as market damages such that overall damages are around 10%.

et al. (2020) and double these damages to account for non-market effects, the comparison appears differently, as depicted in Figure 2. Here, the higher damages slightly lower the RPC (except for the year 2025), as higher non-market damages make rebuilding the non-market good even more important and optimal, which lowers the difference in the growth rates of the market vs. the non-market goods (see Drupp and Hänsel (2021) for a discussion and sensitivity analysis). Moreover, optimal climate policy calls for earlier decarbonization and NETs within this 21st century, which stabilizes the temperature increase below the 1.5°C target by the end of the century. The resulting social cost of carbon with relative price changes increases from around 100 US$ per ton of CO_2 in 2025 in the model by Drupp and Hänsel (2021) to around 300 US$ in 2025 in the updated DICE model by Hänsel et al. (2020).

While the comparison in Figure 2 is driven by different assumptions on climate damages, we present it here to make the differences between both models as transparent as possible. In the following, we will use the updated DICE model with RPC effects that includes higher damages as in Howard and Sterner (2017) as a baseline to depart from the assumption of one aggregate non-market goods and consider two heterogeneous non-market environmental goods next to a pure market consumption good.

3 Relative price changes and climate policy with heterogeneous environmental goods

In a second step, we modify the social welfare function to account for two heterogeneous non-market environmental goods next to the market good. Specifically, we assume that comprehensive non-market good consumption consists of the consumption of a pure public environmental good N that mainly generates non-use values, such as through the existence of biodiversity, and an environmental good e that generates use value, such as recreational ecosystem services, and which can be consumed in per capita terms. In line with our framing of allowing for heterogeneity within the composite non-market good, we assume that the two heterogeneous non-market environmental goods are nested relative to the market composite. The modified social welfare function reads

$$W_0 = \sum_{t=0}^{99} L_t \frac{(1+\delta)^{-5t}}{1-\eta} \left[\left(s_c c_t^{\theta_c} + (1-s_c) \left(s_e e_t^{\theta_e} + (1-s_e) N_t^{\theta_e} \right)^{\frac{\theta_c}{\theta_e}} \right) \right]^{\frac{1-\eta}{\theta_c}}, \tag{5}$$

where s_c and s_e are the share parameters for the market-good, c and the non-market use value generating good, e, respectively. Further, θ_e captures the substitutability within the nest and θ_c determines the substitutability outside the nest, i.e. between the market good c and the composite non-market good consisting of e and N.

Following Drupp and Hänsel (2021), we assume that the dynamics of the two environmental goods are given by

$$E_t = \frac{E_0}{[1+\psi_E T_t^{\phi_E}]}, \tag{6a}$$

$$N_t = \frac{N_0}{[1+\psi_N T_t^{\phi_N}]}. \tag{6b}$$

As the composite environmental good $\tilde{E}$ is given by $\tilde{E} = \left(s_e e_t^{\theta_e} + (1-s_e) N_t^{\theta_e} \right)^{\frac{1}{\theta_e}}$, we can use equation 3 to showcase the determinants of the comprehensive RPC in the setting of two heterogeneous environmental goods measuring the changing scarcity of the composite non-market environmental good as compared to the market good. In the case of two environmental goods, the growth rate of the composite non-market environmental good $g_{\tilde{E}}$ will depend on all parameters in equations 6a-6b, i.e.,

$$RPC_t = (1-\theta_c) \left[g_{C_t}(\delta, \eta, \tau^A, ...) - g_{\tilde{E}_t}(T_t, g_{T_t}, \psi_N \psi_E, \phi_N, \phi_E, ...) \right]. \tag{7}$$

In order to evaluate how environmental good heterogeneity drives the comprehensive RPC-effect as well as key climate policy metrics, the calibration of the two damage scaling parameters ψ_E and ψ_N is critical, given assumptions on initial conditions E_0 and N_0 and damage exponents ϕ_E and ϕ_N. In the following, we suggest two alternative calibration strategies.

3.1 Calibration of heterogeneous climate damages on environmental goods

For the first calibration strategy, we assume that overall damages from climate change in the model are kept constant, such that the differences in climate policy we find under this calibration strategy are only attributable to the structural changes implied by accounting for limited substitutability in the presence of heterogeneous environmental goods. Importantly, this calibration implies that the heterogeneous damage scaling parameters depend on preferences, including the degree of substitutability within and between nests captured by the parameters θ_e and θ_c.

Following Drupp and Hänsel (2021) for the single environmental good case,we calibrate the individual environmental goods scaling parameters ψ_E and Ψ_N such that the impact of individual damages D^C, D^N and D^E for a 3°C temperature increase on C, E and N on social welfare at $t = 0$ is the same as compared to a model where total damages D^T fall on C only. The calibration point for the damage functions at 3°C warming is calibrated in line with the standard DICE model (Barrage and Nordhaus, 2024) for a temperature range from 1-4°C .

$$W_0\left((1-D^T)C_0, E_0, N_0, L_0\right) = W_0\left((1-D^C)C_0, (1-D^E)E_0, (1-D^N)N_0, L_0\right) \tag{8}$$

Importantly, equation 8 implies that this calibration does not change overall economic damages from climate change in the model and thus, the differences in climate policy outcomes we find under this calibration strategy are only attributable to the structural changes implied by accounting for limited substitutability in the presence of heterogeneous environmental goods. The calibration further implies that the damage scaling parameters depend on the substitutability preference parameters θ_e and θ_c. Holding overall welfare damage constant on both sides of equation 8 implies that when damages on E and N are complementary, Ψ_E and Ψ_N decrease to ensure that overall damages are still the same as compared to a model with market damages only. To calculate ψ_E, we plug in $E_0 = {}^{E_o}/_{(1+\psi_E T^{\phi_E})}$ and solve the resulting equation for ψ_E:

$$\begin{aligned} s_c\left((1-D^T)C_0\right)^{\theta_c} + (1-s_c)\left[s_e E_0^{\theta_e} + (1-s_e)N_0^{\theta_e}\right]^{\frac{\theta_c}{\theta_e}} = \\ s_c\left((1-D^C)C_0\right)^{\theta_c} + (1-s_c)\left[s_e\left(\frac{E_o}{(1+\psi_E T^{\phi_E})}\right)^{\theta_e} + (1-s_e)\left((1-D^N)N_0\right)^{\theta_e}\right]^{\frac{\theta_c}{\theta_e}} \end{aligned} \tag{9}$$

With a few steps of algebra we arrive at

$$\psi_E = \left[\frac{E_0}{\left[\left[\left[\left[s_c((1-D^T)C_0)^{\theta_c} + (1-s_c)[s_e E_0^{\theta_e} + (1-s_e)N_0^{\theta_e}]^{\frac{\theta_c}{\theta_e}} - s_c((1-D^C)C_0)^{\theta_c}\right]^{\frac{1}{(1-s_c)}}\right]^{\frac{\theta_e}{\theta_c}} - (1-s_e)((1-D^N)N_0)^{\theta_e}\right]^{\frac{1}{s_e}}\right]^{\frac{1}{\theta_e}}} - 1\right]^{\frac{1}{T^{\phi_E}}}. \tag{10}$$

To calculate ψ_N we use $N_0 = {}^{N_o}/_{(1+\psi_N T^{\phi})}$ and solve equation (11) for ψ_N:

$$s_c\left((1-D^T)C_0\right)^{\theta_c}+(1-s_c)\left[s_e e_0^{\theta_e}+(1-s_e)N_0^{\theta_e}\right]^{\frac{\theta_c}{\theta_e}}=$$
$$s_c\left((1-D^C)C_0\right)^{\theta_c}+(1-s_c)\left[s_e\left((1-D^E)e_0\right)^{\theta_e}+(1-s_e)\left(\frac{N_o}{(1+\psi_N T^{\phi_N})}\right)^{\theta_e}\right]^{\frac{\theta_c}{\theta_e}} \tag{11}$$

$$\psi_N=\left[\frac{N_0}{\left[\left[\left[\left[s_c((1-D^T)C_0)^{\theta_c}+(1-s_c)[s_e E_0^{\theta_e}+(1-s_e)N_0^{\theta_e}]^{\frac{\theta_c}{\theta_e}}-s_c((1-D^C)C_0)^{\theta_c}\right]^{\frac{1}{(1-s_c)}}\right]^{\frac{\theta_e}{\theta_c}}-s_e((1-D^E)E_0)^{\theta_e}\right]^{\frac{1}{(1-s_e)}}\right]^{\frac{1}{\theta_e}}}-1\right]^{\frac{1}{T^{\phi_N}}} \tag{12}$$

For the first calibration strategy, i.e. when the damage scaling parameters depend on θ_e and θ_c, the default is to assume homogeneous quadratic damages across N and E, i.e. that ψ_E and ψ_N are calibrated such that both environmental goods make up 50% of overall non-market damages that equal 5% of global output for a 3°C temperature increase and that $\phi_E = \phi_N = 2$. For the second calibration strategy, we assume that damages are primarily determined by given knowledge about climate impacts on natural capital and are independent of substitutability preferences. Here, we fix ψ_E and ψ_N for the case when the two environmental goods are perfect substitutes, i.e. $\theta_e = 1$ and $\theta_c = -0.11$ is calibrated in line with the central calibration in (Drupp and Hänsel, 2021). The assumptions on the symmetric damage structure implemented in the first calibration strategy hence only apply for these particular assumptions on substitutability.

In the following, we first report the numerical results for the case when climate damages on environmental goods are independent of substitutability preferences, since this might correspond to the more intuitive case. This calibration strategy, which we refer to as "preference-independent damages" in the following, implies that overall damages are not the same as compared to a model where all damages fall on the market consumption good only. In a second step, we relax the assumption on the scaling parameters being fixed to make sure that overall damages are the same across all combinations of substitutability assumptions and refer to this calibration strategy as "preference-dependent damages". For the sensitivity analysis with respect to substitutability assumptions we focus on the year 2025, while we also show the results for the year 2100 in Appendix A.

