Relative Price Changes and Climate Policy under Heterogeneous Environmental Goods Dynamics

Martin C. Hänsel, **Marc N. Conte and Moritz A. Drupp**

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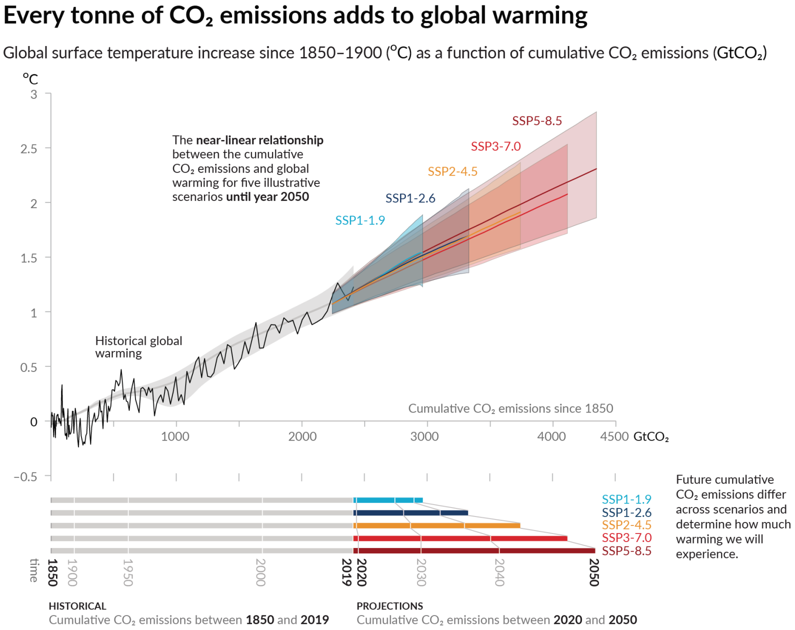
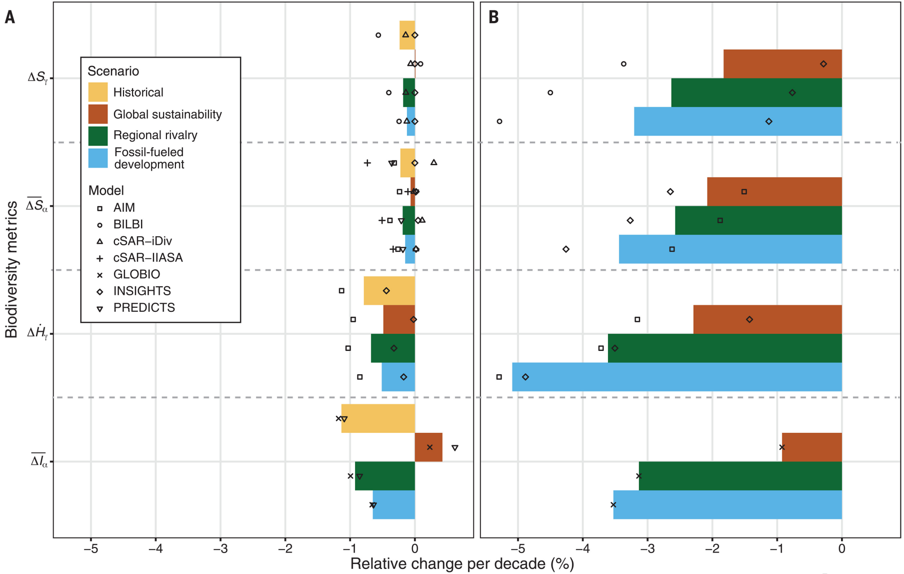
Managing climate change is a central sustainability challenge



IPCC AR6, SPM10

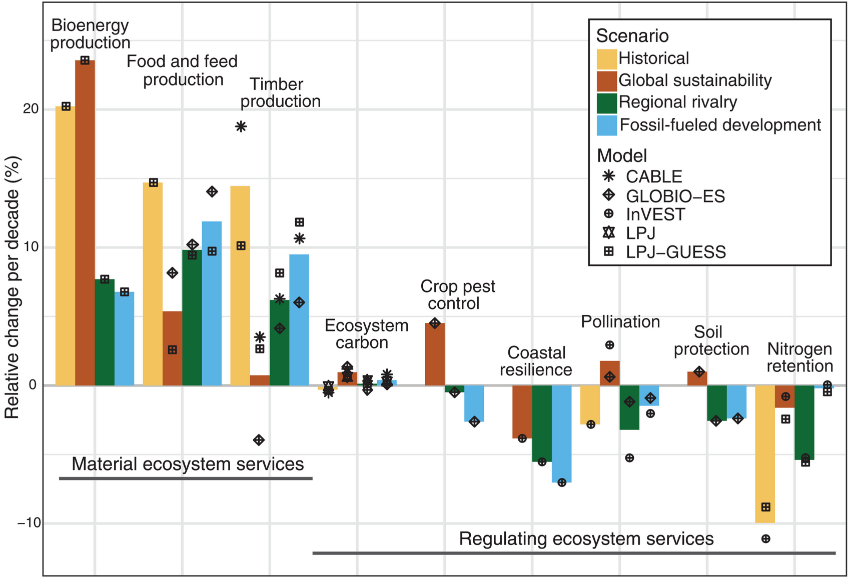
Climate change most important driver of biodiversity loss by mid century?

