God does not play DICE with the climate

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Bachelier Finance Society One World Seminar
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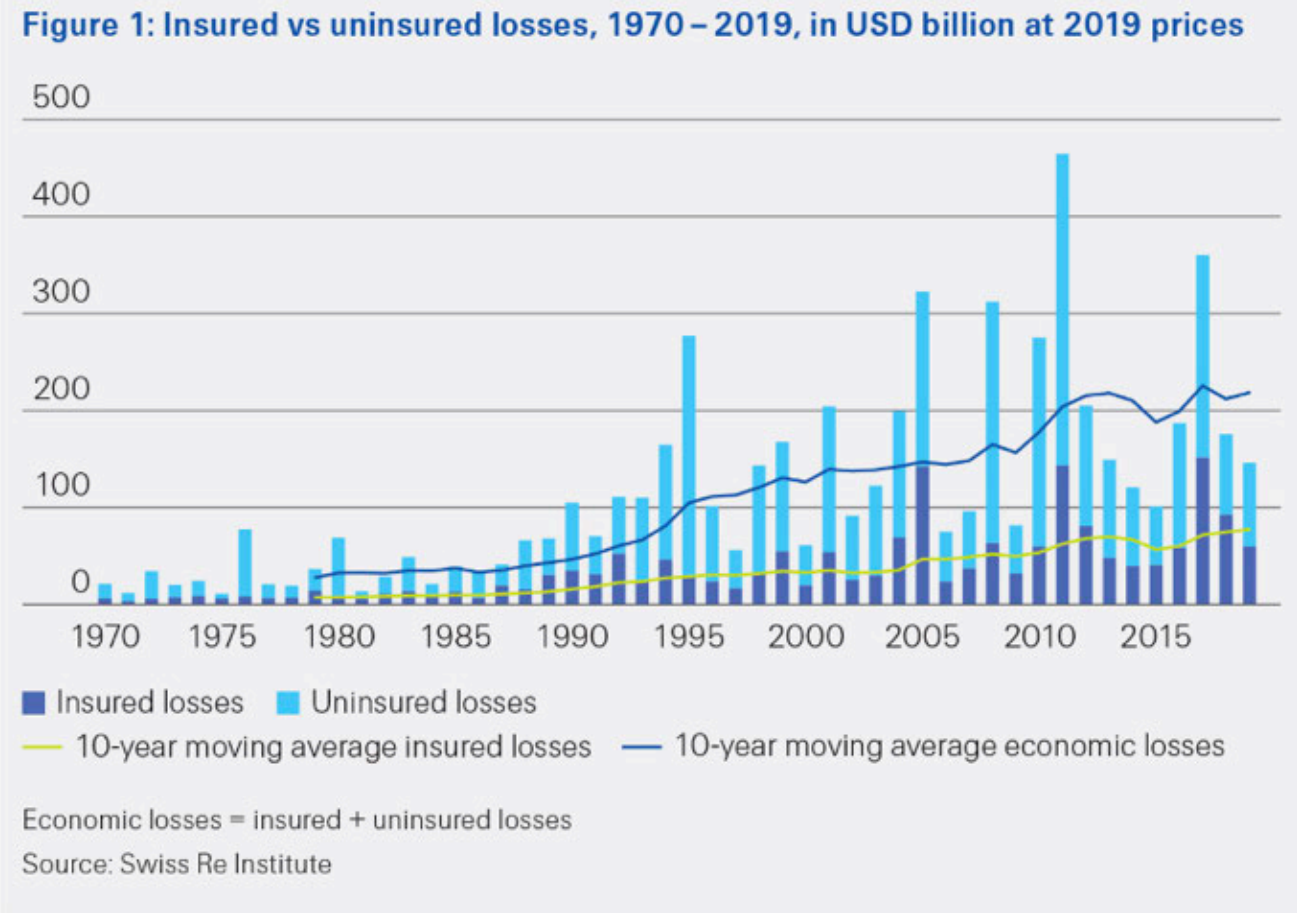
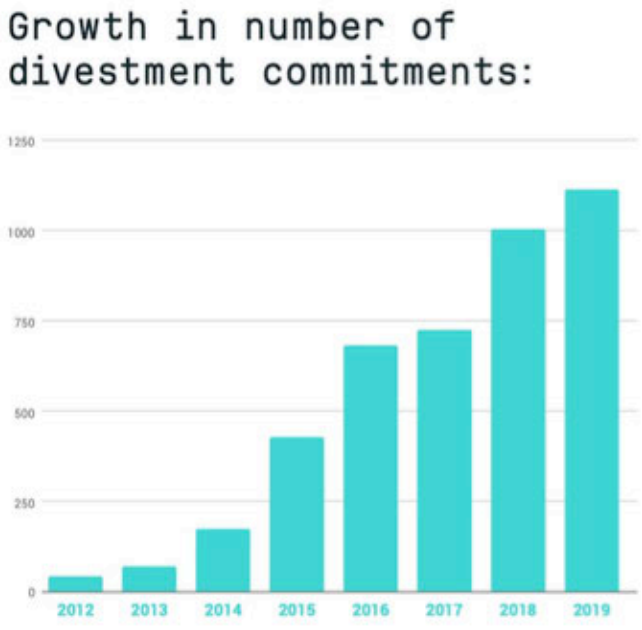
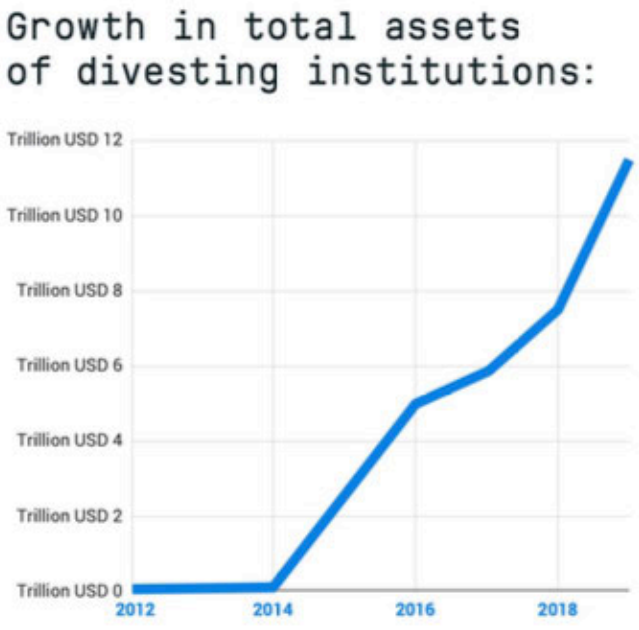
Extreme-weather losses