3.2 Optimal management under preference-independent damages

For the year 2025 and in an optimal management setting, Figure 9 summarizes how different degrees of substitutability between heterogeneous environmental goods θ_e (Panels A and C) and between the market and the composite environmental good θ_c (Panels B and D) influence relative prices changes of the composite environmental good $\tilde{E}$ with respect to market good consumption c as well as the social cost of carbon. We display an interval of the exogenous substitutability parameter from -1 to 1, where 0 marks

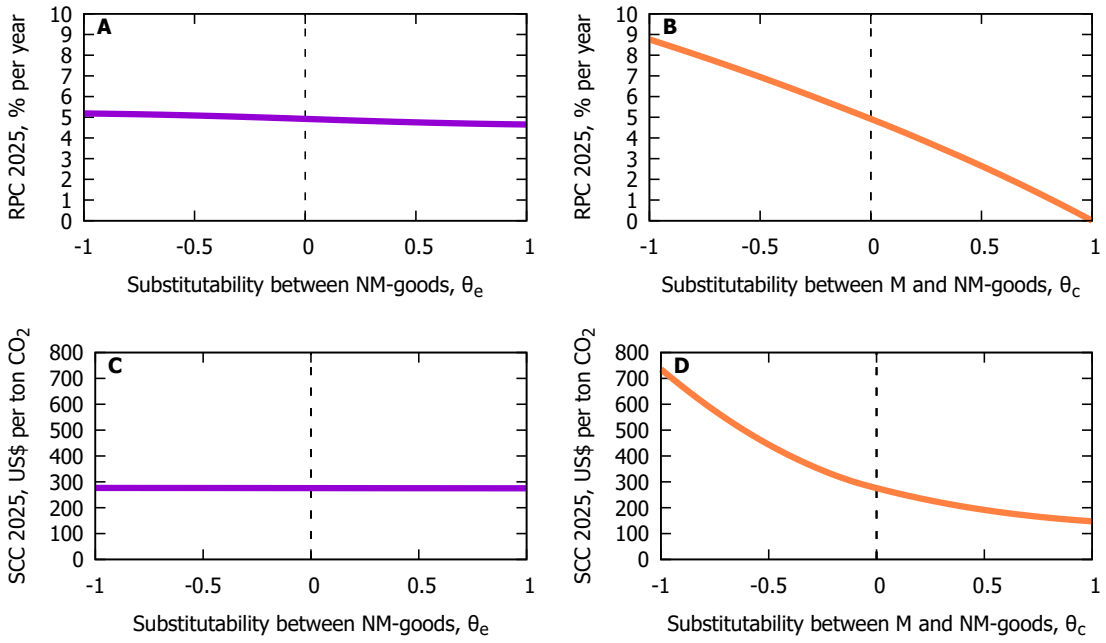


Figure 3: **Relative prices changes and social cost of carbon in 2025 under optimal management and preference-independent damages:** The effect of assumptions on substitutability across non-market environmental goods (purple lines) and between the composite non-market and the market consumption good (orange line) on the comprehensive RPC effect (Panels A and B) and the social cost of carbon (Panel C and D) in 2025. The damage scaling parameters are fixed for the case when $\theta_e = 1$ and $\theta_c = -0.11$, which implies preference-independent climate damages as compared to model where all damages fall on market consumption only.

the dividing case between substitutes and complements and 1 corresponds to perfect substitutability.

Within the structure of the the updated DICE model (Hänsel et al., 2020), Panels B and D confirm the sizable quantitative effect (Drupp and Hänsel, 2021) of limited substitutability between market and non-market goods θ_c on optimal climate policy driven by the RPC of the composite non-market environmental good vis-à-vis market goods: While for perfect substitutability between market and non-market goods the RPC in 2025 vanishes corresponding to a (baseline) SCC in 2025 of around 150 US$ per ton of CO_2, the RPC in 2025 amounts to almost 9% per year when $\theta_c = -1$, which increases the social cost of carbon to more than 700 US$ per ton of CO_2.

The effect of within non-market environmental goods substitutability θ_e has the same direction, i.e. limited substitutability increases the stringency of optimal climate policy, but is quantitatively less sizable as compared to the effect of θ_c previously studied in the literature. The interval between θ_e from 1 (perfect substitutes) to -1 (limited substitutability) increases the comprehensive RPC effect by around 0.5 percentage points, which alters the social cost of carbon by only 1.4 US$.

The minor quantitative effect of limited substitutability among non-market goods on optimal climate policy in 2025 can be explained when inspecting the time dynamics from 2025 to 2100 of the two environmental goods in Figure 4 Panels A-B. The optimal management regime ensures that both environmental goods are being built up to levels

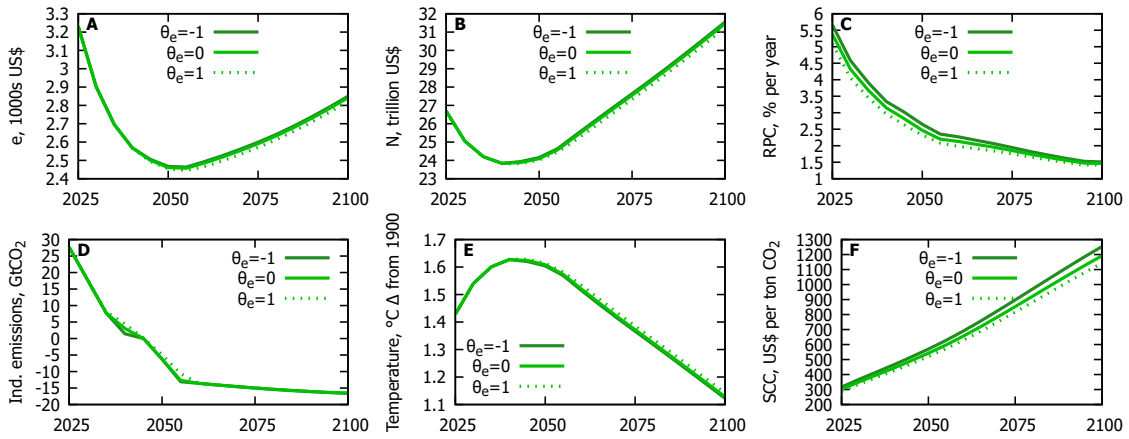


Figure 4: **Optimal climate policy dynamics under different degrees of substitutability across environmental goods.** The damage scaling parameters are fixed for the case when $\theta_e = 1$ and $\theta_c = -0.11$, which implies preference-independent climate damages as compared to model where all damages fall on market consumption only.

that counteract the dampening effect of limited substitutability across the two goods. As a result, Panels D-F then show that, especially near-term, optimal climate policy must only be marginally less stringent when heterogeneous environmental goods are perfect substitutes as compared to when accounting for limited substitutability with respect to market consumption, where growth rates are much more heterogeneous.

3.3 Business-as-usual management under preference-independent damages

In a next step we assume that industrial CO_2 emissions are not controlled, i.e. they follow a business-us-usual scenario. Figure 5 summarizes the numerical results showing that also under this management regime within environmental goods substitutability has almost no effect on the development of both environmental, climate and policy variables. The damage scaling parameters Ψ_E and Ψ_N are fixed for the case when $\theta_c = 0.11$ and $\theta_e = 1$ and thus varying θ_e does not influence the dynamics of e and N in Panels A and B. The comprehensive RPC effect that takes into account how the overall scarcity of the composite environmental good evolves over time is only marginally affected as compared to optimal management.

3.4 Heterogeneous management under preference-independent damages

We now turn to the more interesting case when one of the two environmental goods can be managed optimally and the other remains unmanaged. We refer to this management regime as heterogeneous management. Specifically, we assume that while recreational services e are managed optimally, biodiversity N declines according to a business as usual (BAU) scenario that is fixed to the BAU path for N in Figure 5. This might be a realistic scenario since managing the effects of climate change on recreational ecosystem services (for example natural park visits) may be easier to implement as compared

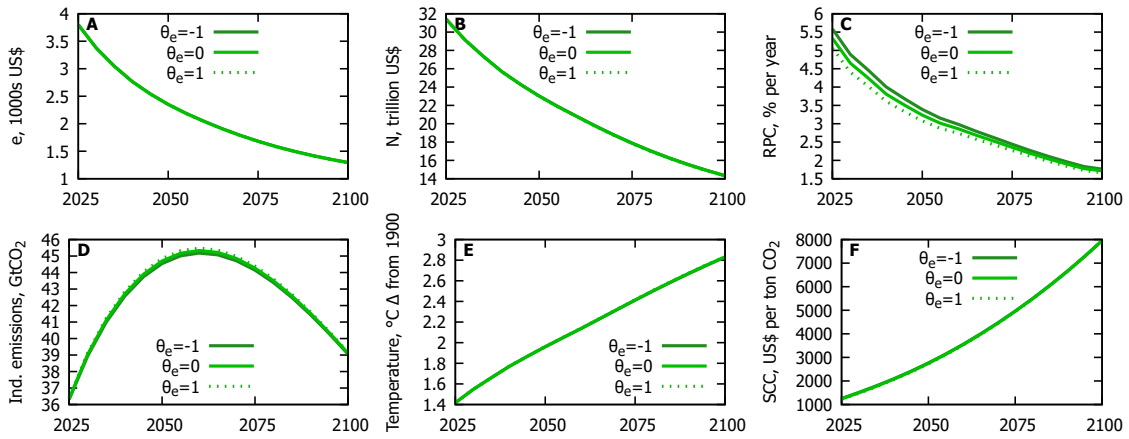


Figure 5: **Business as usual climate management under different degrees of substitutability across environmental goods.** The damage scaling parameters are fixed for the case when $\theta_e = 1$ and $\theta_c = -0.11$, which implies preference-independent climate damages as compared to model where all damages fall on market consumption only.

to halting global biodiversity loss. Figure 6 summarizes the numerical results under heterogeneous management of environmental goods.