A: Historical trends (1900 to 2015); B: projections to 2050 of different biodiversity metrics



Pereira et al. (2024), *Science*

Negative effects especially on non-market ecosystem services



Pereira et al. (2024), *Science*

SCC: The “single most important number you’ve never heard of”

Social Cost of Carbon (SCC): How to value the damage cost of CO_2?

Money-measured present value welfare loss from emitting an additional (marginal) ton of CO_2 into the atmosphere

They depend on (among others)

- climate and natural science, i.e. the carbon cycle, energy-balance,...

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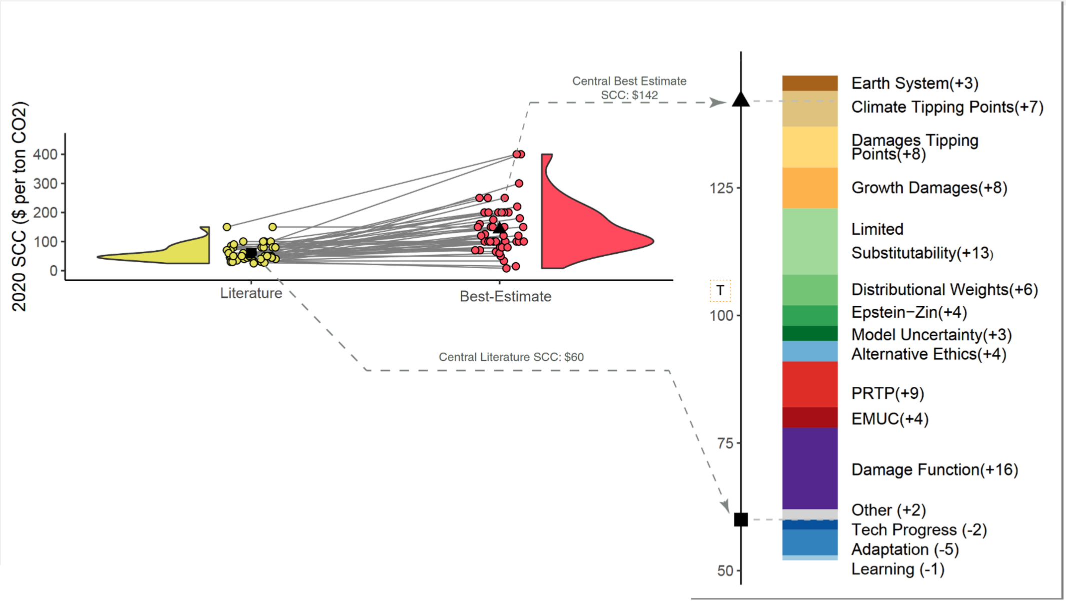
- preferences about the intergenerational distribution of well-being
- limited substitutability between market and non-market environmental good consumption

$\Rightarrow$ underappreciated in SCC literature so far (Moore et al. 2024, *PNAS*)

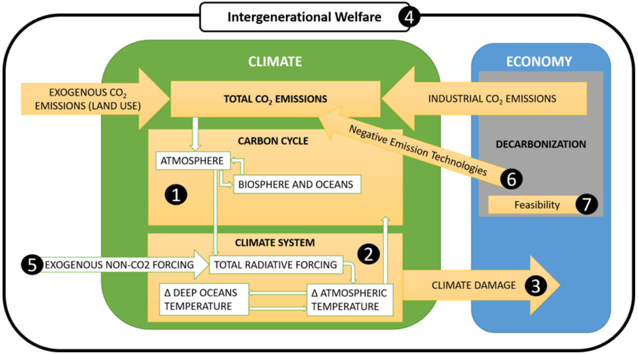
Limited substitutability of nature underappreciated in SCC literature so far



Moore et al. (2024, *PNAS*)

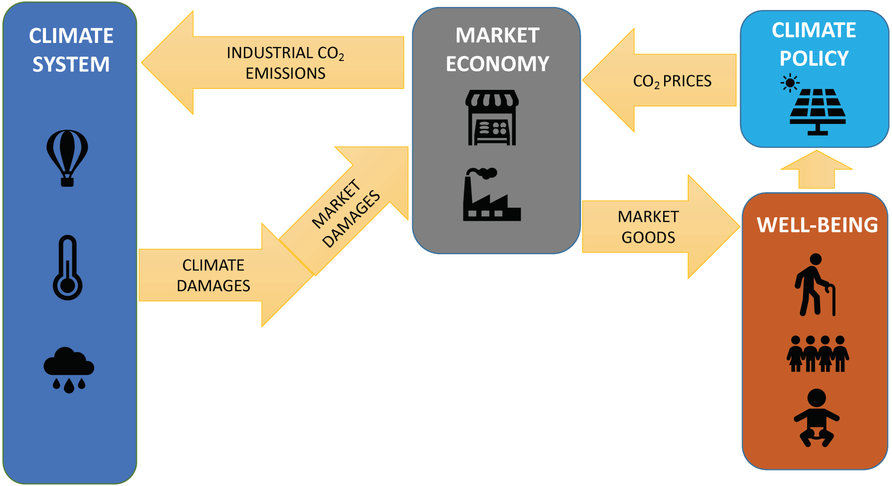
The SCC are typically estimated with Integrated Assessment Models