Portfolio Decarbonization - source: gofossilfree.org

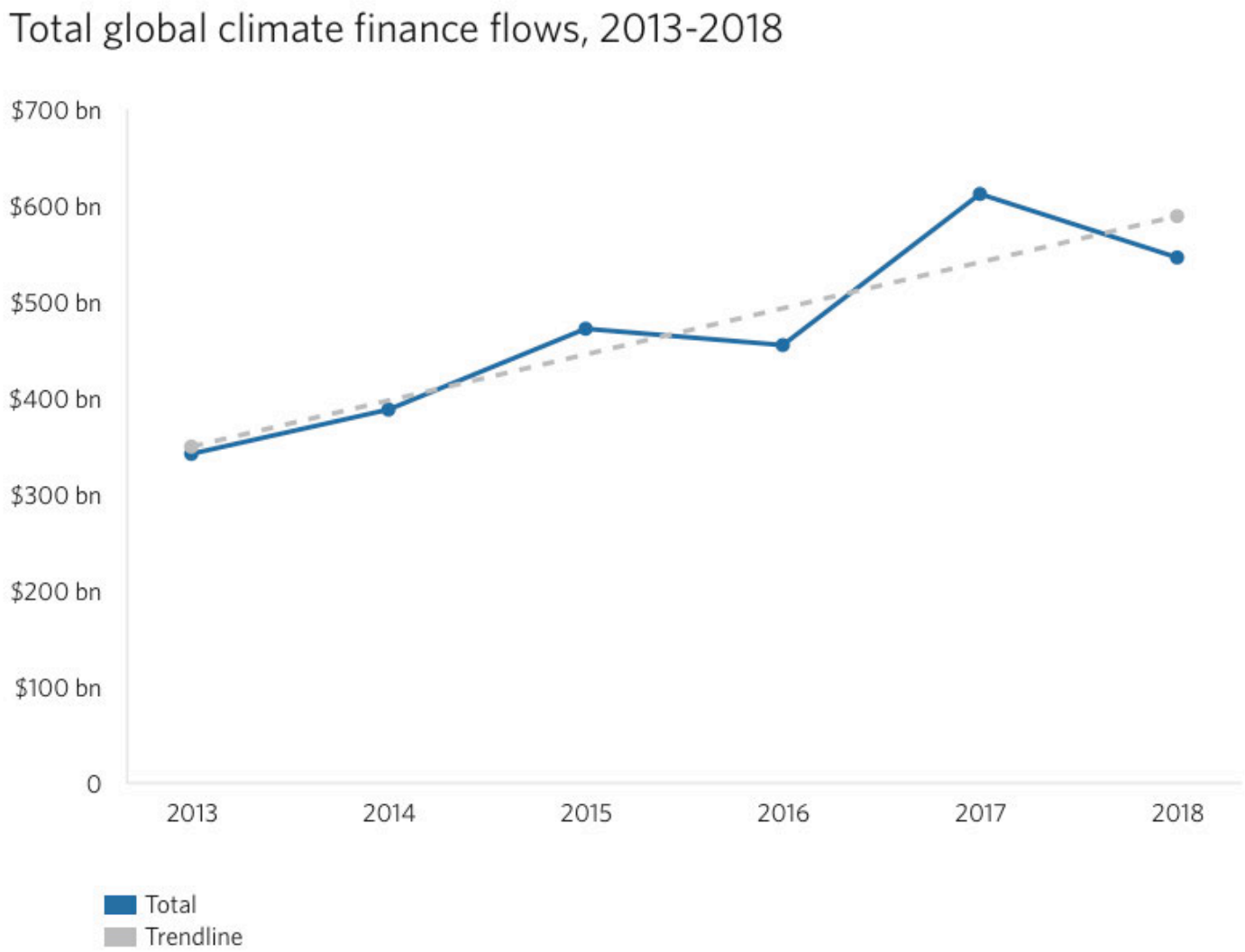




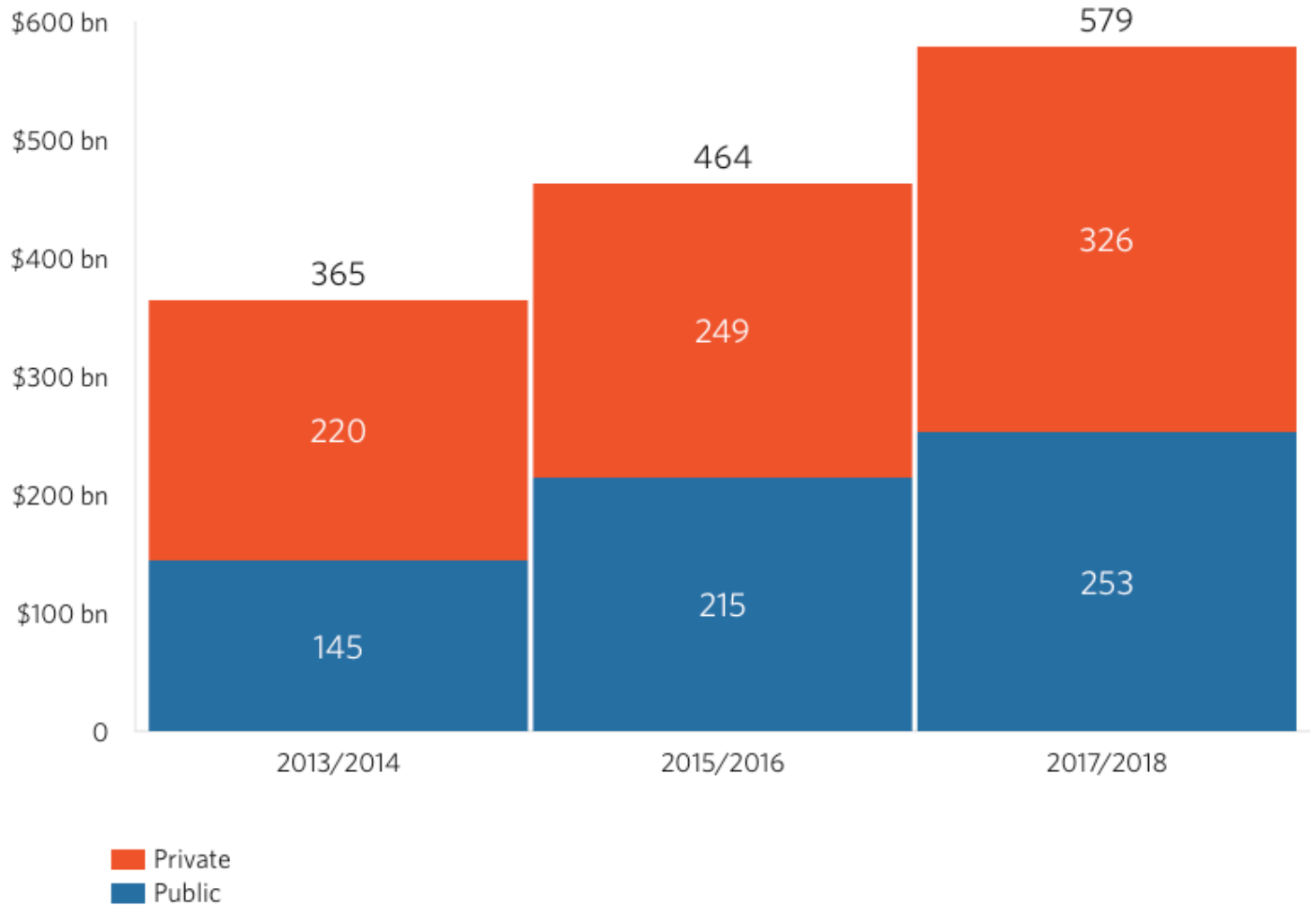
Investment needs and opportunities

- Required low-carbon infrastructure investment is $1.6-3.8T annually between 2016 and 2050 (IPCC 2018).
- Cost of adaptation is estimated to be of the order of $300B per year from 2020 to 2030 (GCA 2019).
- This $2-4T range should be compared with the current annual financial flow of $400-600B directed towards green investment (CFI 2019).
- Cumulative Green Bond issuance to date is still about 1% of the $100T global bond market (GBI 2021).

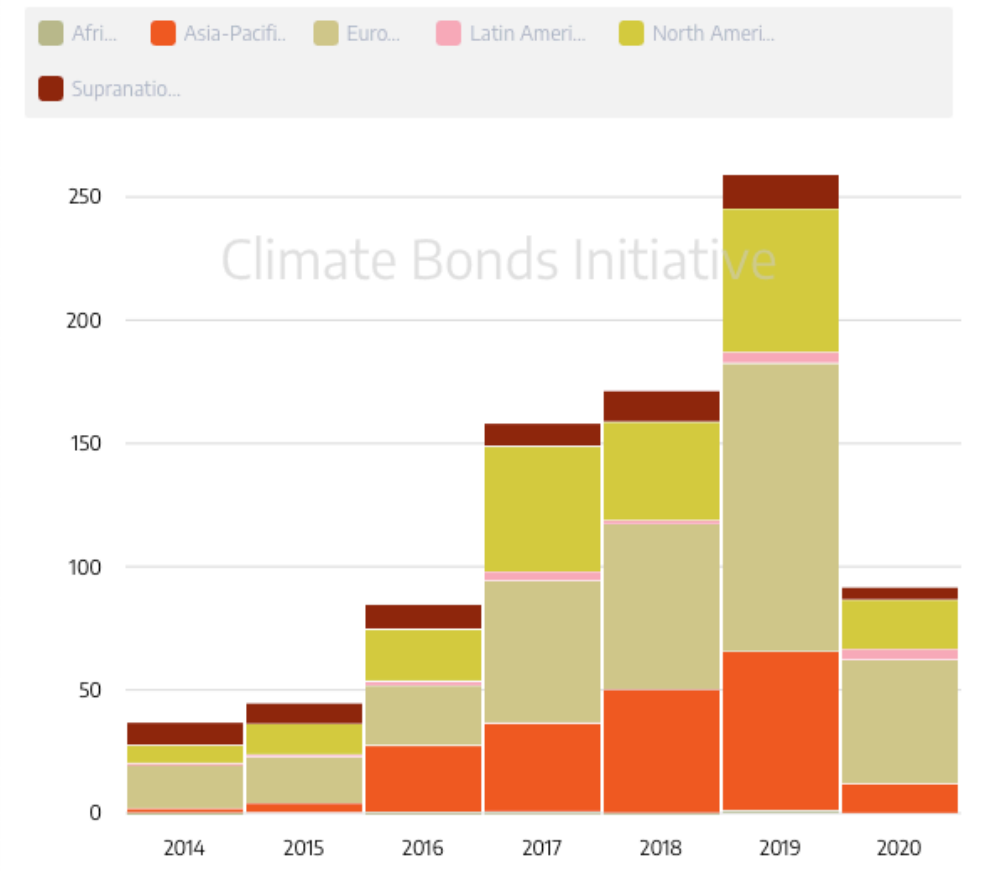
Green Finance flows - source: CFI (2019)



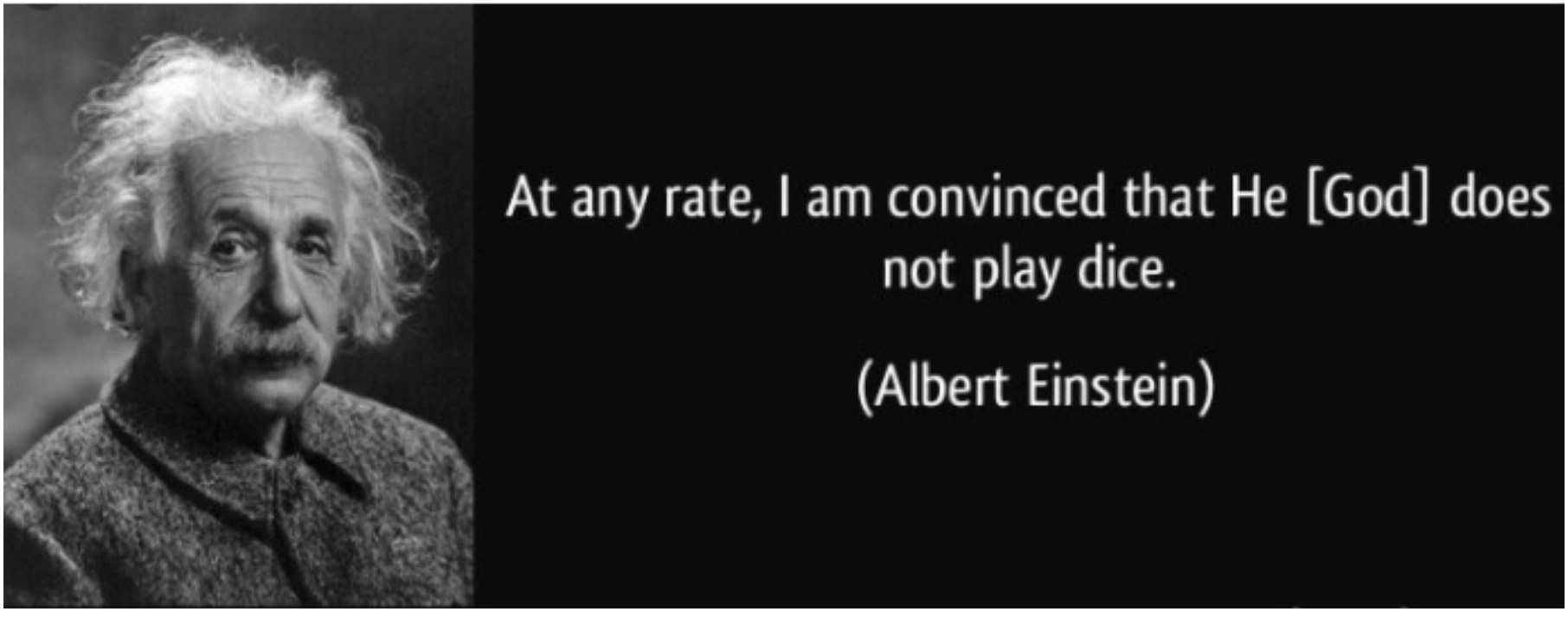
Green Finance by sector - source: CFI (2019)