While N follows the predetermined BAU path (Panel 6B), the speed and level to which e is built up over time is determined by the optimal management regime for e and depends in particular on whether the two environmental goods are complements or substitutes. Specifically, the more environmental goods are complementary ($\theta_e = -1$), the more optimal management makes sure that larger amounts of e are available over time to be able to provide the composite aggregate environmental good (Panel 6A). This development is reflected in the comprehensive RPC effect (Panel 6C), which displays that complementarity between the environmental goods means that the overall changing scarcity of the composite environmental goods must be managed more stringently when management is heterogeneous. Managing the changing scarcity of environmental goods is only possible by mitigating climate change and thus Panels 6D to 6E reflect that policy ambition must increase the more complementary the environmental goods are.

Figure 7 compares the sensitivity of the comprehensive RPC effect in 2025 and the SCC to assumptions on the standard substitutability parameter between market and non-market goods (Panels B and D) and the parameter that captures substitutability across environmental goods (Panel A and C). While substitution possibilities between market and non-market goods remain the dominant driver of overall changing scarcity also under heterogeneous management, changing the RPC from 0 to 10 when θ_c moves from 1 to -1 , the effect of limited substitutability across environmental goods has the same qualitative direction but is quantitatively smaller. However, as compared to optimal management, the comprehensive RPC when lowering θ_e from 1 to -1 amounts to 1 percentage point, i.e. it doubles as compared to the case of optimal management. Furthermore, the effect of limited substitutability across environmental goods on the SCC is more pronounced in the case of heterogeneous management. The SCC increases by 100

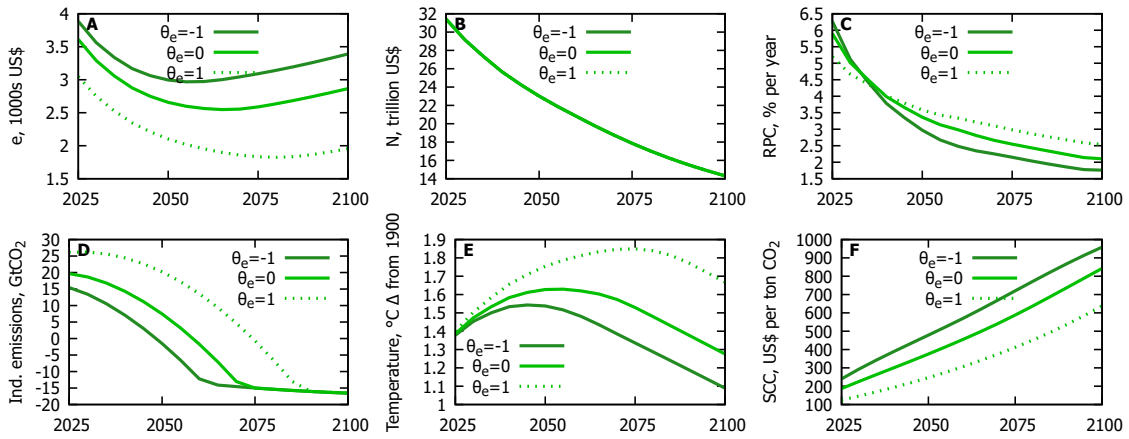


Figure 6: **Heterogeneous climate management under different degrees of substitutability across environmental goods.** The damage scaling parameters are fixed for the case when $\theta_e = 1$ and $\theta_c = -0.11$, which implies preference-independent climate damages as compared to model where all damages fall on market consumption only.

US$ when θ_e decreases from 1 to -1 (compared to 1.4 US$ in the case of optimal management), while the effect of θ_c on the SCC is dampened. Thus, under heterogeneous management, limited substitutability across environmental goods has a more sizable quantitative effect on the SCC than it does under optimal management.

We now turn to describing our numerical results for the case when the damage scaling parameters for the two environmental goods depend on substitutability preferences, captured by θ_c and θ_e, which ensures that overall damages in the model extended for heterogeneous environmental goods are comparable to a model where all damages fall on market consumption only.

3.5 Optimal management under preference-dependent damages

Figure 8 presents the optimal pathways from 2025 to 2100 for the recreational environmental good that is consumed in per capita terms (Panel A), the public environmental good (Panel B), the comprehensive RPC effect (Panel C) industrial emissions (Panel D), the atmospheric temperature change as compared to the 1900 level (Panel E) and the SCC (Panel F).

Panel A and B of Figure 8 show both environmental goods initially decline, due to the damages from climate change, before they stabilize and increase due to the optimal management of the climate-economy system. Importantly and in contrast to Figure 4, the higher the degree of complementarity between both environmental goods, as captured by the parameter θ_e, the higher are the optimal values of both goods. The intuition is that in the case of complementarity the optimal management of the climate-economy system would demand higher absolute levels of both environmental goods in order to guarantee the provision of the composite environmental good. The resulting comprehensive RPC effect is higher the more complementary the two environmental

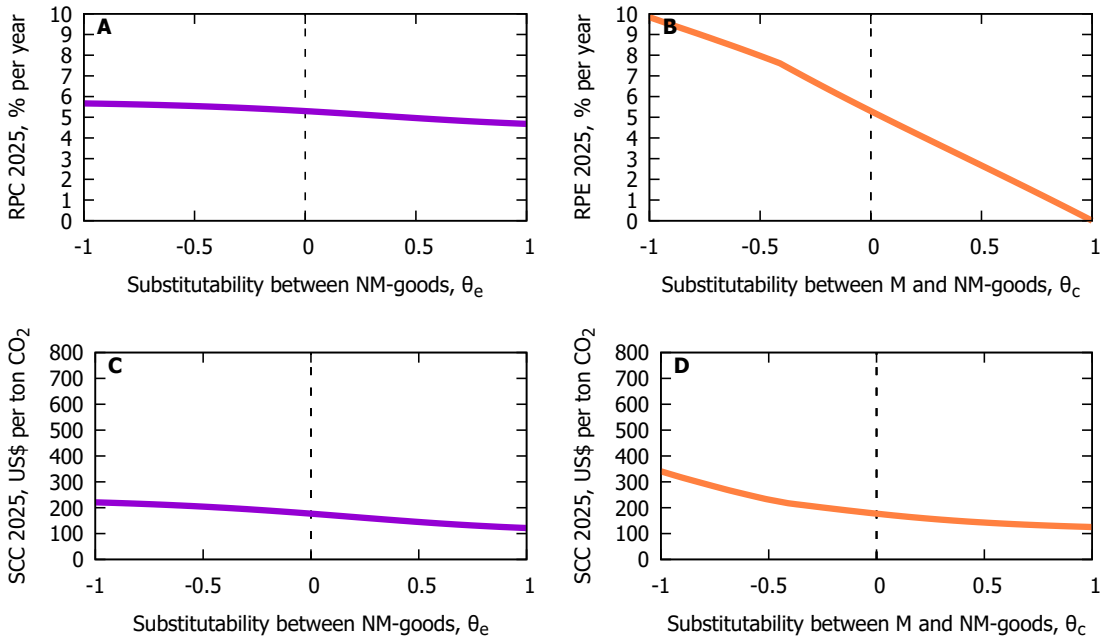


Figure 7: **Relative prices changes and social cost of carbon in 2025 under heterogeneous climate management and preference-independent damages:** The effect of assumptions on substitutability across non-market environmental goods (purple lines) and between the composite non-market and the market consumption good (orange line) on the comprehensive RPC effect (Panels A and B) and the social cost of carbon (Panels C and D) in 2025. The damage scaling parameters are fixed for the case when $\theta_e = 1$ and $\theta_c = -0.11$, which implies preference-independent climate damages as compared to model where all damages fall on market consumption only.

goods are and declines over time due to the optimal management regime, which lowers the difference between the growth rate of the market and the composite non-market environmental good.

While Panels A-C summarize the optimal dynamics of the environmental goods and the implied overall changing scarcity of the composite environmental good as compared to the market good, Panels D-F summarize the implications for key indicators of optimal climate policy. All three panels show that a higher degree of complementarity between the two environmental goods leads to less stringent climate policy as compared to the case when these two goods are perfect substitutes, which is in contrast to the results obtained when economic damages are assumed to preference-independent (compare Figures 4 to 3.

The reason for these contrasting results with respect to the effect of substitutability assumptions across environmental goods on the stringency of optimal climate policy is due to the calibration strategy that ensures that overall damages in the extended DICE model are comparable to a model where all damages fall on market consumption only. With this calibration strategy and our model parameterization, Ψ_E and Ψ_N are increasing in θ_e, i.e. in the ease with which the two environmental goods are substitutable with each (see Section 3.1). When climate change that affects the environment consisting of complementary environmental goods is managed optimally, each of these goods will be provided in higher absolute levels by decreasing damages through controlling CO_2

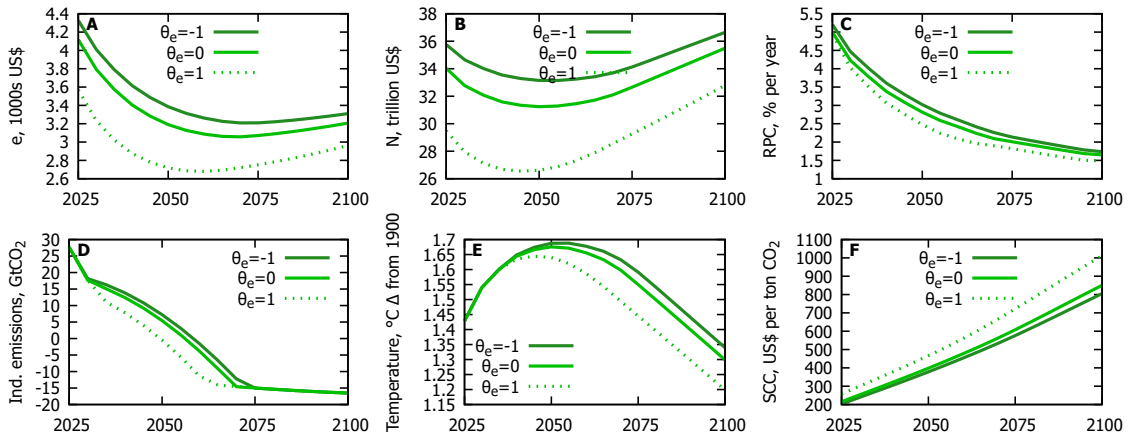


Figure 8: **Optimal climate policy under different degrees of substitutability across environmental goods and preference-dependent damages.** The scaling parameters for climate damages on the environment depend on subsitutability preferences θ_e and θ_c. The substitutatbility between the market good and the composite non-market environmental good is assumed to be Cobb-Douglas, i.e. $\theta_c = 0$.

emissions. As welfare depends on market and non-market goods, the welfare impact of an additional ton of CO_2, i.e. the social cost of carbon, will be lower when the stocks of both environmental goods are higher. This means that optimal climate policy must be less stringent in that case.