This paper: Updated DICE 2020 IAM as baseline model (Hänsel et al. 2020, *NCC*)



1. Carbon cycle based on FAIR model (Millar et al. 2017, Smith et al. 2018)
2. Energy balance model (Geoffroy et al .2013)
3. Economic damage function (Howard and Sterner 2017)
4. Intergenerational welfare (Drupp et al. 2018)
5. Non-CO_2 forcing (Riahi et al. 2017)
6. Negative emission technologies (Anderson and Peters 2017, Rogelj et al. 2018)
7. Maximum rate of decarbonization (Clarke et al. 2014, Rogelj et al. 2018)

How to integrate limited substitutability in DICE IAM?



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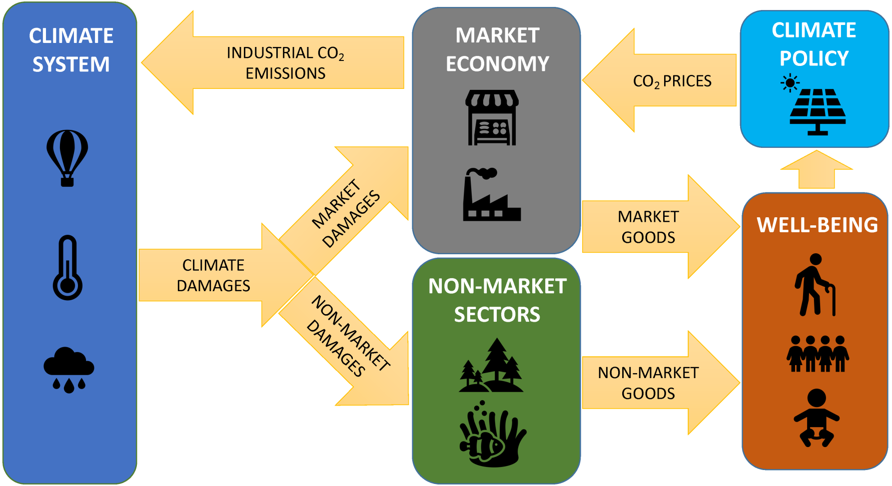

How to integrate limited substitutability in measurement of well-being?

1. Use two different discount rates for market and non-market goods: ‘ecological’ or dual discounting
2. Compute the relative price of non-market goods with respect to market goods in each period and then use a single discount rate

see, e.g., Baumgärtner et al. (2015), Gollier (2010), Traeger (2011), Drupp et al. (2024)

⇒ Relative price change (RPC) rule with $U(c,E) = \left(s c_t^{\frac{\sigma-1}{\sigma}} + (1-s) E_t^{\frac{\sigma-1}{\sigma}} \right)^{\frac{\sigma}{\sigma-1}}$

$$RPC = \frac{\frac{d}{dt}\left(\frac{U_E}{U_c}\right)}{\left(\frac{U_E}{U_c}\right)} = \frac{1}{\sigma}(g_c - g_E).$$

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2. growth rate of the market-good g_{c_t}
3. growth rate of the non-market good g_{E_t} ⇒ **Typical assumption: E is homogeneous!**

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This paper: Environmental goods are heterogeneous

- Different ecosystem services: Provisioning, maintenance and regulating, cultural

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⇒ We study environmental good heterogeneity in the context of relative price changes of non-market environmental goods and the social cost of carbon in an extended DICE model

Social welfare with two heterogeneous environmental goods

$$W_0 = \sum_{t=0}^{99} L_t \frac{(1+\delta)^{-5t}}{1-\eta} \left[\left(s_c c_t^{\theta_c} + (1-s_c) \underbrace{\left(s_e e_t^{\theta_{\tilde{e}}} + (1-s_e) N_t^{\theta_{\tilde{e}}} \right)^{\frac{\theta_c}{\theta_{\tilde{e}}}}}_{\text{composite environmental good } \tilde{E}} \right) \right]^{\frac{1-\eta}{\theta_c}} \quad (1)$$

- market consumption c with share parameters s_c, public environmental good N (e.g. biodiversity), use-value generating environmental good e (e.g. recreational ecosystem services) with share parameters s_e
- substitutability *across* env. goods $\theta_{\tilde{e}}$ and between the market and the composite env. good θ_c ($\sigma = {}^1/_{1-\theta}$)

- Dynamics of environmental goods:

$$E_t = \frac{E_0}{[1 + \psi_E T_t^{\phi_E}]}, \qquad N_t = \frac{N_0}{[1 + \psi_N T_t^{\phi_N}]} \quad (2)$$

- Comprehensive relative price change and social cost of carbon (SCC)

$$RP\tilde{C}_t = (1-\theta_c) \left[g_{C_t}(\delta, \eta, \ldots) - g_{\tilde{E}_t}(T_t, g_{T\,t}, \psi_N, \psi_E, \phi_N, \phi_E, \ldots) \right], \quad SCC_t = -\frac{\partial W_0 / \partial CO2_t}{\partial W_0 / \partial C_t}$$

How to calibrate climate damages on environmental goods?