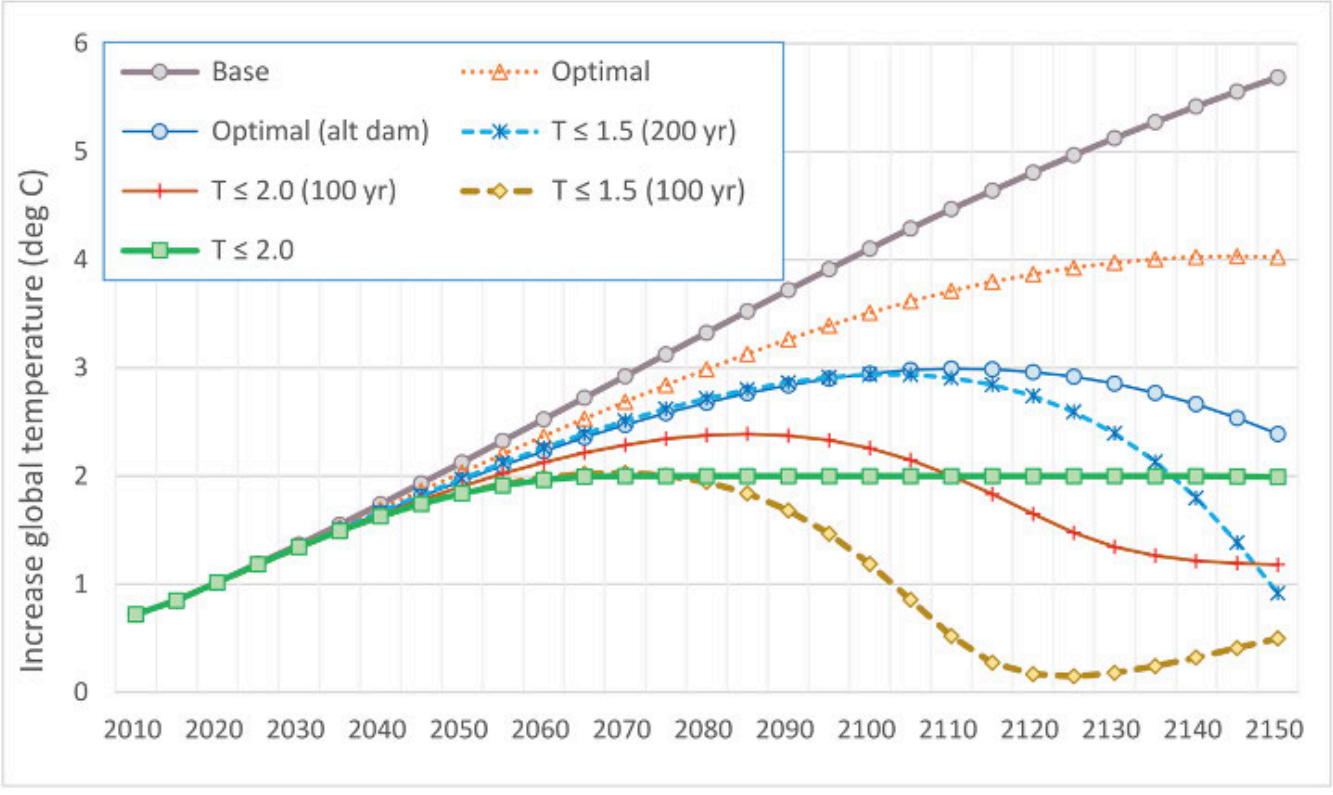
Green bonds - source: GBI (2021)



Dynamic Integrated Climate-Economy (DICE)



"Optimal" global warming according to Nordhaus



Slide 6 in Nordhaus's lecture, showing the "optimal" temperature path peaking at a 4°C increase by 2150

Hothouse Earth bifurcation (Steffen et al, PNAS 2018)

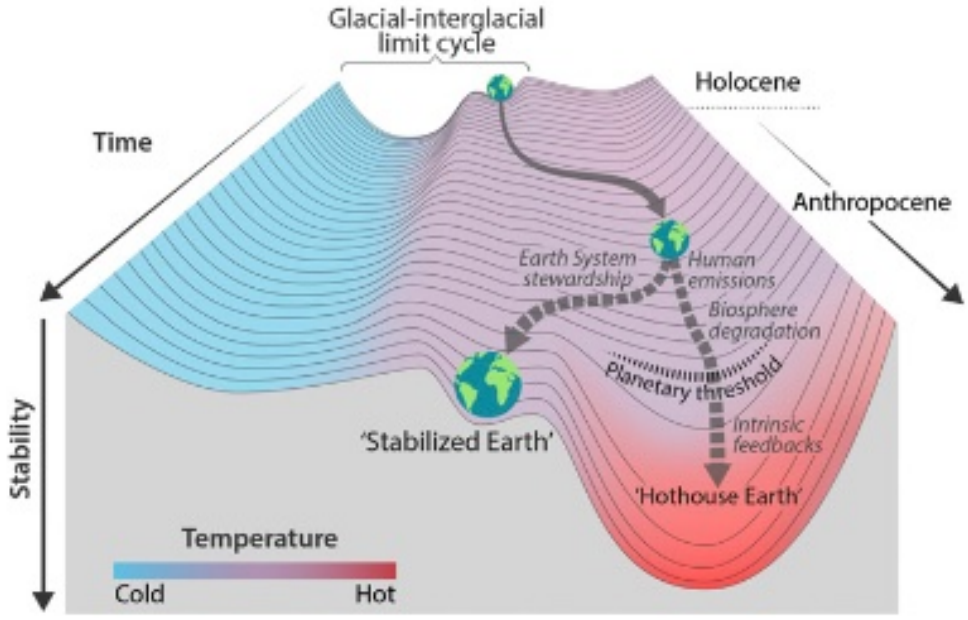
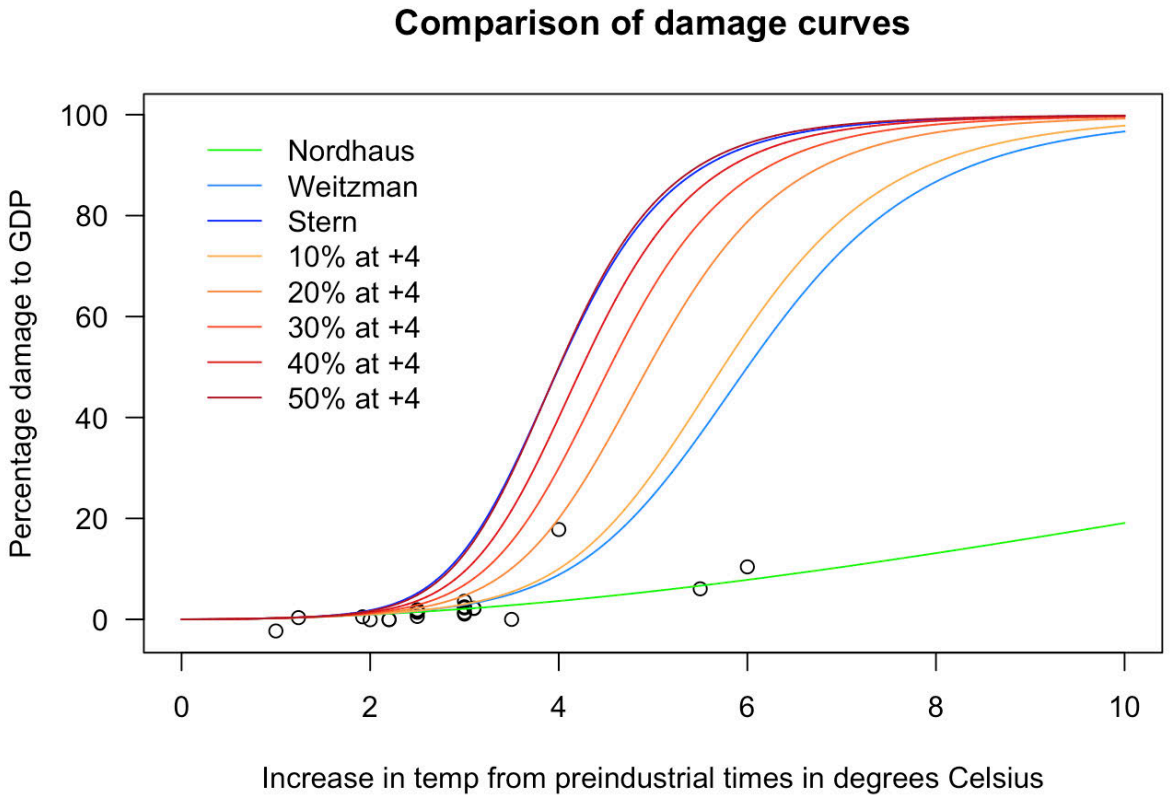
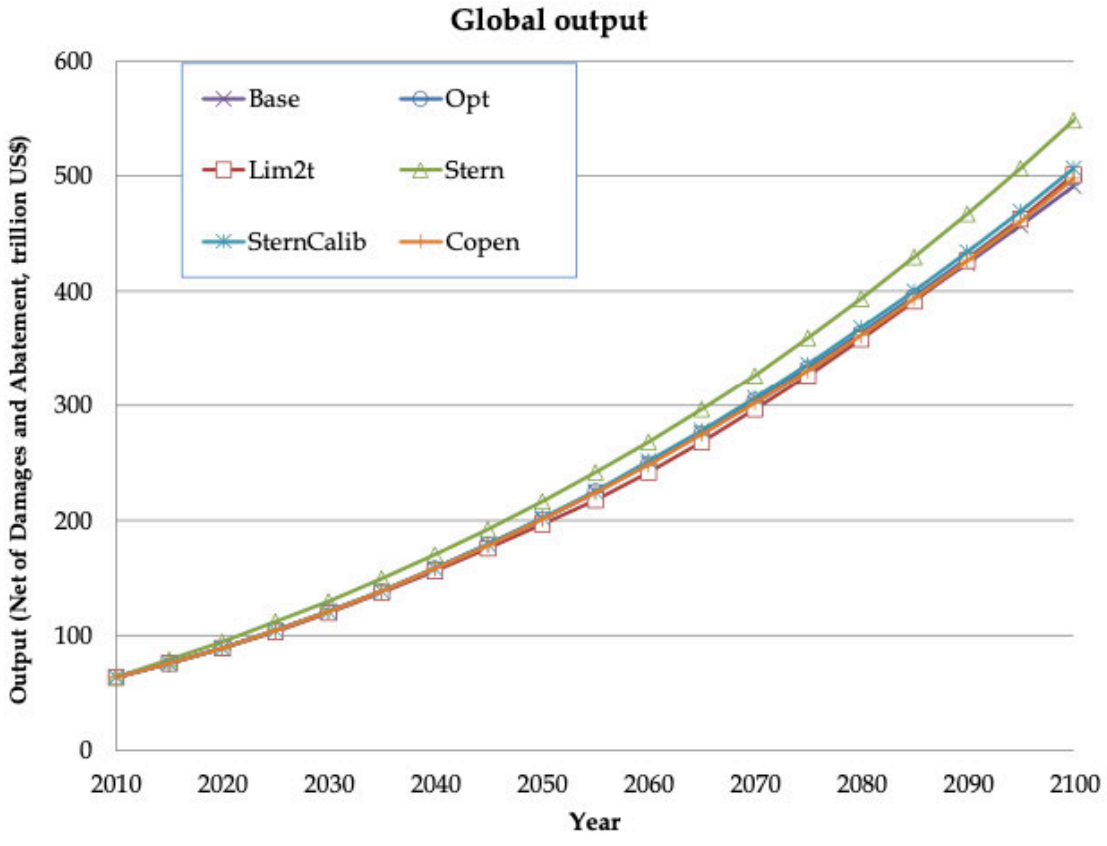