Figure 9 shows how comprehensive relative prices changes and the social cost of carbon in 2025 are affected by different assumptions on substitutability across non-market environmental goods (purple lines) and between the composite non-market and the market consumption good (orange lines). The RPC increases by around 0.3 percentage points over the range from $\theta_e = 1$ to $\theta_e = -1$, while the effect of θ_c on the RPC is about 1 percentage point lower for $\theta_c = -1$ as compared to the case with optimal management and preference-independent damages. The social cost of carbon increases with θ_e moving from -1 to 1 by around 80 US$ per ton of CO_2, while it first increase by 7 US$ when moving from $\theta_c = -1$ to $\theta_c = 0$ (dashed vertical line in Panel D) and then decreases by around 100 US$ for the interval from 0 to 1. This is much in contrast to the quantitative effects in the case of optimal management under preference-independent damages (see Figure 3, where the SCC decreased by more then 700 US$ when moving from $\theta_c = 1$ to $\theta_c = -1$.

Thus, under optimal management the calibration strategy with preference-dependent damages implies that the qualitative direction of the effect of limited substitutability on the SCC is reversed but is quantitatively more sizable as compared to the case when damages are independent from substitutability preferences. Notably, the effect of θ_c on the SCC is dampened due to the optimal and preference-dependent management of environmental goods that ensures equal (initial) climate damages at the calibration point of 3 degrees global warming as compared to a model where all damages fall on market consumption only.

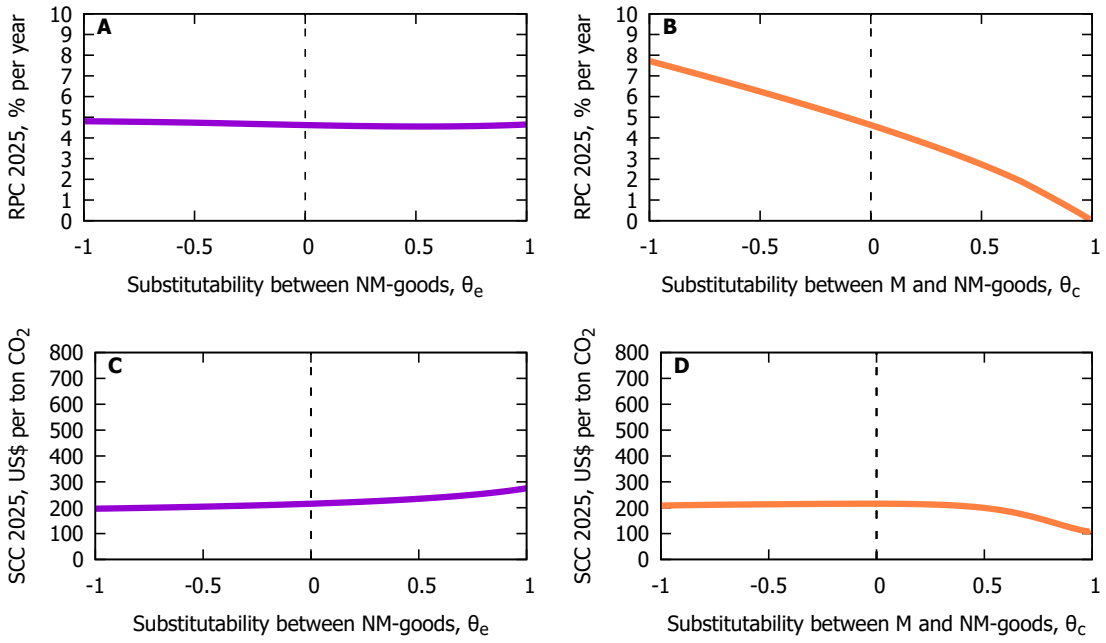


Figure 9: **Relative prices changes and social cost of carbon in 2025 under optimal management and preference-dependent damages:** The effect of assumptions on substitutability across non-market environmental goods (purple lines) and between the composite non-market and the market consumption good (orange line) on the comprehensive RPC effect (Panels A and B) and the social cost of carbon (Pabel C and D) in 2025. The damage scaling parameters for environmental goods depend positively on substitutability preferences θ_e and θ_c, which ensures that overall damages are comparable to a model where all damages fall on market consumption only.

3.6 Business-as-usual management with preference-dependent damages

When we compare the optimal management regime to a business as usual scenario where the emission control rate is set to zero over the whole modelling horizon, the environmental goods decline steadily over the century, while their different levels reflect different degrees of within-environmental good substitutability as discussed in the above section on optimal management.

The effects of different degrees of within-good substitutability on climate policy are negligible on the depicted scales as the effect of uncontrolled industrial emissions dominates.

3.7 Heterogeneous management with preference-dependent damages

We now explore the effects of heterogeneous management. Specifically, we assume that while recreational services e are managed optimally (Panel A), biodiversity N declines according to the preference-dependent business-as-usual (BAU) paths in Figure 10 Panel B. As in the case heterogeneous management under preference-independent damages, we argue that this might be a realistic scenario since managing the effects of climate change on recreational ecosystem services (for example natural park visits) may be easier to implement as compared to halting global biodiversity loss. The key difference here is that now the BAU paths for N vary with θ_e, i.e. are "preference-dependent".

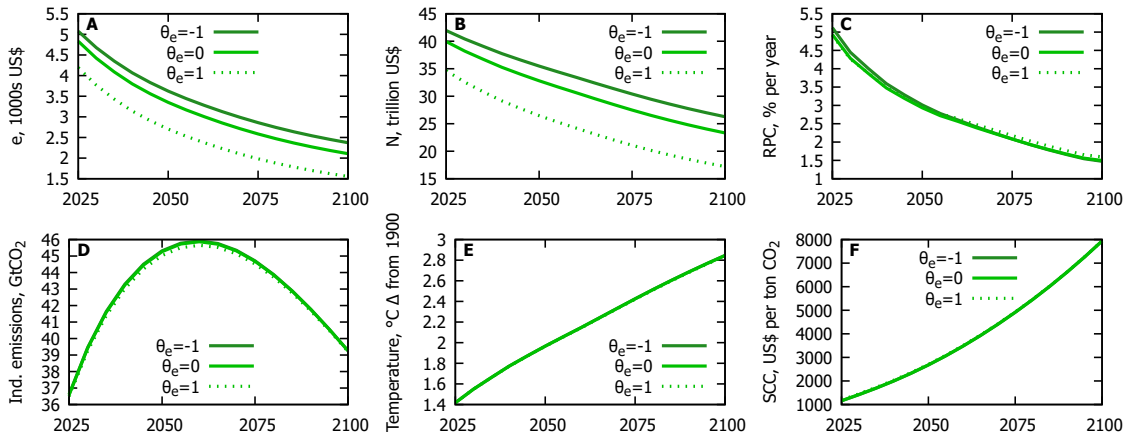


Figure 10: **Business as usual management under different degrees substitutability across environmental goods and preference-dependent damages** The scaling parameters for climate damages on the environment depend on subsitutability preferences θ_e and θ_c. The substitutability between the market good and the composite non-market environmental good is assumed to be Cobb-Douglas, i.e. $\theta_c = 0$.

Panel A shows that the optimal management of recreational services e bends the declining curve around the year 2075. As in the case when both environmental goods are managed optimally (see Figure 8), the higher the degree of complementarity between both environmental goods, as captured by the parameter θ_e, the higher are the optimal values of both goods to guarantee the provision of the composite environmental good. In contrast to the optimal management regime in Figure 8, recreational services e are build up to higher levels by 2100 in order to compensate the effect a declining unmanaged N. The resulting comprehensive RPC (Panel C) is higher in 2025 the more complementary the two environmental goods are and declines over time due to the optimal management of e. Importantly, from around mid-century onward the comprehensive RPC is lower with higher complementarity of the two environmental goods, which is in contrast with the optimal management regime in Figure 8 but is very similar to the dynamics under preference-independent damages. Thus, under heterogeneous management the comprehensive RPC is not sensitive to the calibration strategy for climate damages on the environment.

Panels D-F in Figure 20 show that for the case of heterogeneous management under preference-dependent damages, limited substitutability across environmental goods results in more stringent climate policy in order to dampen the adverse effects of climate change on nature that can only partly be managed. Hence, the qualitative direction of the effect of limited substitutability across environmental goods is reversed as compared to the case when both environmental goods are managed optimally (see Figure 8. In turn, the qualitative direction of this effect is the same as compared to the case under heterogeneous management and preference-independent damages, while the stringency of climate policy is slowed down.