- 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

$$W_0\left((1-D^T)C_0, E_0, N_0, L_0\right) = W_0\left((1-D^C)C_0, (1-D^E)E_0, (1-D^N)N_0, L_0\right) \tag{3}$$

1. Preference-dependent damages: Overall initial damages are *always* comparable to a model where all damages fall on market consumption

   ⇒ damage scaling parameters for environmental goods depend on substitutability preferences $\theta_{\tilde{e}}$ and θ_c

2. Preference-independent damages: Fix ψ_E and ψ_N for the case when the two environmental goods are perfect substitutes, i.e. $\theta_{\tilde{e}} = 1$ and $\theta_c = -0.11$ (Drupp and Hänsel 2021, *AEJ*)

   ⇒ damages are primarily determined by given knowledge about climate impacts on natural capital and are independent of substitutability preferences

Calibration and management regimes

Calibration: Follows Drupp and Hänsel (2021, *AEJ*) and Hänsel et al. (2020, *NCC*)

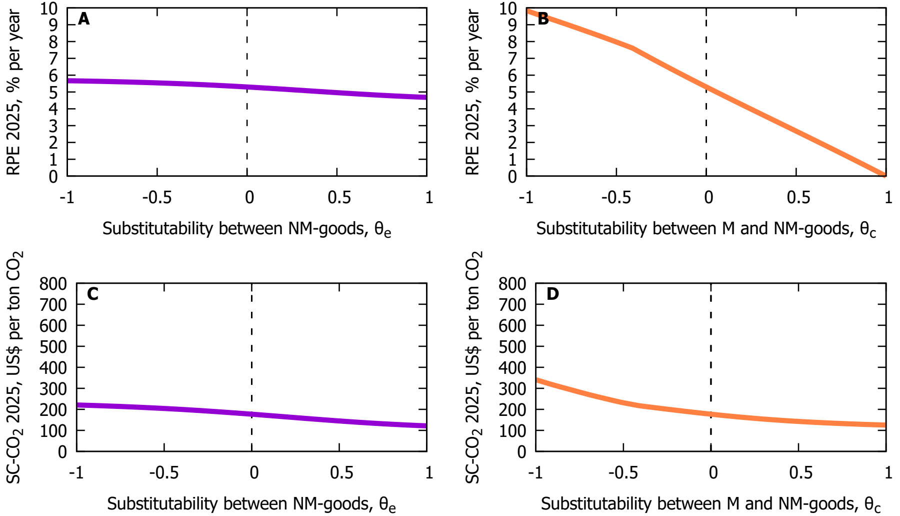
- **Discounting and share parameters:** $\delta = 1.1\%$, $\eta = 1.35$, $s_c = 0.9$, $s_e = 0.5$
- **GDP Damages** for 3°C under preference-dependent damages: $D^T = 10\%$, $D^C = 5\%$ $D^E = 2.5\%$, $D^N = 2.5\%$,
- **Initial conditions:** $C_0 = \tilde{E}_0$, $E_0 = N_0$

Management regimes

1. **Optimal management:** Climate damages on both environmental goods are managed optimally (optimal emission control)
2. **Business-as-usual management (BAU):** No emission control
3. **Heterogeneous management:** Recreational ecosystem services e are managed optimally, while biodiversity value N declines according to BAU path

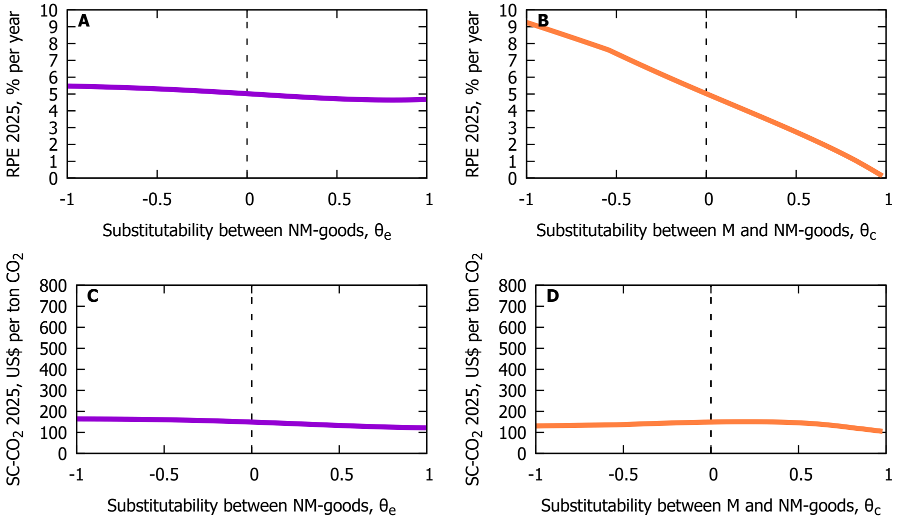
$\Rightarrow$ Let's focus on heterogeneous management in the following

Heterogeneous management under preference-independent damages



	Δ RPC 2025, pp	Δ SCC 2025, US$ $/tCO_2$
$\theta_{\tilde{e}}$ [1,-1]	+1	+100 *(+82%)*
θ_c [1,-1]	+10	+218 *(+173%)*