Fig. 2. Stability landscape showing the pathway of the Earth System out of the Holocene and thus, out of the glacial–interglacial limit cycle to its present position in the hotter Anthropocene. The fork in the road in Fig. 1 is shown here as the two divergent pathways of the Earth System in the future (broken arrows). Currently, the Earth System is on a Hothouse Earth pathway driven by human emissions of greenhouse gases and biosphere degradation toward a planetary threshold at ~2 °C (horizontal broken line at 2 °C in Fig. 1), beyond which the system follows an essentially irreversible pathway driven by intrinsic biogeophysical feedbacks. The other pathway leads to Stabilized Earth, a pathway of Earth System stewardship guided by human-created feedbacks to a quasistable, human-maintained basin of attraction.

Damage functions



GDP according to the DICE model



The COPING Model

	Households		Firms	Banks	Sum
Balance Sheet					
Capital stock			pK		pK
Deposits	M^h		M^f	$-M$	
Loans			$-L$	L	
Equities	$E^b + E^f$		$-E^f$	$-E^b$	
Sum (net worth)	X^h		X^f	X^b	X
Transactions		current	capital		
Consumption	$-pC$	pC			
Investment		pI	$-pI$		
Accounting memo [GDP]		$[pY]$			
Wages	W	$-W$			
Dividends	$Di + r(L-M)$		$-Di$	$-r(L-M)$	
Interests on loans		$-rL$		rL	
Interests on deposits	$+rM^h$	$+rM^f$		$-rM$	
Financial Balances	S^h	Π	$-pI - Di$	0	
Flow of funds					
Gross Fixed Capital Formation			pI		pI
Change in Deposits	$\dot{M}^h$		$\dot{M}^f$	$-\dot{M}$	
Change in loans			$-\dot{L}$	$\dot{L}$	
Change in equities	$\dot{E}^f + \dot{E}^b$		$-\dot{E}^f$	$-\dot{E}^b$	
Column sum	S^h		$\Pi - Di$	0	pI
Change in net worth	$\dot{X}^h = S^h$	$\dot{X}^f = \Pi - Di + \left[\dot{p} - (\delta + \mathbf{D}^K + \frac{G}{\nu})p\right]K$		$\dot{X}^b = 0$	$\dot{X} = pI + \left[\dot{p} - (\delta + \mathbf{D}^K + \frac{G}{\nu})p\right]K$

Table 1: Balance sheet, transactions, and flow of funds in the economy

Basic Definitions

$$Y^0 = \frac{K}{\nu} = aL, \quad Y = (1 - A)(1 - \mathbf{D}^Y)Y^0$$

$$\Pi = pY - wL - rD + p(S_C - T_C)$$

$$\omega = \frac{wL}{pY}, \quad d = \frac{D}{pY}, \quad \pi = \frac{\Pi}{pY}, \quad \lambda = \frac{L}{N}$$

$$I = \kappa(\pi)Y, \quad \dot{K} = I - (\delta + \mathbf{D}^K)K$$

$$\dot{D} = pI - \Pi + Div$$

$$Div = \Delta(\pi)pY$$

$$i = \frac{\dot{p}}{p} = \eta(\xi c - 1)$$

$$\dot{w} = w[\varphi(\lambda) + \gamma i]$$

Special case - the Keen model

If we decouple this model from the climate, it reduces to

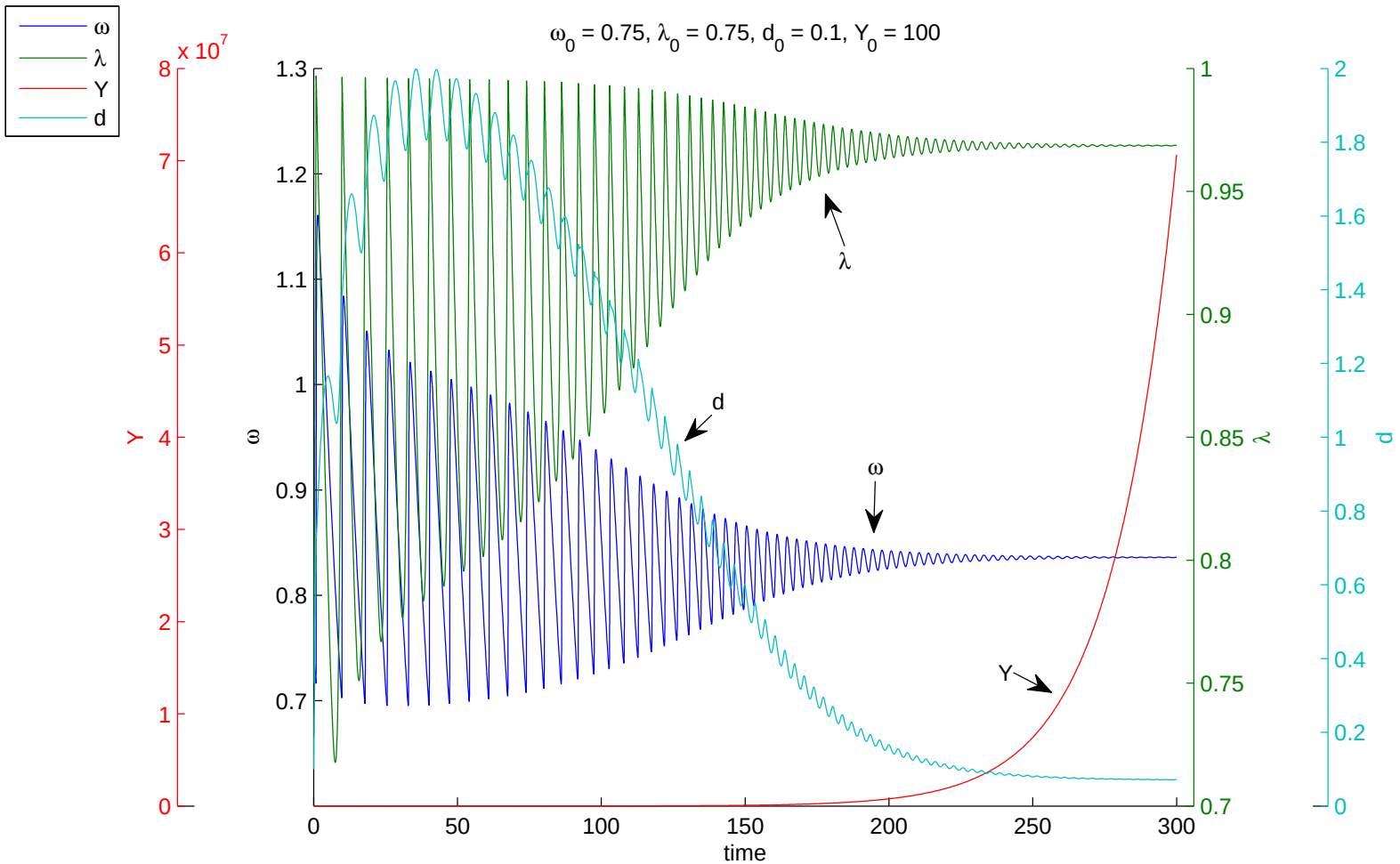
$$\dot{\omega} = \omega \left[\Phi(\lambda) - \alpha - (1-\gamma) i(\omega)\right]$$

$$\dot{\lambda} = \lambda \left[\frac{\kappa(\pi^0)}{\nu} - \alpha - \beta(N) - \delta\right] \tag{1}$$

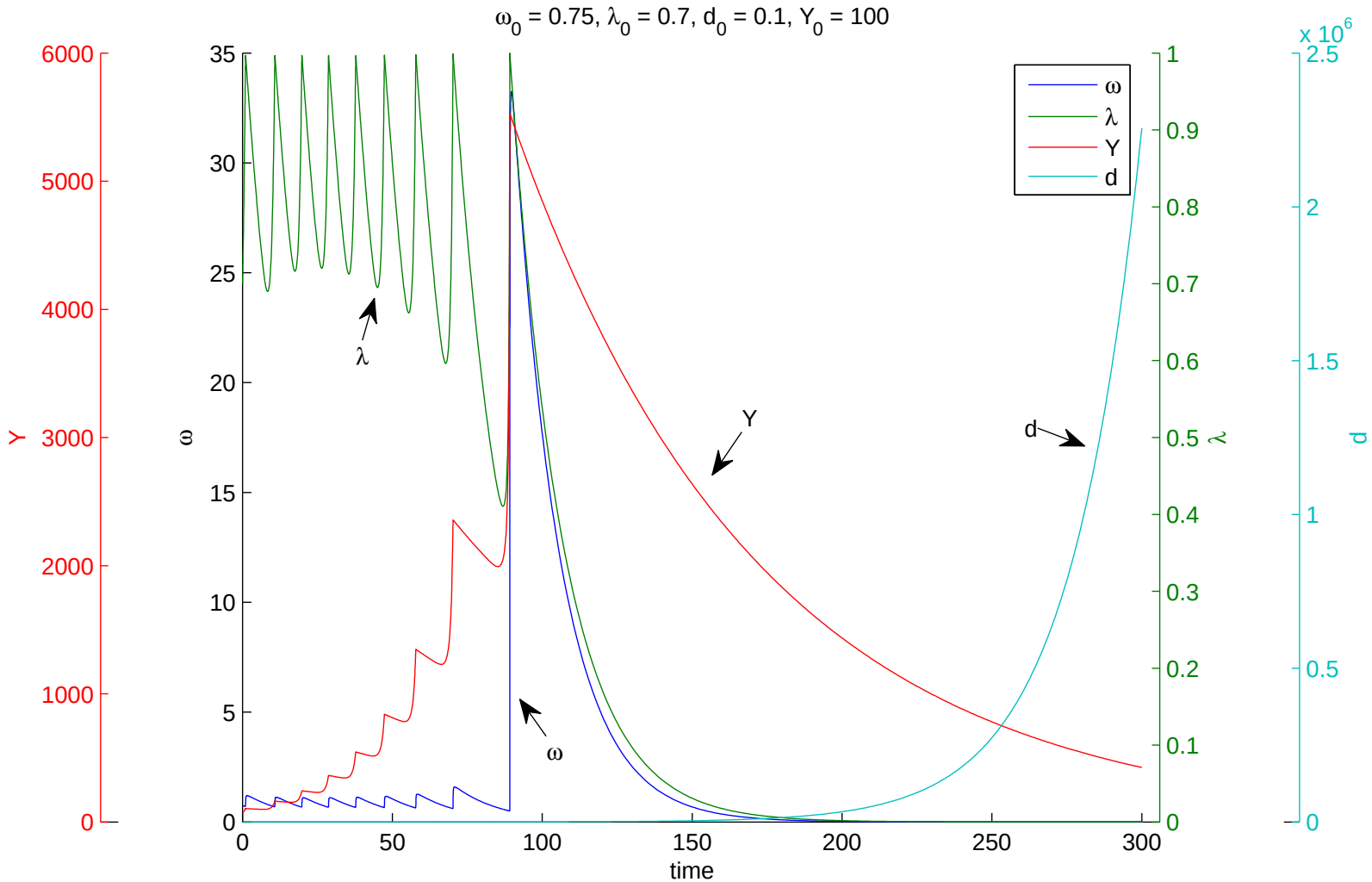
$$\dot{d} = \kappa(\pi^0) - \pi^0 + \Delta(\pi^0) - \left[i(\omega) + \frac{\kappa(\pi^0)}{\bar{\nu}} - \delta\right]$$