Figure 12 sheds further light on the qualitative and quantitative effect of limited substitutability across environmental goods and between the market and the composite

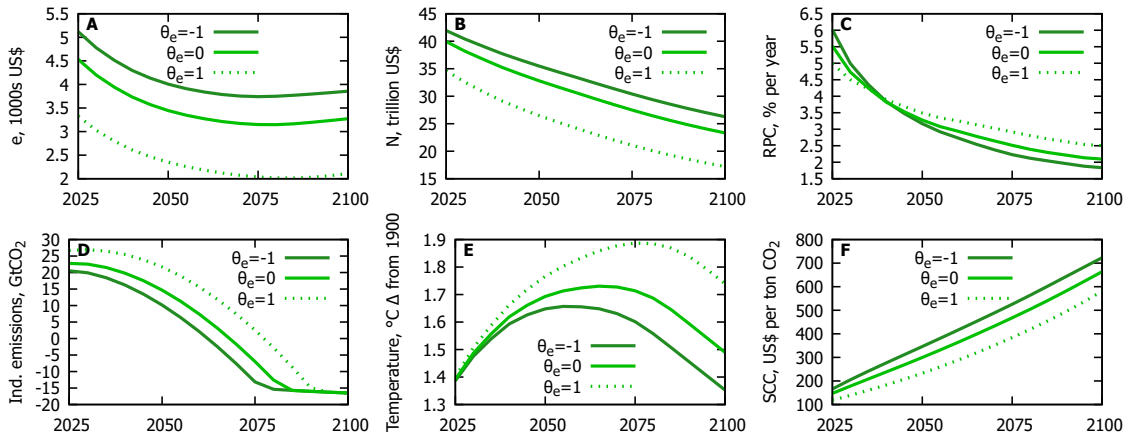


Figure 11: **Heterogeneous management under different degrees substitutability across environmental goods and preference-dependent damages** The scaling parameters for climate damages on the environment depend on subsitutability preferences θ_e and θ_c. The substitutatbility between the market good and the composite non-market environmental good is assumed to be Cobb-Douglas, i.e. $\theta_c = 0$.

environmental good on the RPC and the social cost of carbon in 2025. The RPC increases by around 0.8 percentage points over the range from $\theta_e = 1$ to $\theta_e = -1$, while the effect of θ_c on the RPC is very similar as compared to the case with optimal management and preference-independent damages. The social cost of carbon decreases with θ_e moving from -1 to 1 by around 42 US$ per ton of CO_2, while it first increase by 20 US$ when moving from $\theta_c = -1$ to $\theta_c = 0.2$ and then decreases by around 45 US$ for the interval from 0.2 to 1. Hence, while the qualitative direction of the effect of limited substitutatbility across environmental goods is reversed as compared to optimal management under preference-dependent damages, the qualitative direction of the the effect of limited substitutability between the market and the composite non-market environmental good is similar (but quantitatively different) to the case of optimal management under preference-dependent damages in Figure 9.

Table 1 summarizes our results on the qualitative direction and quantitative effect of limited substitutability between market and non-market environmental goods as well across environmental goods on the RPC and the SCC in 2025.

Our results, that focus on the two most important management regimes analyzed in this paper, highlight that the sign of the effect of limited substitutability on RPCs is positive in all cases, while the sign is positive for the effect on the SCC in all cases except for the effect of limited substitutability across environmental goods under optimal management and preference-dependent damages. Both the RPC and the social cost of carbon are always more sensitive to limited substitutability when the calibration method is independent of preferences. We find the highest impact of limited substitutability across environmental goods on the SCC under heterogeneous management and preference-independent damages, where moving from perfect substitutes to environmental good complementarity with $\theta_e = -1$ increases the SCC in 2025 by 100 US$ or 82%.

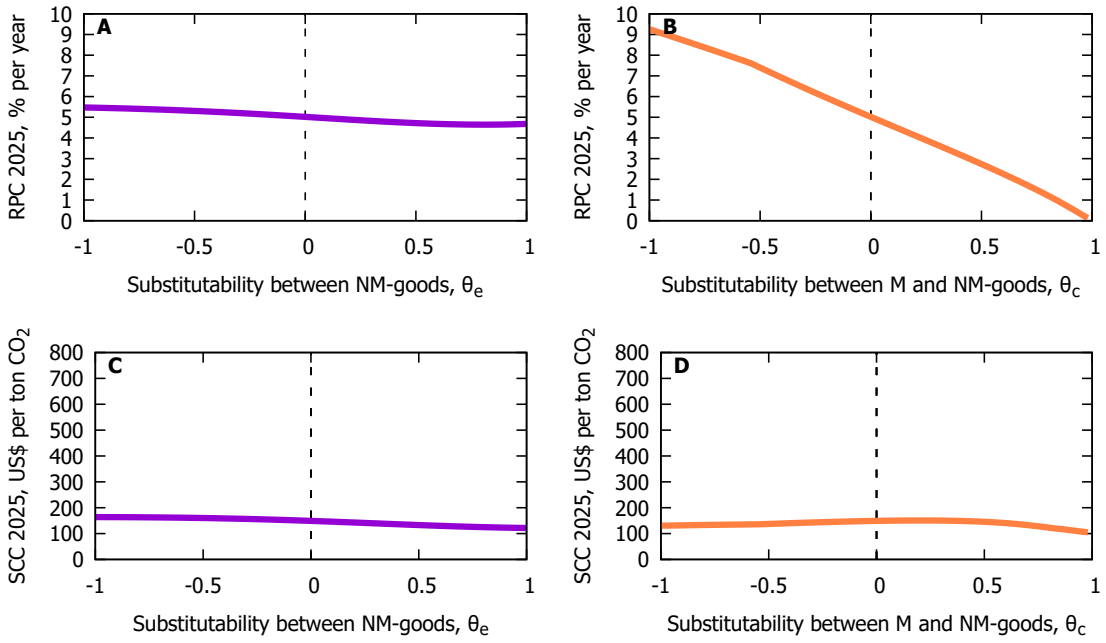


Figure 12: **Relative prices changes and social cost of carbon in 2025 under heterogeneous management and preference-dependent damages:** The effect of assumptions on substitutability across non-market environmental goods (purple lines) and between the composite non-market and the market consumption good (orange line) on the comprehensive RPC (Panels A and B) and the social cost of carbon (Pabel C and D) in 2025. The damage scaling parameters for environmental goods depend positively on substitutability preferences θ_e and θ_c, which ensures that overall damages are comparable to a model where all damages fall on market consumption only.

	Optimal Management		**Heterogeneous Management**	
	Δ RPC 2025	Δ SCC 2025	Δ RPC 2025	Δ SCC 2025
PI, θ_e [1,-1]	+0.5	+1.4 *(+0.5%)*	+1	+100 *(+82%)*
PI, θ_c [1,-1]	+9	+595 *(+405%)*	+10	+218 *(+173%)*
PD, θ_e [1,-1]	+0.3	-80 *(-24%)*	+0.8	+42 *(+34%)*
PD, θ_c [1,-1]	+8	+94 *(+82%)*	+9	+25 *(+24%)*

Table 1: The impact of management regimes and climate damage calibration strategy on the qualitative direction and quantitative effect of limited substitutability between market and non-market environmental goods, θ_c, as well across environmental goods, θ_e, on the RPC (percentage points) and the social cost of carbon (SCC) in the year 2025, measured in US$/ tCO_2 and as *(%)*-change, when moving from the case of perfect substitutes to complements. PI = preference-independent damages from climate change on the environment, PD= preference-dependent damages from climate change on the environment

4 Plausible ranges for relative price changes and climate policy

As a final step of our analysis, we move beyond the partial sensitivity analysis in the previous section and propose plausible ranges as well as a central calibration for comprehensive RPCs and their implications for climate policy. This exercise is based on Monte Carlo simulations with 1,000 draws. Following Drupp and Hänsel (2021), we summarize the best available evidence on the main determinants of RPCs of non-market environmental goods in the DICE model and, using the Monte Carlo results, construct

95th- and 66th-percentile ranges around the mean. Since our focus is on the analysis of heterogeneous environmental goods, we additionally introduce a central calibration and plausible ranges for the degree of substitutability between environmental goods, θ_e, as well as for environmental good–specific damages. We compare our proposed central calibration with the benchmark case of perfect substitutability across environmental goods, i.e., $\theta_e = 1$. We make the following assumptions regarding the distributions and central calibrations of the determinants of comprehensive RPCs.

For the degree of substitutability between the market good and the comprehensive non-market environmental good, θ_c, we follow Drupp and Hänsel (2021) and assume a normal distribution such that the 95 percent confidence interval encompasses both the mean empirical estimate of $\theta_c = 0.23$ reported in Drupp and Hänsel (2021) and the mean estimate of $\theta_c = -0.44$ derived from expert opinions based on the applied theory literature.[1] As a central calibration, we use the overall mean value of $\theta_c = -0.11$.

For the degree of substitutability between heterogeneous environmental goods, θ_e, we assume a uniform distribution on the interval $[-10, 1]$. This range encompasses the median estimate $\theta_e = -3.02$ of the degree of complementarity between ocean biodiversity and sense of place—a cultural ecosystem service—reported in a recent study on the determinants of an ocean health index (Disque et al., 2025), which elicited public preference for complementarities in general population samples using generalized dictator games.

To calibrate non-market environmental damages, D^E and D^N, we follow Howard and Sterner (2017) and assume that market damages amount to 5% of global output for a 3°C increase in global mean temperature relative to 1900 levels. Based on the expert survey by Howard and Sylvan (2015), we then double this monetary damage to account for non-market effects, using the mean and standard deviation reported in their data. Finally, we evenly allocate the resulting mean and standard deviation of damages between D^E and D^N.

For the discounting parameters δ and η, we follow Drupp and Hänsel (2021) and adopt the mean expert recommendations from the survey by Drupp et al. (2018) as our central calibration. We then draw 1,000 times from the distribution of expert recommendations and use these draws in the 1,000 Monte Carlo simulations to construct the 95th- and 66th-percentile ranges.