Heterogeneous management under preference-dependent damages



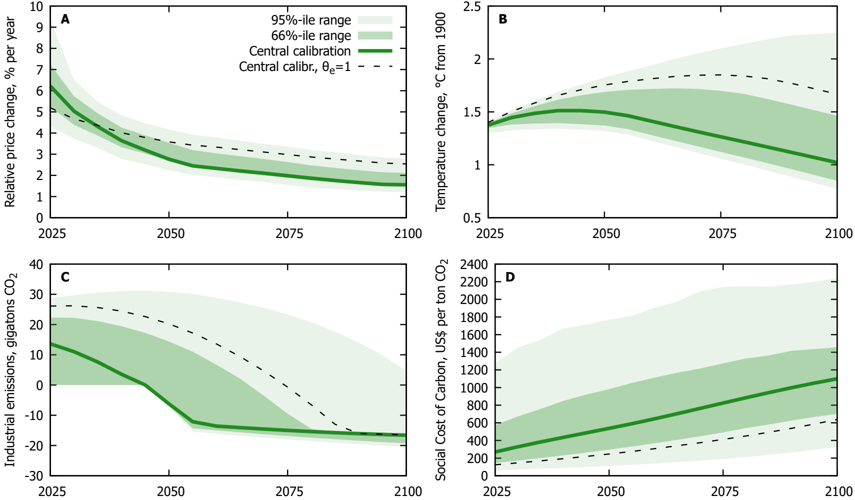
	Δ RPC 2025, pp	Δ SCC 2025, US$ /tCO_2
$\theta_{\tilde{e}}$ [1,-1]	+0.8	+42 (+34%)
θ_c [1,-1]	+9	+25 (+24%)

Plausible ranges and central cailbration

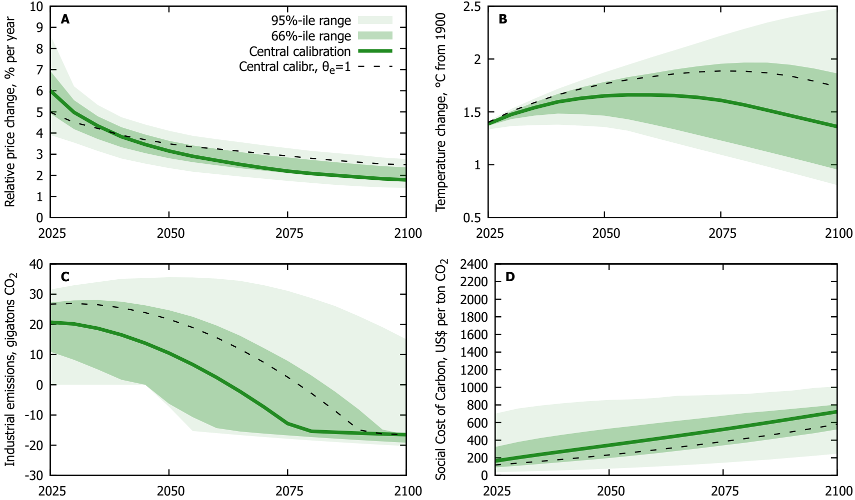
Parameter	Source	Distribution	Central Calibration
θ_c	Drupp and Hänsel (2021)	Normal; $\mu = -0.11, \sigma = 0.17$ *	-0.11
θ_e	Disque et al. (2025)	Uniform; $[-10, 1]$	-3.02
D^E	H/Syl (2015), H/St (2017) ⋆	Normal; $\mu = 2.51\%, \sigma = 1.4\%$**	2.51%
D^N	H/Syl (2015), H/St (2017) ⋆	Normal; $\mu = 2.51\%, \sigma = 1.4\%$**	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)

Heterogeneous management, preference-independent damages



Heterogeneous management, preference-dependent damages



⇒ Sizable underestimation of the 2025 SCC by between 39 and 117%, depending on management and calibration strategy

Key Takeaways

- Limited substitutability is a crucial driver of the social cost of carbon (SCC)
- The SCC can be more sensitive to the substitutability among the environmental goods than across the market composite and the environmental composite

  $\Rightarrow$ SCC under heterogeneous management and preference-dependent damages increases by 34% for θ_e [1,-1] as compared to 24% for θ_c [1,-1]
- Quantitative effects on SCC crucially depend on management regimes as well as on how to conceptualize, compare and calibrate climate damages
- Central calibr. compared to perfect substitutability across environ. goods: RPC + 1pp

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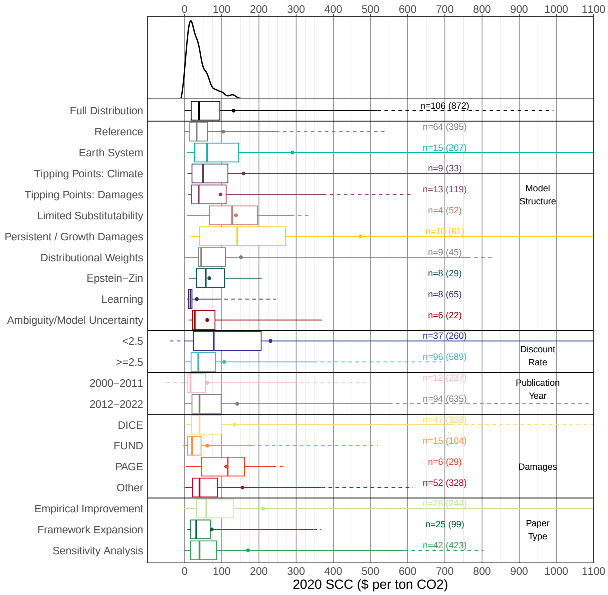
BACKUP SLIDES