$$\dot{N} = \beta(N) N \tag{2}$$

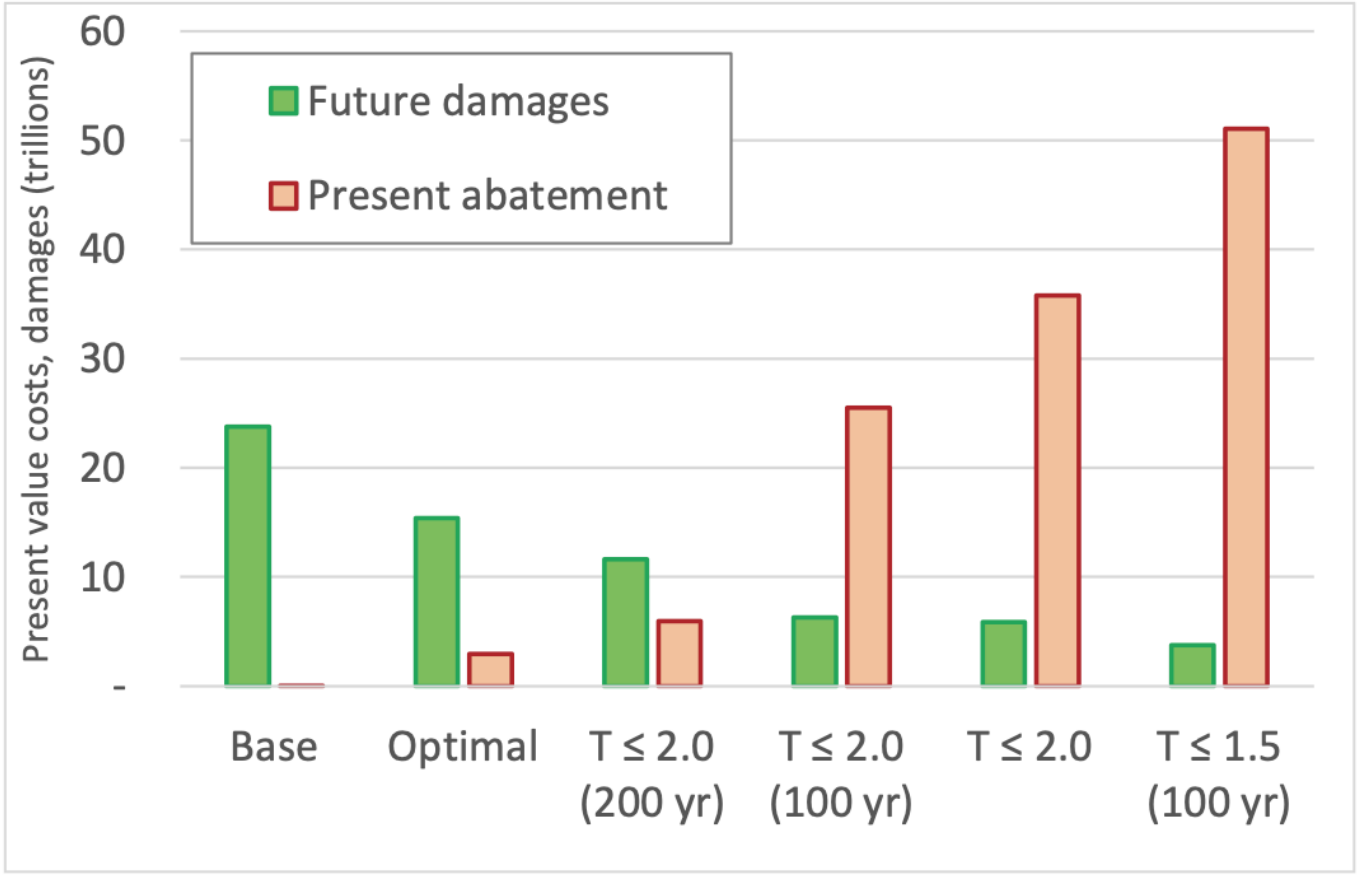
Example: convergence to the interior equilibrium in a Keen model



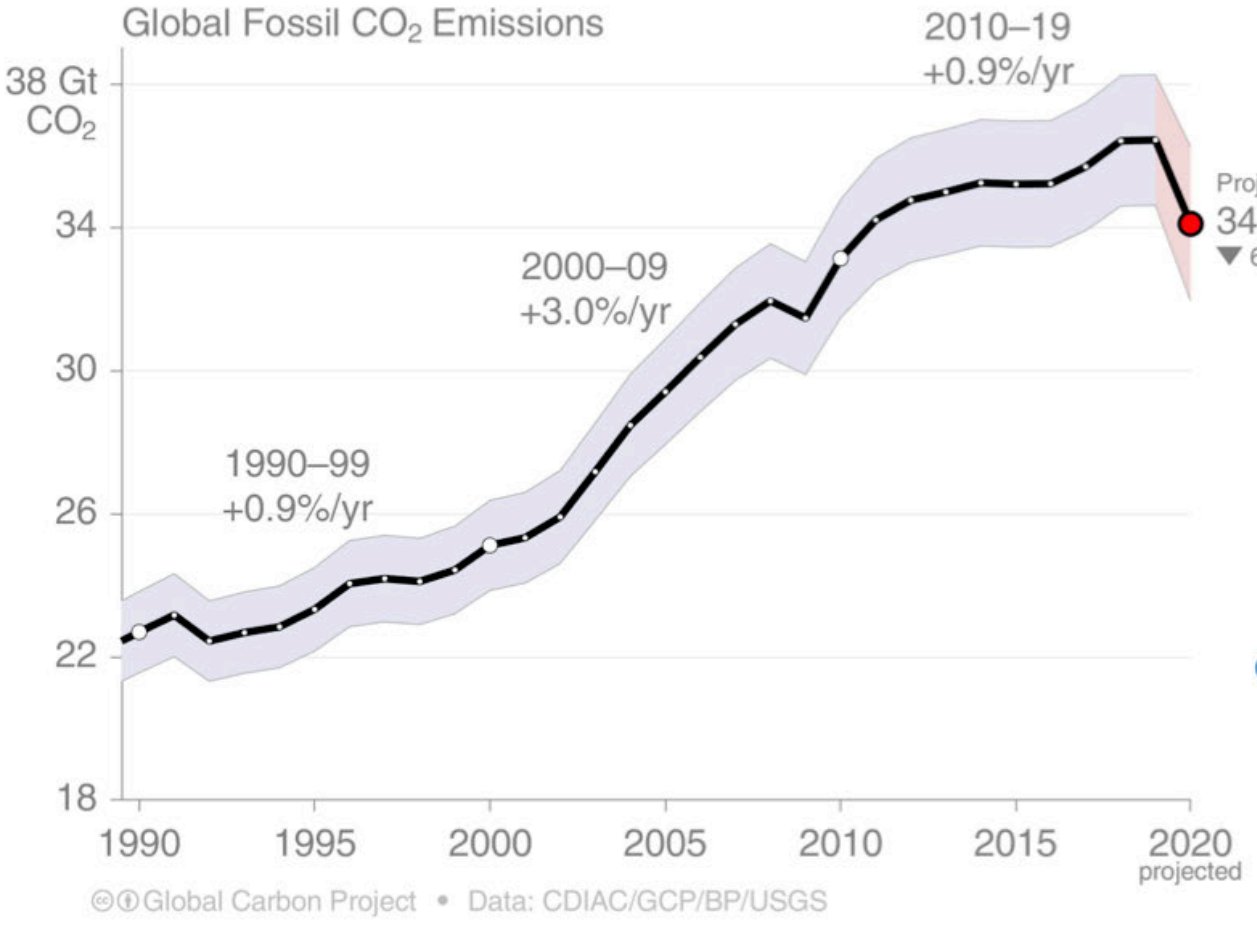
Example: explosive debt in a Keen model

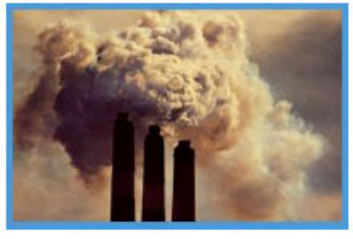


Trade-offs in the DICE model



Global Emissions





Uncertainty is ±5% for one standard deviation (IPCC "likely" range)