Finally, for the decline rate of total factor productivity, τ^A, we take the mean estimate from Nordhaus (2018) and construct a normal distribution such that the 95 percent confidence interval is bounded below by zero. Table 2 summarizes our choices of parameters and distributions that we use to calculate plausible ranges and the central calibration.

We now turn to the discussion of the results from the Monte Carlo analysis. In the main text, we focus on heterogeneous management under both preference-independent and preference-dependent damages, while the corresponding results for optimal management are presented in Appendix B. Although optimal management represents an

[1] Gollier (2012), Kopp et al. (2012), and Sterner and Persson (2008).

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

Parameter	Source	Distribution	Central Calibration
θ_c	Drupp and Hänsel (2021)	Normal; $\mu = -0.11, \sigma = 0.17$ *	-0.11
θ_e	Disque et al. (2025)	Uniform; $[-10, 1]$	-3.02
D^E	H/Syl (2015), H/St (2017) ⋆	Normal; $\mu = 2.51\%, \sigma = 1.4\%$**	2.51%
D^N	H/Syl (2015), H/St (2017) ⋆	Normal; $\mu = 2.51\%, \sigma = 1.4\%$**	2.51%
δ	Drupp et al. (2018)	Raw expert data	1.10%
η	Drupp et al. (2018)	Raw expert data	1.35
τ^A	Nordhaus (2018)	Normal; $\mu = 0.1\%, \sigma = 0.05\%$**	0.1%

* Truncated above 1; ** Truncated below 0;
⋆ H/Syl (2015) = Howard and Sylvan (2015); H/St (2017) = Howard and Sterner (2017)

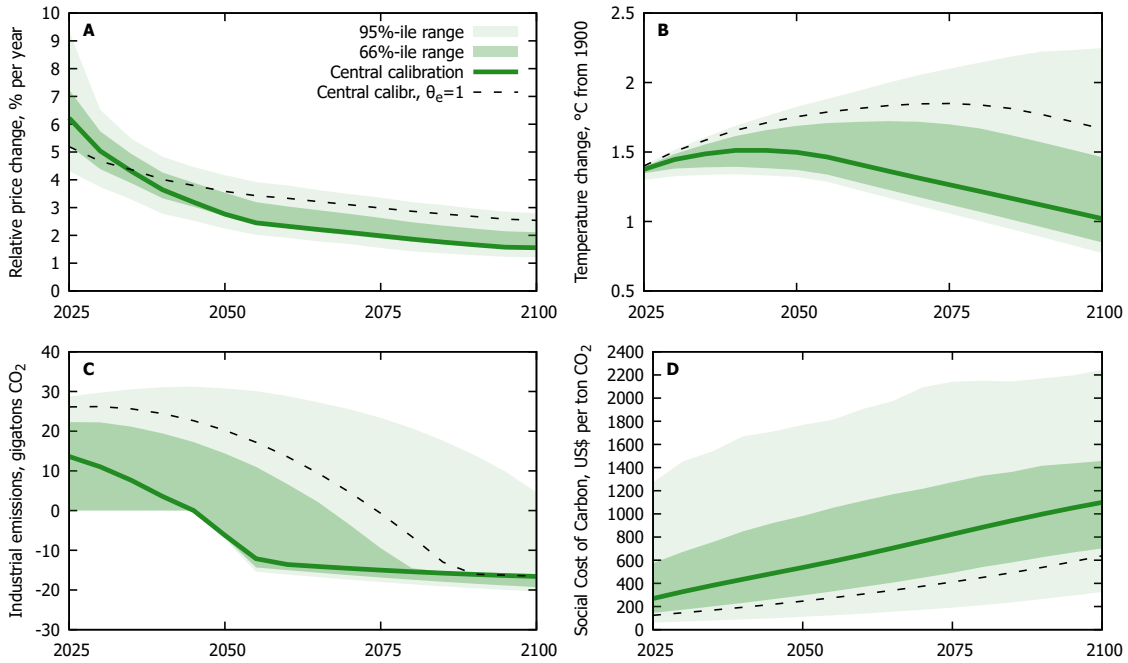


Figure 13: **Plausible ranges for relative price changes and climate policy under heterogeneous management and preference-independent damages.**

important benchmark and has been discussed in the preceding section, we view heterogeneous management as the more relevant case, as it captures important real-world heterogeneities in the growth rates of heterogeneous environmental goods.

Figures 13 and 14 present the central calibration (thick green line), the central calibration assuming perfect substitutability across environmental goods, i.e., $\theta_e = 1$ (dashed line), and the plausible ranges defined by the 95th-percentile (light green shaded area) and 66th-percentile (green shaded area) intervals. Panel A displays the comprehensive RPCs of the composite non-market environmental good, while Panels B–D show the corresponding implications for key climate policy outcomes—industrial emissions, atmospheric temperature change, and the social cost of carbon (SCC)—under heterogeneous management over the period 2025–2100.

Both figures exhibit substantial plausible ranges and overall indicate that, under het-

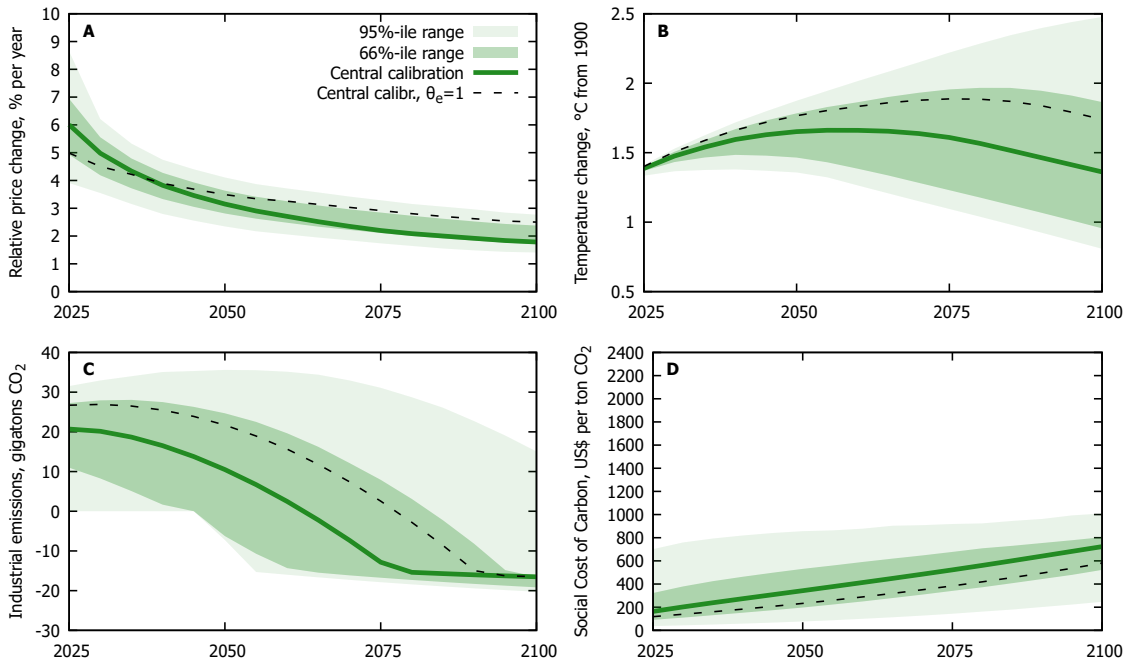


Figure 14: **Plausible ranges for relative price changes and climate policy under heterogeneous management and preference-dependent damages.**

erogeneous management, limited substitutability across environmental goods results in higher (lower) comprehensive RPCs of the composite non-market environmental good in 2025 (2100). Under preference-independent damages, the RPC ranges between 4.3 and 9.4% per year in 2025, declining to between 1.2 and 2.8% per year by 2100. Under preference-dependent damages, the RPC is of similar magnitude, with a slightly narrower range of 3.9 to 8.7% per year in 2025 and 1.4 to 2.8% per year in 2100. In the central calibration, the RPC equals 6.2 (6.0)% per year in 2025 and declines to 1.8 (1.6)% per year by the end of the century under preference-independent (preference-dependent) damages. Across calibration approaches, assuming perfect substitutability between heterogeneous environmental goods underestimates the comprehensive 2025 RPC by approximately one percentage point. Optimal management of only one environmental good (while the other follows a business-as-usual decline) implies even lower overall relative environmental scarcity by 2100 compared to the case of perfect environmental substitutes. This result does not hold under optimal management of both environmental goods (see Appendix B).

While the two approaches to calibrating climate damages on environmental goods have only minor effects on the comprehensive RPC of the composite environmental good, their implications for climate policy outcomes are considerably more pronounced. When climate damages affecting the two environmental goods are independent of substitutability preferences, the central calibration implies higher overall damages than in a model in which all damages accrue exclusively to market consumption. As a result, preference-independent damages lead to earlier decarbonization in 2045, whereas under preference-dependent damages the global economy reaches zero industrial emis-

sions between 2060 and 2065. Moreover, the 95th- and 66th-percentile ranges indicate a more rapid decline in emissions—particularly at the upper bounds—under preference-independent damages, while the timing and magnitude of optimal negative emissions are broadly similar across both calibration approaches. In the central calibration, both approaches yield cost–benefit–optimal temperature pathways consistent with the 1.5°C target by 2100, albeit with different overshoot dynamics. Specifically, the preference-independent calibration results in only minimal overshoot due to earlier decarbonization, whereas the preference-dependent calibration implies an overshoot of approximately 0.2°C. The plausible ranges further suggest more ambitious climate policy under preference-independent damages, for instance by excluding temperature increases above 2.2°C by 2100 at the upper 95th-percentile bound.