SCC variation in the literature: Mean: 132 USD vs. Median: 39 USD



Moore et al. 2024

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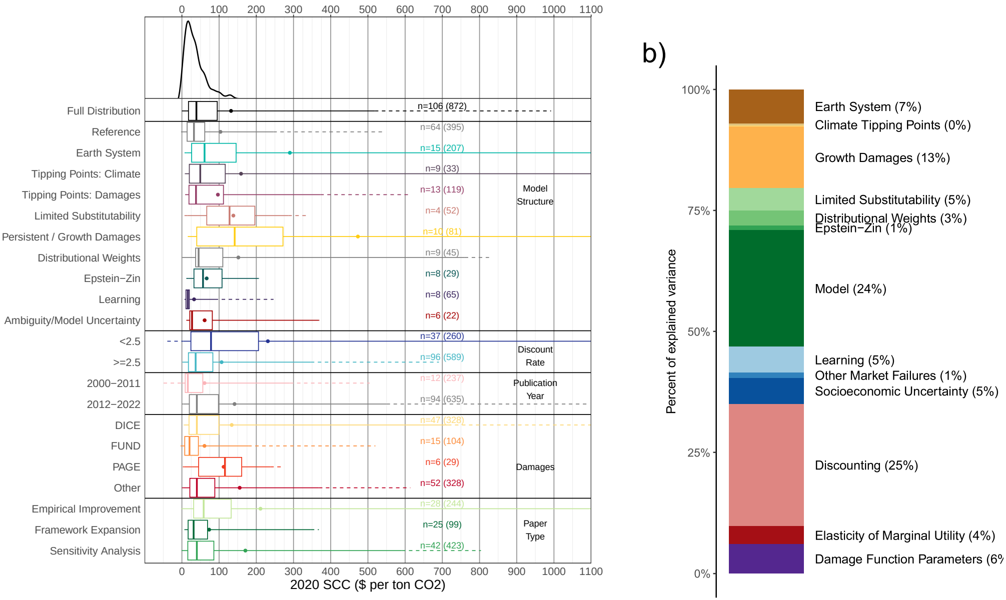
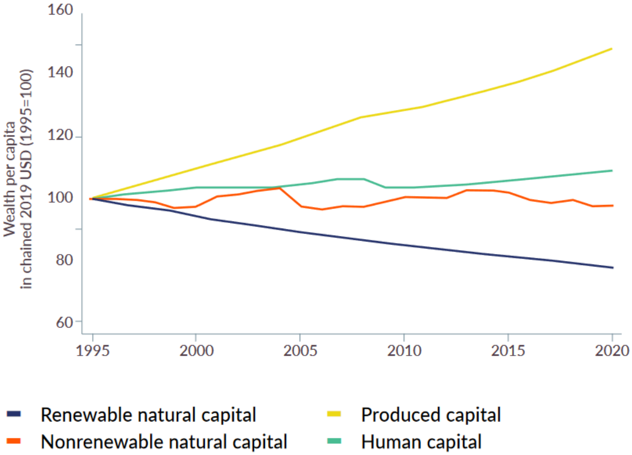


Moore et al. 2024

Natural capital is in decline

FIGURE ES.4A

Trends in global wealth per capita, by asset category, 1995–2020 (1995=100)



World Bank Group (2024)

How to determine the Relative Price Effect empirically?

- Ebert (2003) has shown that the constant elasticity of substitution σ between a market and a non-market good is inversely related to the income elasticity of the willingness to pay ξ for the non-market good, i.e. $1/\sigma = \xi$
- If income increases by 1%, WTP increases by ξ percent

$$RPE = SDR_c - SDR_E = \frac{1}{\sigma}(g_c - g_E) = \xi(g_c - g_E)$$

- Intuition: The more strongly people perceive non-market environmental goods as complementary to market goods, the more rapidly the benefits from environmental goods rise as real incomes grow $\Rightarrow$ real income effect $\xi \times g_c$
- this effect becomes stronger when the real scarcity of non-market environmental goods rises $\Rightarrow$ real scarcity effect $-\xi \times g_E$

How to determine the Relative Price Effect empirically?

- Compute income elasticity of willingness to pay ξ for non-market environmental goods based on non-market valuation studies $\Rightarrow$
  - Jacobsen and Hanley (2009): Meta-analysis using 46 contingent valuation studies on global biodiversity conservation; $\xi = 0.4$
  - Subroy et al. (2019): Threatened species; $\xi = 0.4 - 0.7$
  - Heckenhahn and Drupp (2024): 36 studies on WTP for environmental goods in Germany; $\xi = 3$
- Use ξ from applied modelling studies, e.g. Sterner and Persson (2008): $\xi = 2$
- What's the guidance on other non-market goods (e.g. health or travel time)? Typical assumption: WTP increases proportional to income, i.e. $\xi = 1$
- Suggestion in Drupp et al. (2024): Make $\xi = 1$ the new default