Emissions

$$E = E_{ind} + E_{land}, \quad E_{ind} = \sigma(1-n)Y^0, \quad \dot{E}_{land} = \delta_{E_{land}} E_{land}$$

$$\dot{\sigma} = g_\sigma \sigma, \quad g_\sigma < 0 \quad \text{(carbon intensity)}$$

$$\dot{g_\sigma} = \delta_{g_\sigma} g_\sigma, \quad \delta_{g_\sigma} < 0$$

$$T_C = p_C E_{ind} \qquad \text{(carbon tax)}$$

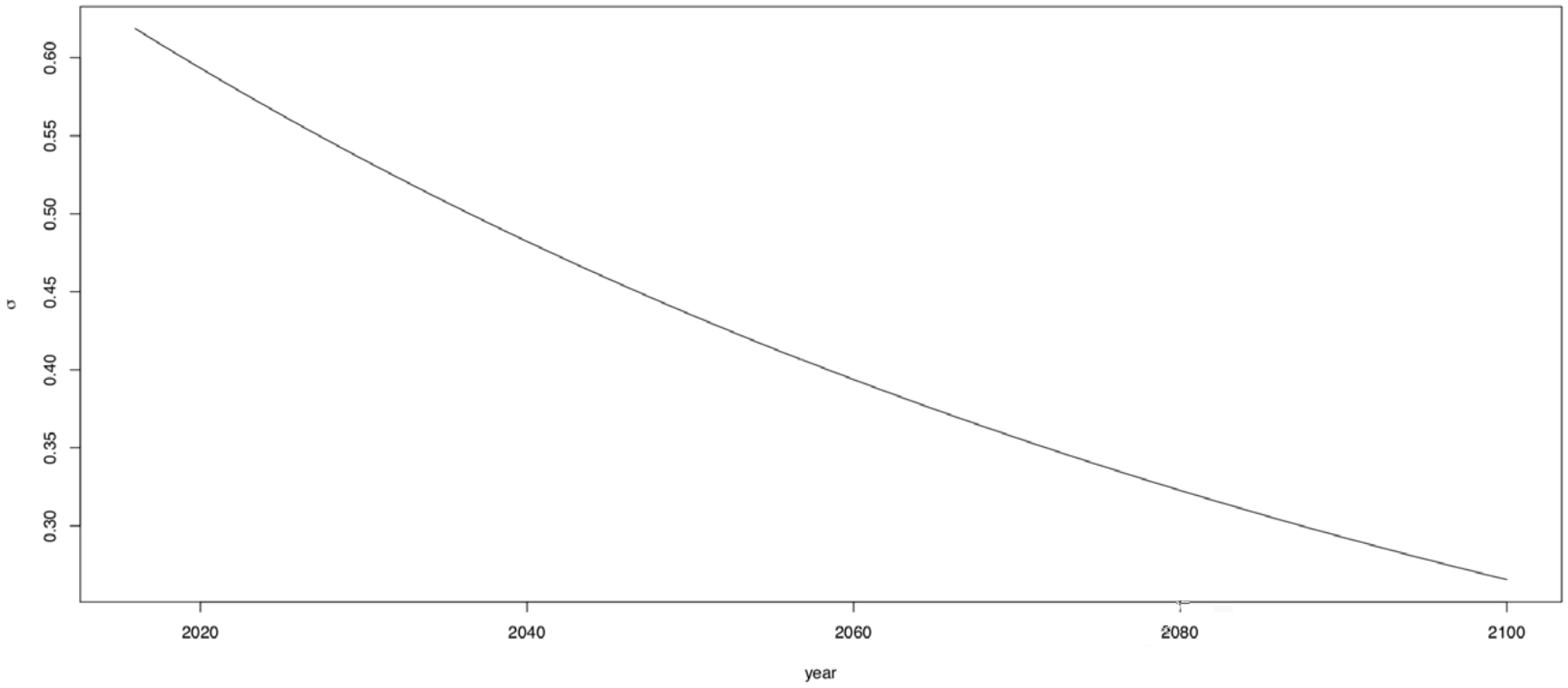
$$A = \frac{\sigma p_{BS} n^\theta}{\theta}, \quad \theta > 1 \qquad \text{(abatement cost)}$$

$$n = \min\left\{ \left(\frac{p_C}{(1-s_A)p_{BS}} \right)^{\frac{1}{\theta-1}}, 1 \right\} \quad \text{(optimal emissions reduction)}$$

$$\frac{\dot{p_{BS}}}{p_{BS}} = \delta_{BS} \leq 0 \quad \text{(backstop technology)}$$

$$\frac{\dot{p_C}}{p_C} = \delta_C(\cdot) \geq 0 \quad \text{(carbon)}$$

Carbon intensity

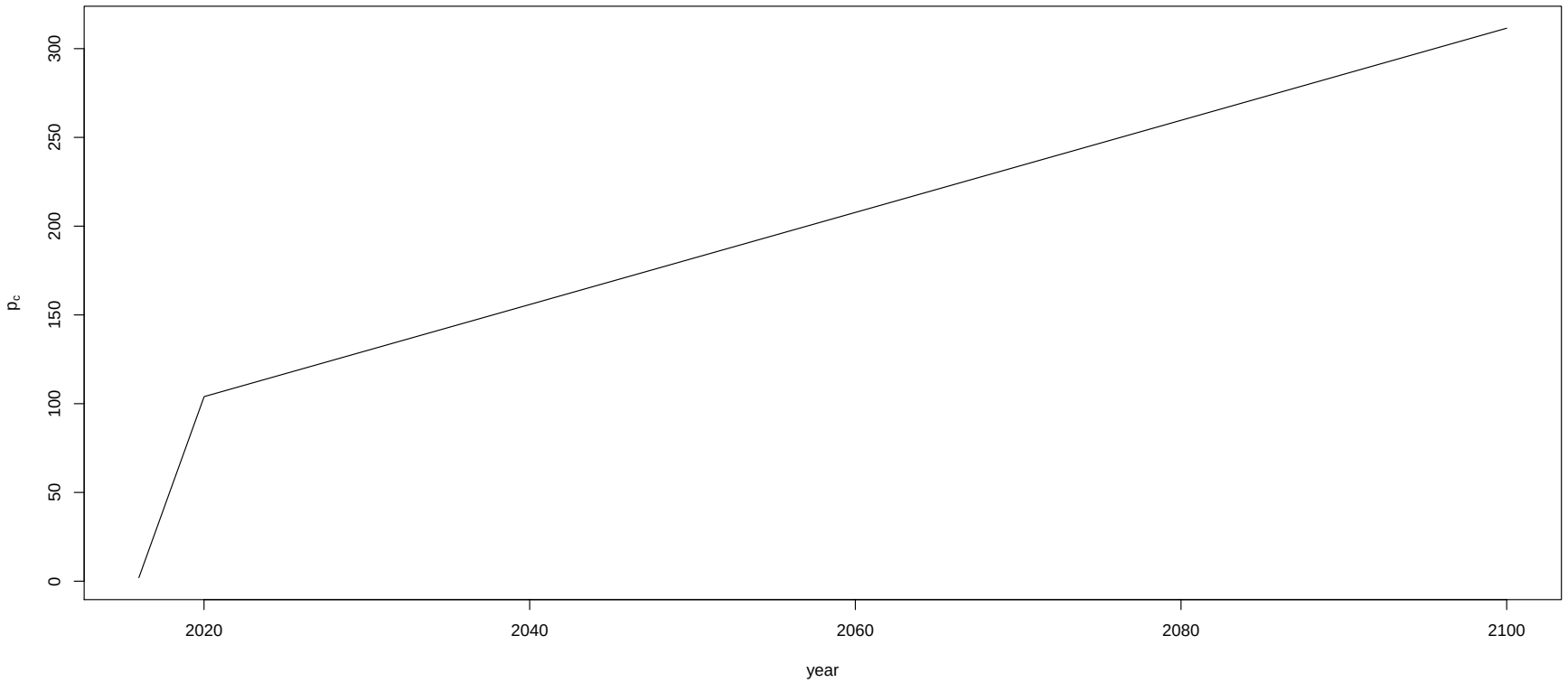


Backstop technology

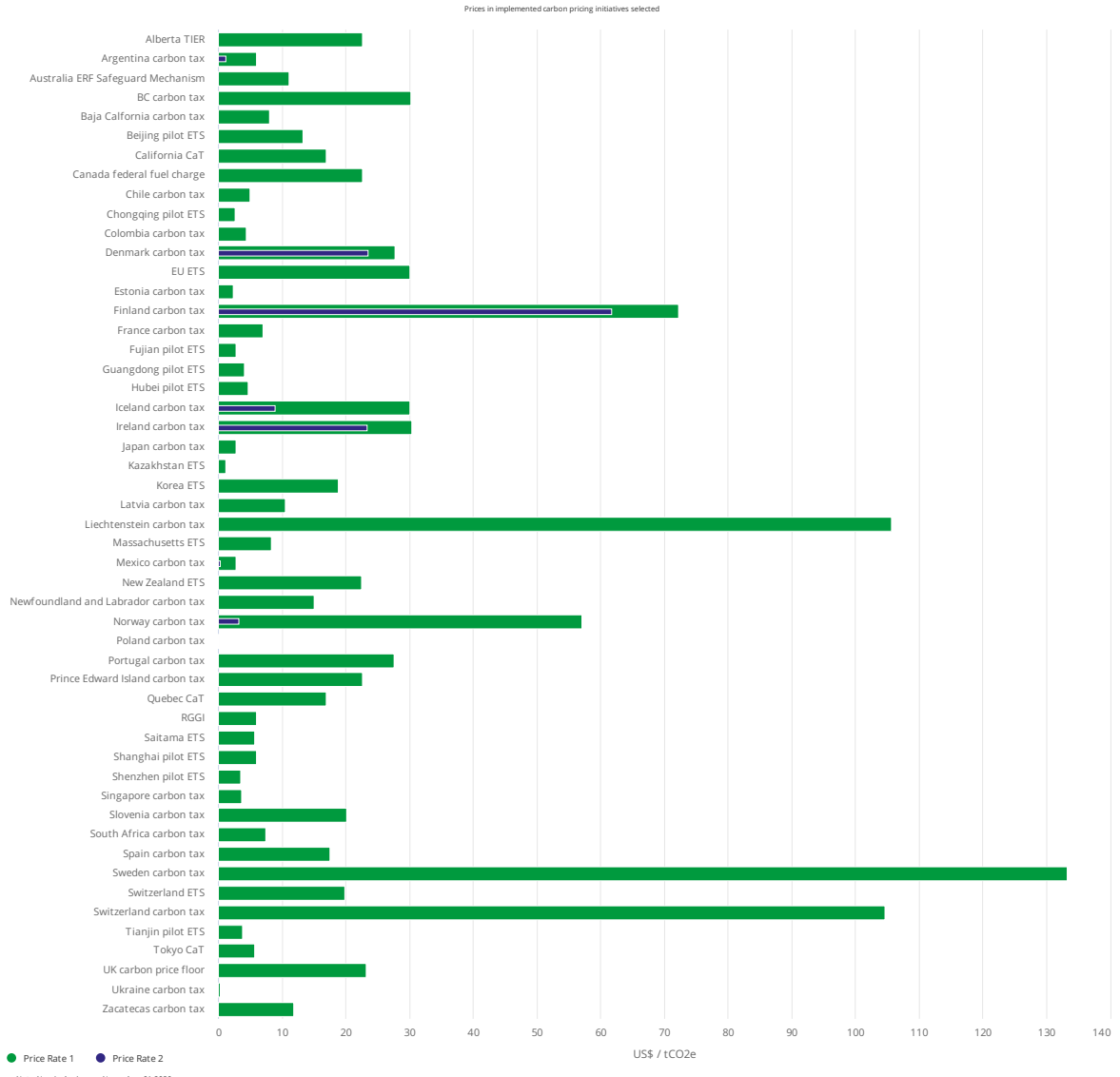
	Global Weighted-Average Cost of Electricity (USD/kWh)	Decrease in the Cost of Electricity 2017-2018 (%)
Bioenergy	0.062	14
Geothermal	0.072	1
Hydro	0.047	11
Solar PV	0.085	13
Offshore wind	0.127	1
Onshore wind	0.056	13