The largest quantitative differences between the two calibration approaches emerge in the social cost of carbon. When climate damages are calibrated such that at a 3°C temperature increase the model generates the same damages as the standard DICE framework – in which all damages are expressed as reductions in market consumption – the resulting 95th-percentile SCC in 2025 ranges from 36 to 702 US$, increasing to between 246 and 1,010 US$ by 2100. This contrasts sharply with the case in which overall damages increase due to limited substitutability across environmental goods. In that case, the 95th-percentile SCC in 2025 ranges from 60 to 1,273 US$, rising to between 325 and 2,245 US$ by 2100. In the central calibration, the SCC in 2025 amounts to 164 US$ under preference-dependent damages and is substantially higher at 269 US$ under preference-independent damages. By contrast, assuming perfect substitutability across environmental goods yields SCC values in 2025 of 118 (124) US$ under preference-dependent (preference-independent) damages.

Overall, our results indicate that under heterogeneous management of environmental goods, accounting for RPCs leads to more stringent climate policy compared to the case of perfect substitutability within the composite environmental good. Neglecting limited substitutability across environmental goods results in an underestimation of the 2025 social cost of carbon by between 39 and 117%, depending on the calibration of climate damages.

5 Conclusion

We have examined how accounting for the dynamics of heterogeneous environmental goods and their limited substitutability—both among themselves and with market consumption goods—under alternative management regimes affects climate policy outcomes, with a particular focus on the social cost of carbon (SCC). Moving beyond the standard assumption of a single homogeneous environmental good is essential, as the services provided by nature are diverse and are affected by climate change in heterogeneous ways. We propose a framework for incorporating limited substitutability among heterogeneous environmental goods into an extended version of Nordhaus's DICE integrated assessment model. Our analysis indicates that limited substitutability—not only

among the market and non-market composites but also among heterogeneous environmental goods—constitutes a key driver of optimal climate policy, likely to an extent that has so far been underappreciated.

While limited substitutability between market and non-market environmental goods remains a central determinant of the SCC, we show that the role of limited substitutability among non-market environmental goods is more nuanced and depends critically on how climate damages are conceptualized, compared, and calibrated, as well as on how heterogeneous environmental goods are managed—ranging from optimal to suboptimal and business-as-usual regimes. The resulting heterogeneous dynamics across management regimes lead to subtle differences in both the magnitude and the direction of their effects on the SCC. In a final step, we synthesize the best available evidence on the key drivers of comprehensive relative price changes of non-market environmental goods within an integrated assessment framework and propose plausible ranges and a central calibration for these relative price changes and their implications for climate policy outcomes.

We argue that, in practice, at least one of the two environmental goods is likely to be managed suboptimally. For this case, we find that the relative price change in 2025 amounts to between 4 and 9 percent and is approximately one percentage point higher in our central calibration than in a model assuming perfect substitutability across goods. The implications for climate policy outcomes—particularly the SCC—depend crucially on the management regime and on the magnitude of non-market climate damages. Under heterogeneous environmental goods management, the SCC in 2025 ranges from 36 to 1,273 US$, with a central estimate between 164 and 269 US$. Relative to the standard assumption of perfect substitutability among environmental goods, this implies a potentially sizable underestimation of the 2025 SCC by between 39 and 117% in our IAM-based illustration.

Overall, our results suggest that SCC estimates should be adjusted not only to account for limited substitutability between market and non-market environmental goods, but also reflect limited substitutability among the heterogeneous services provided by nature. While we could base our analysis only on still rather thin evidence base, and quantitative magnitudes are mainly illustrative, it suggest that it is crucial to improve the empirical evidence base also of non-market effects and their heterogeneities, including additional empirical research on substitutability preferences as well as on the magnitude and distribution of climate damages across different ecosystem services.

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Appendix

A Relative prices changes and social cost of carbon in 2100

A.1 Preference-independent damages

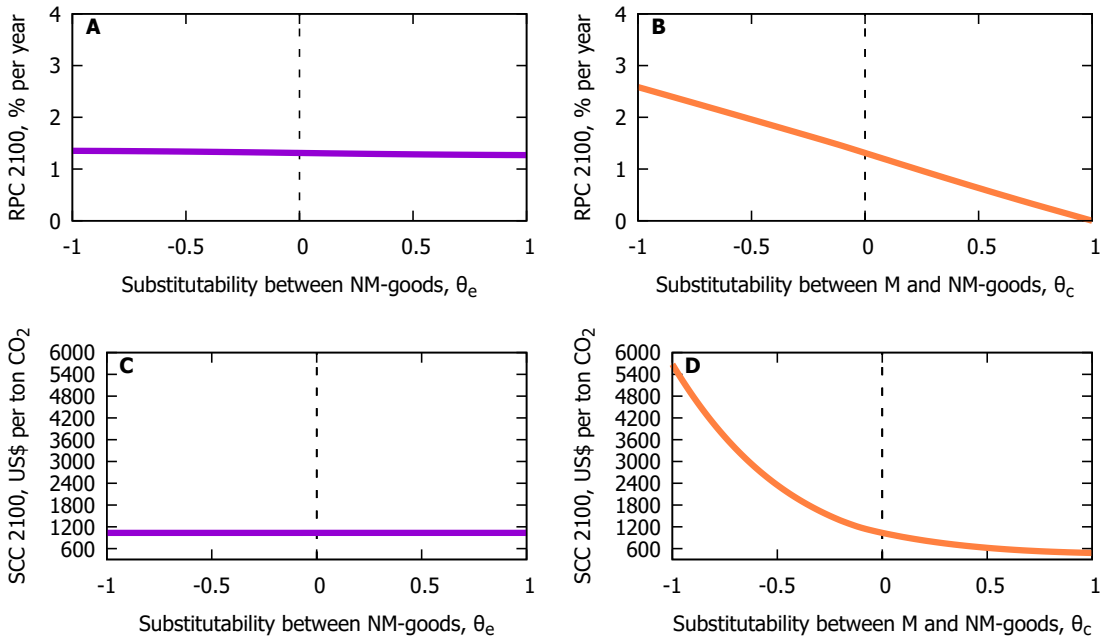


Figure 15: **Relative prices changes and social cost of carbon in 2100 under optimal management and preference-independent damages:** The effect of assumptions on substitutability across non-market environmental goods (purple lines) and between the composite non-market and the market consumption good (orange line) on the comprehensive RPC (Panels A and B) and the social cost of carbon (Pabel C and D) in 2100. The damage scaling parameters are fixed for the case when $\theta_e = 1$ and $\theta_c = -0.11$, which implies preference-independent climate damages as compared to model where all damages fall on market consumption only.

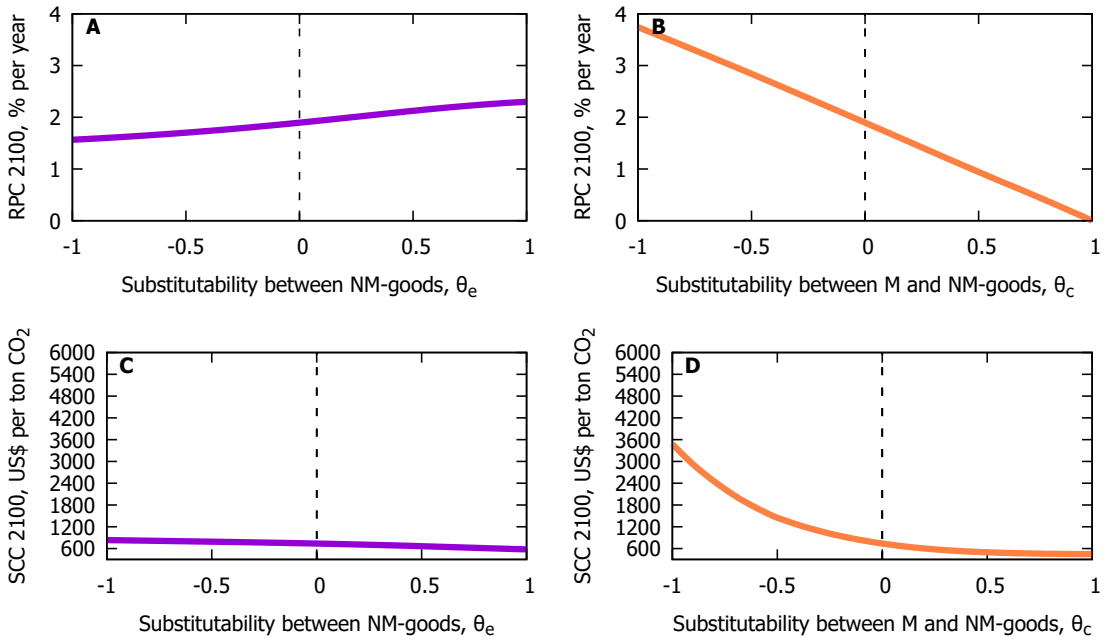


Figure 16: **Relative prices changes and social cost of carbon in 2100 under heterogeneous management and preference-independent damages:** The effect of assumptions on substitutability across non-market environmental goods (purple lines) and between the composite non-market and the market consumption good (orange line) on the comprehensive RPC (Panels A and B) and the social cost of carbon (Panels C and D) in 2100. The damage scaling parameters are fixed for the case when $\theta_e = 1$ and $\theta_c = -0.11$, which implies preference-independent climate damages as compared to model where all damages fall on market consumption only.