Social welfare with stylized homogeneous environmental good

- DICE modelling horizon of 100 periods, each period t comprises 5 years; Social welfare in $t = 0$, W_0 is given by

$$W_0(c_t, \tilde{E}_t, L_t) = \sum_{t=0}^{99} L_t \frac{(1+\delta)^{-5t}}{1-\eta} \left[s_c c_t^\theta + (1-s_c)\tilde{e}_t^\theta \right]^{\frac{1-\eta}{\theta}} . \qquad (4)$$

population size L_t, rate of pure time preference δ , market consumption $c = {}^{C}\!/\!{}_{L}$, environmental good consumption $\tilde{e} = {}^{\tilde{E}}\!/\!{}_{L}$, inverse of the elasticity of the marginal utility of comprehensive consumption η, exogenous substitutability parameter θ determines elasticity of substitution, $\sigma = \frac{1}{1-\theta}$

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- Damages on non-market environmental good

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

$\psi_{\tilde{E}}$ scales up temperature damages on the environmental good $\tilde{E}_t$

Drupp and Hänsel(2021) *AEJ* calibration

Parameter	Source	Distribution	Central Calibration
θ	Own calculations	Normal; $\mu = -0.11, \sigma = 0.17$	-0.11
NMD	Howard and Sylvain (2015)	Normal; $\mu = 1.65\%, \sigma = 4.15\%$	1.65%
$\bar{E}/E_0$	Assumption	Normal; $\mu = 10\%, \sigma = 5.10\%$	10%
δ	Drupp et al. (2018 *AEJ*)	Raw expert data	1.10%
η	Drupp et al. (2018 *AEJ*)	Raw experts data	1.35
τ^A	Nordhaus (2017 *PNAS*)	Normal; $\mu = 0.1\%, \sigma = 0.05\%$	0.1%

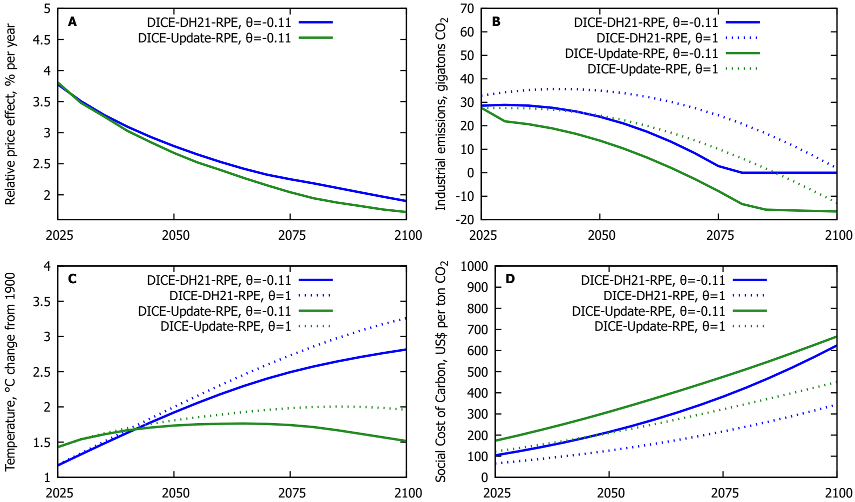
$\Rightarrow$ We perform Monte Carlo analysis with 1000 draws to construct plausible ranges

Substitutability as a key determinant of the *RPC*

Parameter	Source	Distribution	Central Calibration
θ	Own calculations	Normal; $\mu = -0.11, \sigma = 0.17$	-0.11

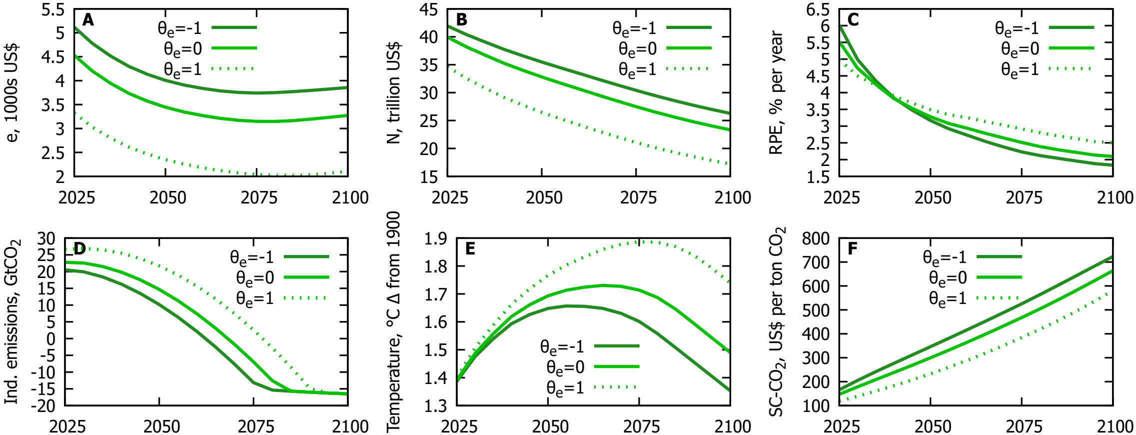
- We construct this range by drawing on
  1. expert judgements, i.e. values used by Gollier (2010), Sterner& Persson (2008), ... (mean $\theta = -0.44$)
  2. indirect empirical estimates derived from the non-market valuation literature, using the relationship between the income elasticity of WTP and θ (Ebert 2003 *ERE*)
     - We identify 40 relevant and usable studies with a keyword-based search in SCOPUS $\Rightarrow$ 21 on environmental goods and 19 on health & culture (overall mean $\theta = 0.23$)
- We assume a Normal distribution, using the mean expert value and the mean empirical estimate to specify the central calibration and to inform the plausible range