Table 2: Table depicting the 2018 prices of renewable energy and the percentage change in price

Carbon price



Carbon price dashboard 2020 - source: World Bank



Carbon cycle

$$\begin{pmatrix} \dot{CO_2}^{AT} \\ \dot{CO_2}^{UP} \\ \dot{CO_2}^{LO} \end{pmatrix} = \begin{pmatrix} E \\ 0 \\ 0 \end{pmatrix} + \Phi \begin{pmatrix} CO_2^{AT} \\ CO_2^{UP} \\ CO_2^{LO} \end{pmatrix}$$

where

$$\Phi = \begin{pmatrix} -\phi_{12} & \phi_{12} C_{UP}^{AT} & 0 \\ \phi_{12} & -\phi_{12} C_{UP}^{AT} - \phi_{23} & \phi_{23} C_{LO}^{UP} \\ 0 & \phi_{23} & -\phi_{23} C_{LO}^{UP} \end{pmatrix}$$

Radiative Forcing

The accumulation of CO_2 increases radiative forcing

$$F := F_{ind} + F_{exo}$$

as follows

$$F_{ind} := \frac{F_{dbl}}{\log(2)} \log\left(\frac{CO_2^{AT}}{CO_{2preind}^{AT}}\right)$$

where F_{dbl} is an exogenous parameter that represents the effect on forcing of a doubling of pre-industrial CO_2 levels and F_{exo} increases exogenously over time.

Temperature and Damages

$$C\dot{T} = F - \frac{F_{dbl}}{S}T - \gamma^*(T - T_{LO}) \quad \text{(Atmospheric temp increase)}$$

$$C_{LO}\dot{T_{LO}} = \gamma^*(T - T_{LO}) \quad \text{(Deep ocean temp increase)}$$

$$0 \leq \mathbf{D}(T) \leq 1 \quad \text{(Damages)}$$

$$\mathbf{D}^K = f_k\mathbf{D}, \quad 0 \leq f_k \leq 1 \quad \text{(Damages to capital)}$$

$$\mathbf{D}^Y = 1 - \frac{1 - \mathbf{D}}{1 - \mathbf{D}^K} = \frac{(1 - f_k)\mathbf{D}}{1 - f_k\mathbf{D}} \quad \text{(Damages to output)}$$

Alternatively, we assume that $\mathbf{D}^Y = \mathbf{D}$

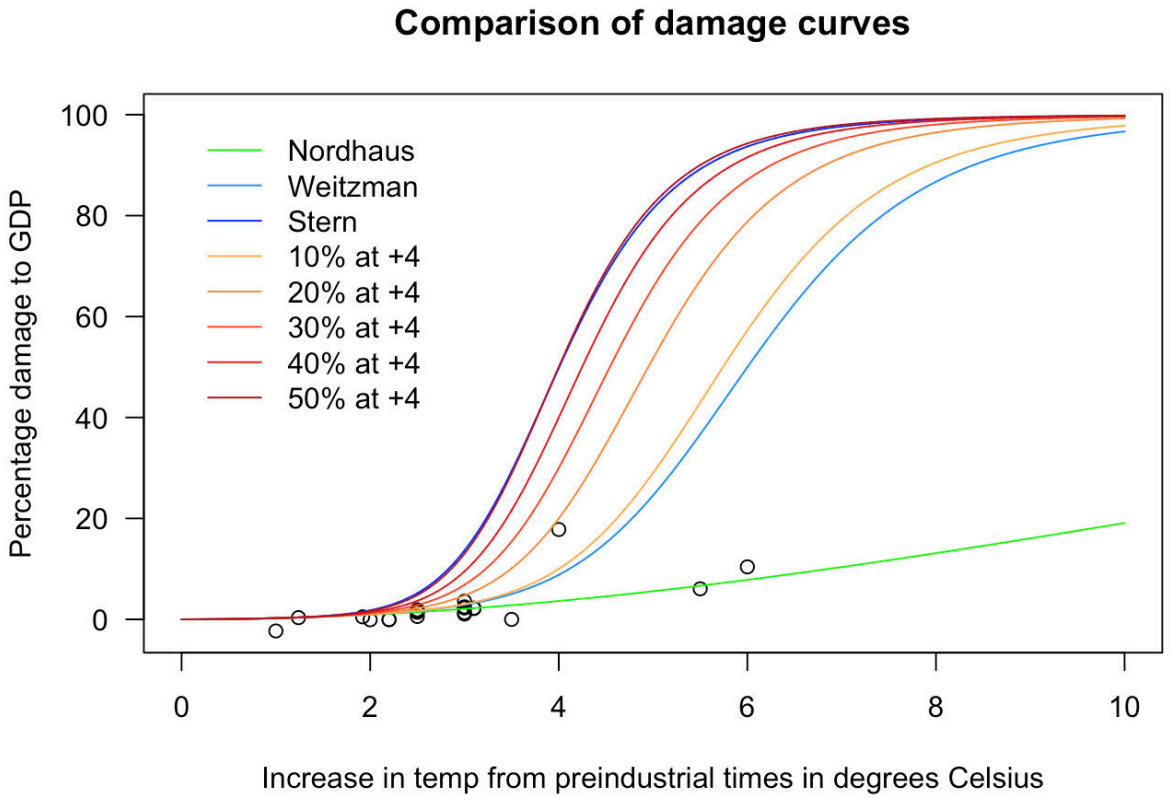
Alternative Damage Functions

$$\mathbf{D} = 1 - \frac{1}{1 + 2.84 \times 10^{-3} T^2} \qquad \text{(Nordhaus)}$$

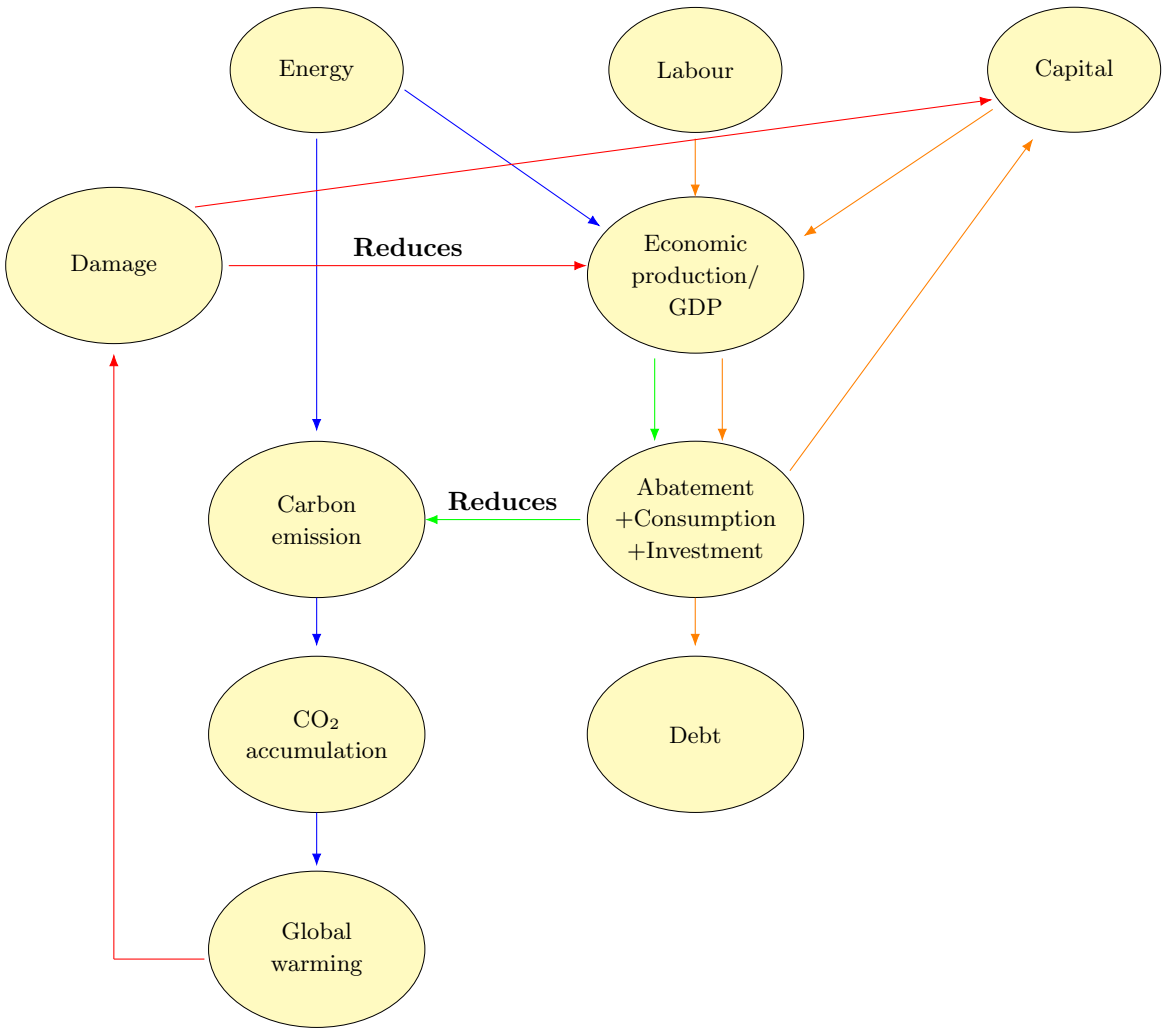
$$\mathbf{D} = 1 - \frac{1}{1 + 2.84 \times 10^{-3} T^2 + 5.070 \times 10^{-6} T^{6.754}} \qquad \text{(Weitzman)}$$

$$\mathbf{D} = 1 - \frac{1}{1 + 2.84 \times 10^{-3} T^2 + 8.19 \times 10^{-5} T^{6.752}} \qquad \text{(Dietz and Stern)}$$