A.2 Preference-dependent damages

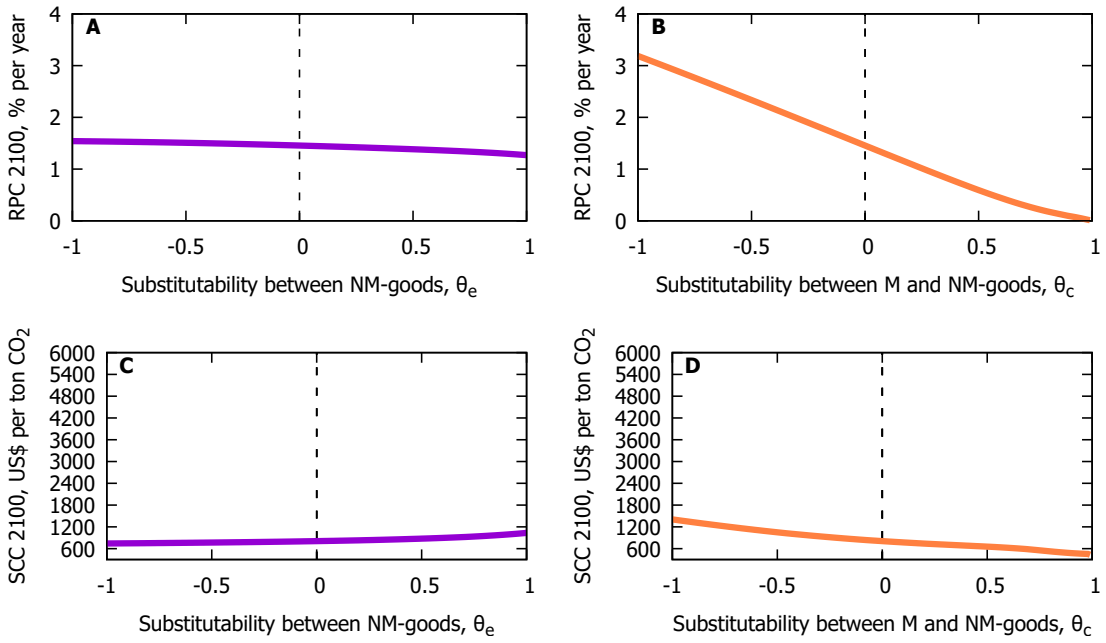


Figure 17: **Relative prices changes and social cost of carbon in 2100 under optimal management and preference-dependent damages:** The effect of assumptions on substitutability across non-market environmental goods (purple lines) and between the composite non-market and the market consumption good (orange line) on the comprehensive RPC (Panels A and B) and the social cost of carbon (Panel C and D) in 2100. The damage scaling parameters for environmental goods depend positively on substitutability preferences θ_e and θ_c, which ensures that overall damages are comparable to a model where all damages fall on market consumption only.

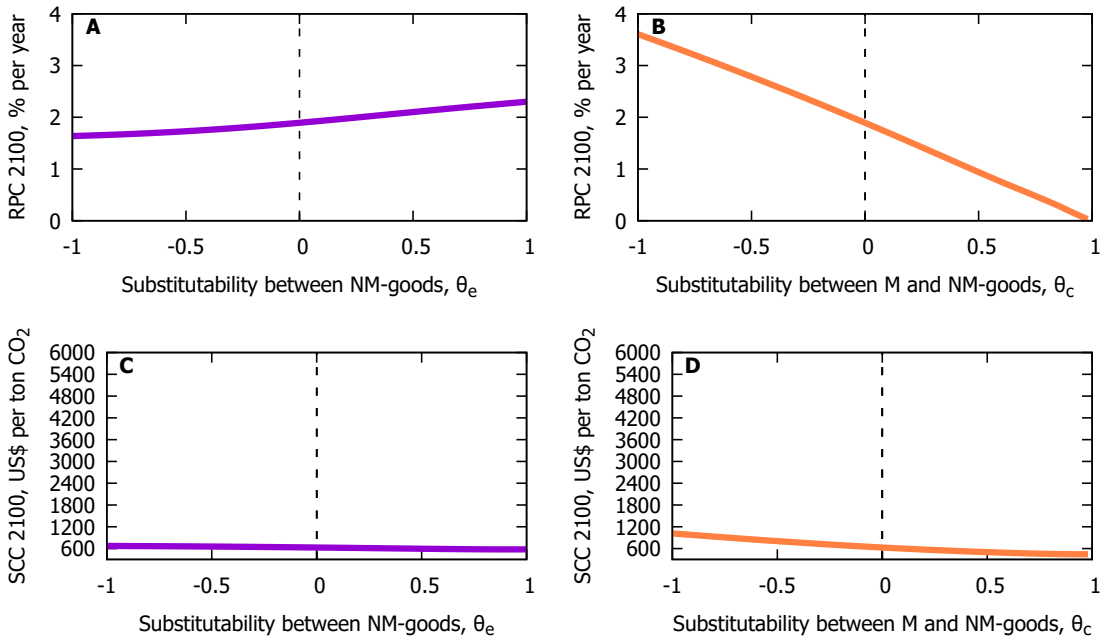


Figure 18: **Relative prices changes and social cost of carbon in 2100 under heterogeneous management and preference-dependent damages:** The effect of assumptions on substitutability across non-market environmental goods (purple lines) and between the composite non-market and the market consumption good (orange line) on the comprehensive RPC (Panels A and B) and the social cost of carbon (Panel C and D) in 2100. The damage scaling parameters for environmental goods depend positively on substitutability preferences θ_e and θ_c, which ensures that overall damages are comparable to a model where all damages fall on market consumption only.

B Plausible ranges for relative price changes and climate policy under optimal management

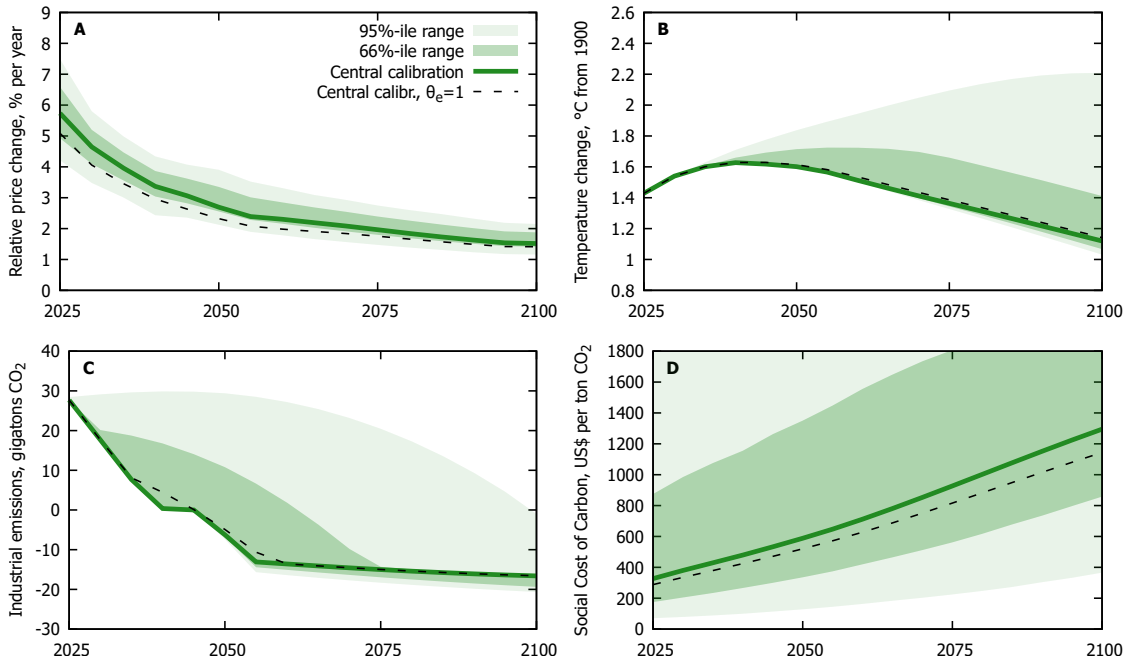


Figure 19: **Plausible ranges for relative price changes and climate policy under optimal management and preference-independent damages.**

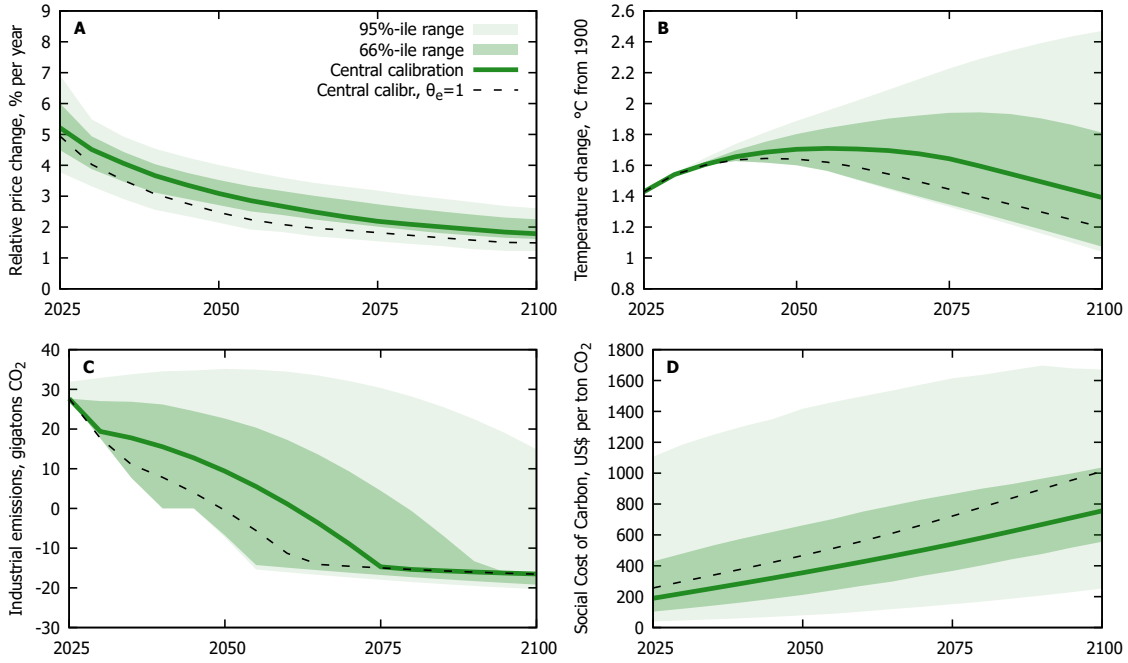


Figure 20: **Plausible ranges for relative price changes and climate policy under optimal management and preference-dependent damages.**