Relative price changes and climate policy, homog. environmental good

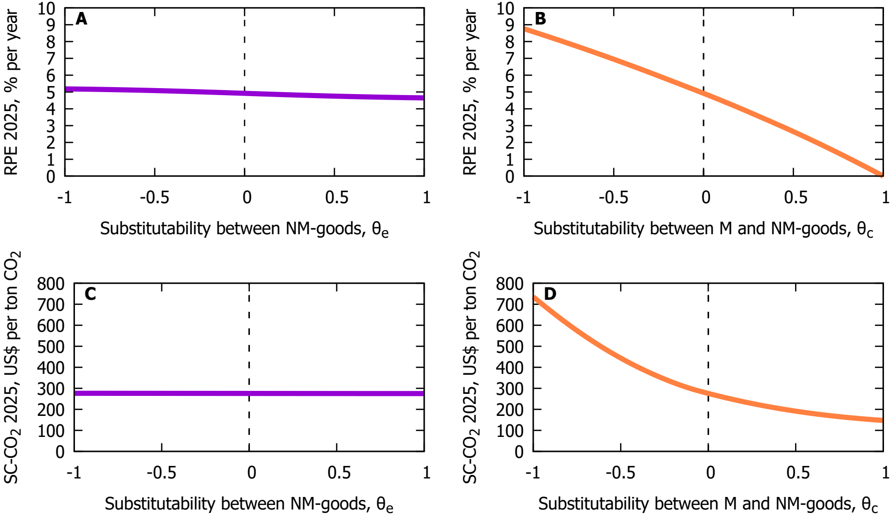


- Central calibration Drupp and Hänsel (2021, *AEJ*) (DICE-DH21-RPC) *versus* DICE-Update Hänsel et al. (2020, *NCC*) (DICE-Update-RPC)
- One key difference: DICE-Update-RPC has overall damages of 10% for a 3°C temperature increase (5% market + 5% non-market) as opposed to 3.2% in DH21

Full time path to 2100: Het. management under PD-damages

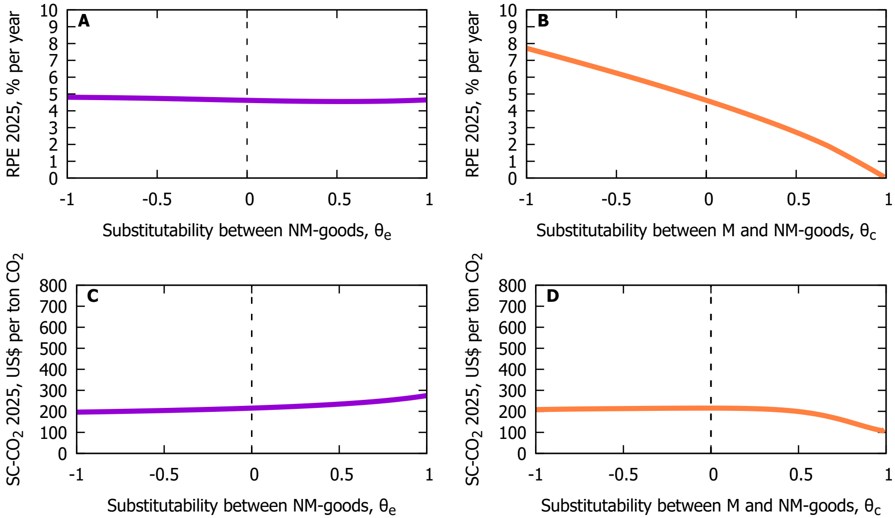


Optimal management under preference-independent damages



	Δ RPC 2025, pp	Δ SCC 2025, US\$ $/tCO_2$
$\theta_{\tilde{e}}$ [1,-1]	+0.5	+1.4
θ_c [1,-1]	+9	+595

Optimal management under preference-dependent damages



	Δ RPC 2025, pp	Δ SCC 2025, US\$ /tCO_2
$\theta_{\tilde{e}}$ [1,-1]	+0.3	−80 (-24%)
θ_c [1,-1]	+8	+94 (+82%)

Summary of results

	Optimal Management		Heterogeneous Management	
	RPC 2025	SCC 2025	RPC 2025	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%)*

- Relative price changes (pp) positive in all cases
- SCC change (absolute in US$ per ton CO_2 and as a %-change) is positive in all cases except for the effect of limited substitutability across environmental goods under optimal management and preference-dependent damages (PD)
- Effect depends on calibration method and management regime:
  $\Rightarrow$ Highest impact of limited substitutability across environmental goods on the SCC under *heterogeneous management and preference-independent damages*
  $\Rightarrow$ $\theta_{\tilde{e}}$ [1,-1] increases the SCC in 2025 by 100 US$ or 82%.