Damage functions



Model Schematic



Example 1: No damages - Bovari et al (2018a)

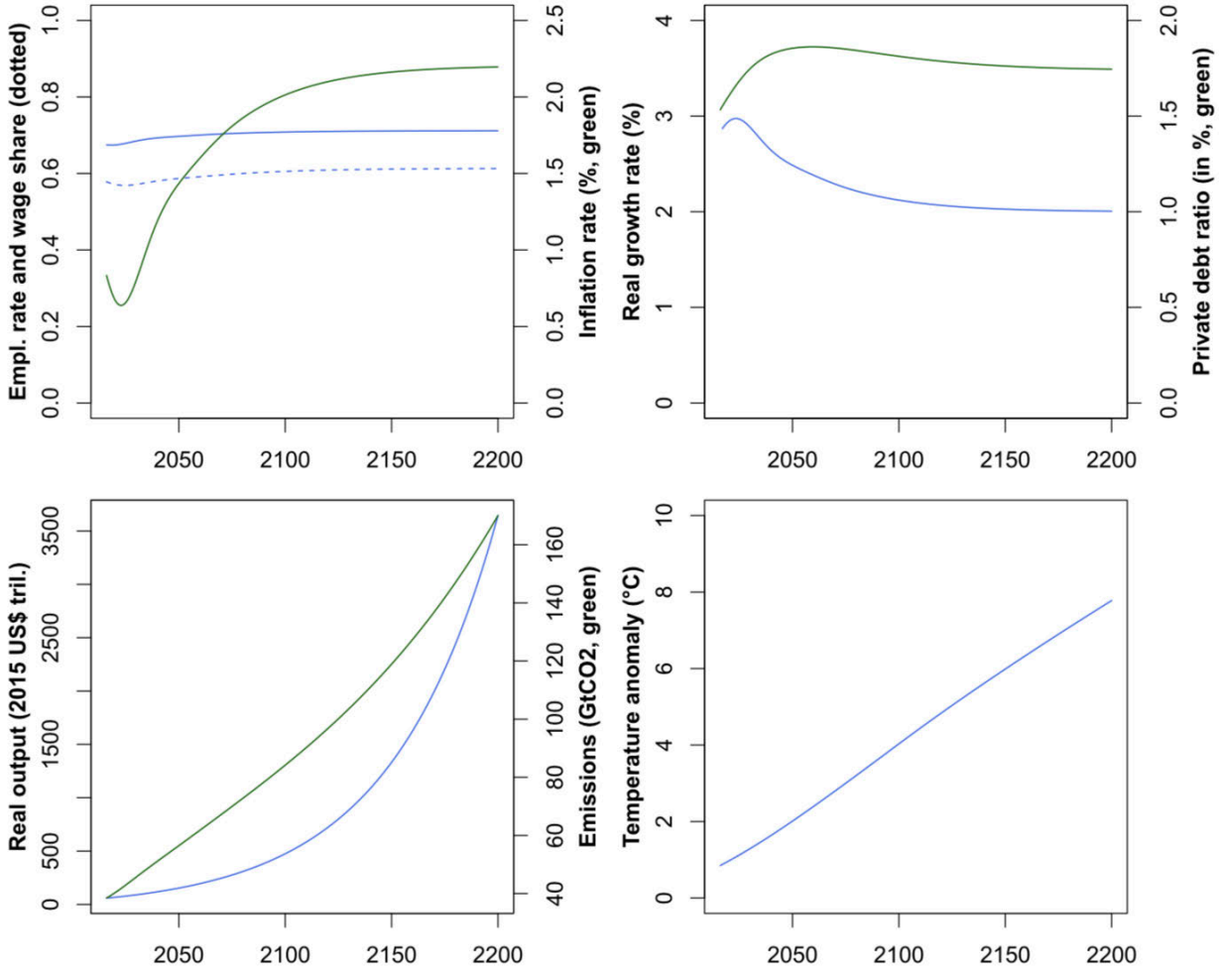


Fig. 1. Trajectories of the main simulation variables in the *No feedback loop scenario*.

Example 2: Bifurcation - Bovari et al (2018a)

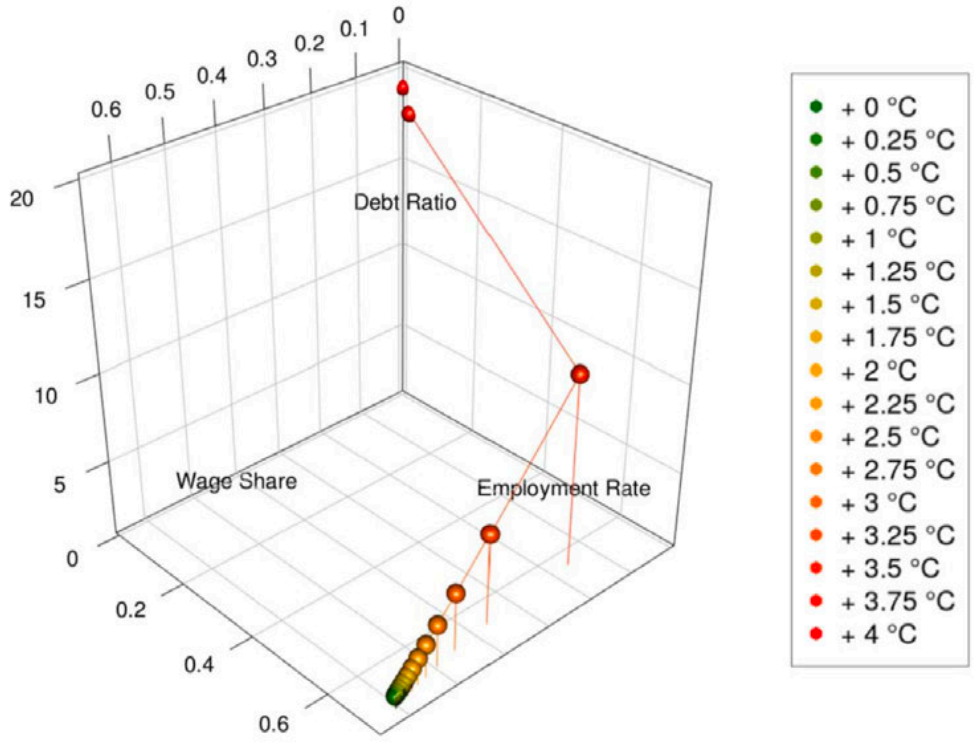


Figure: Temperature bifurcation with Weitzman damages, no policy.

Example 3: No-policy Collapse - Bovari et al (2018a)

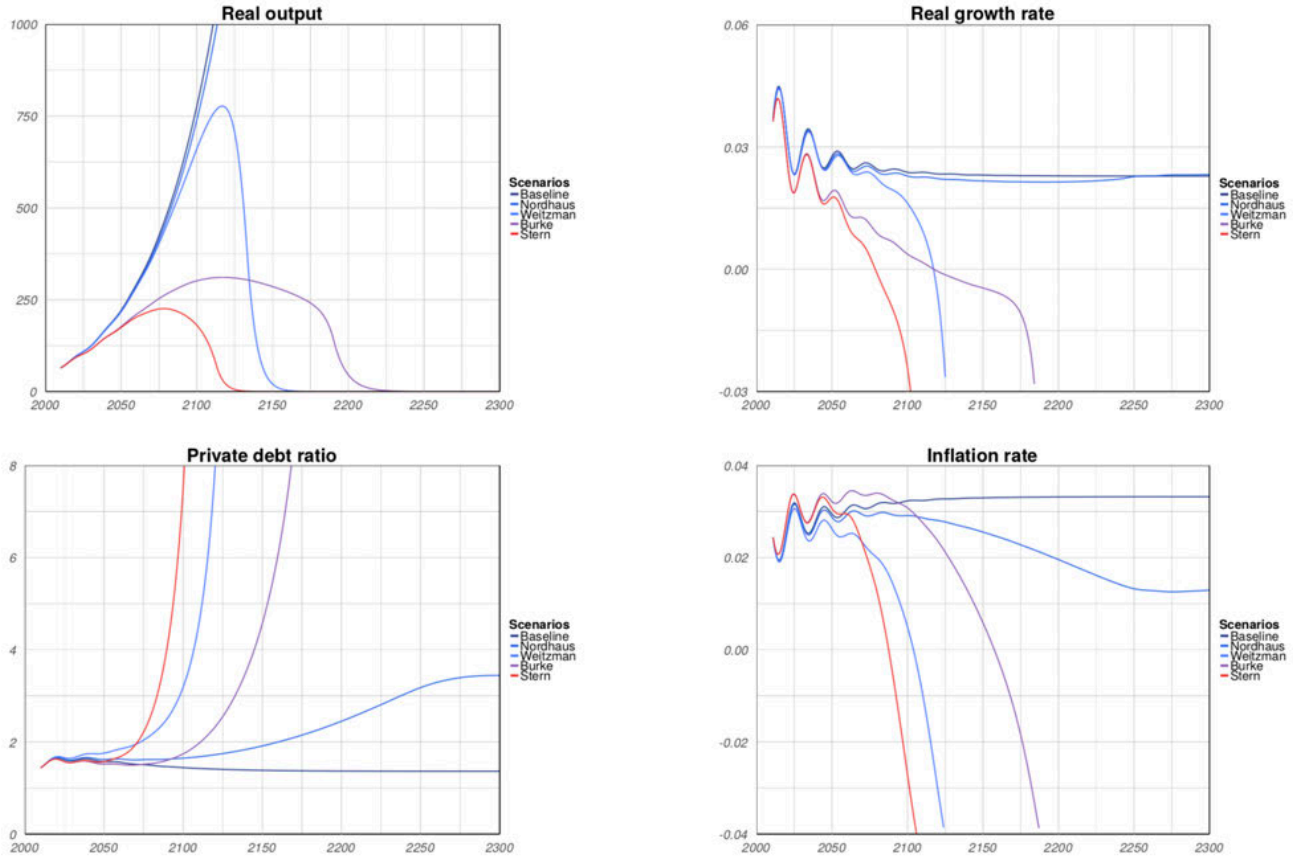


Figure: Outcomes with initial carbon price of $1 and growth rate of 2%.

Example 4: Effect of Policy - Bovari et al (2018a)

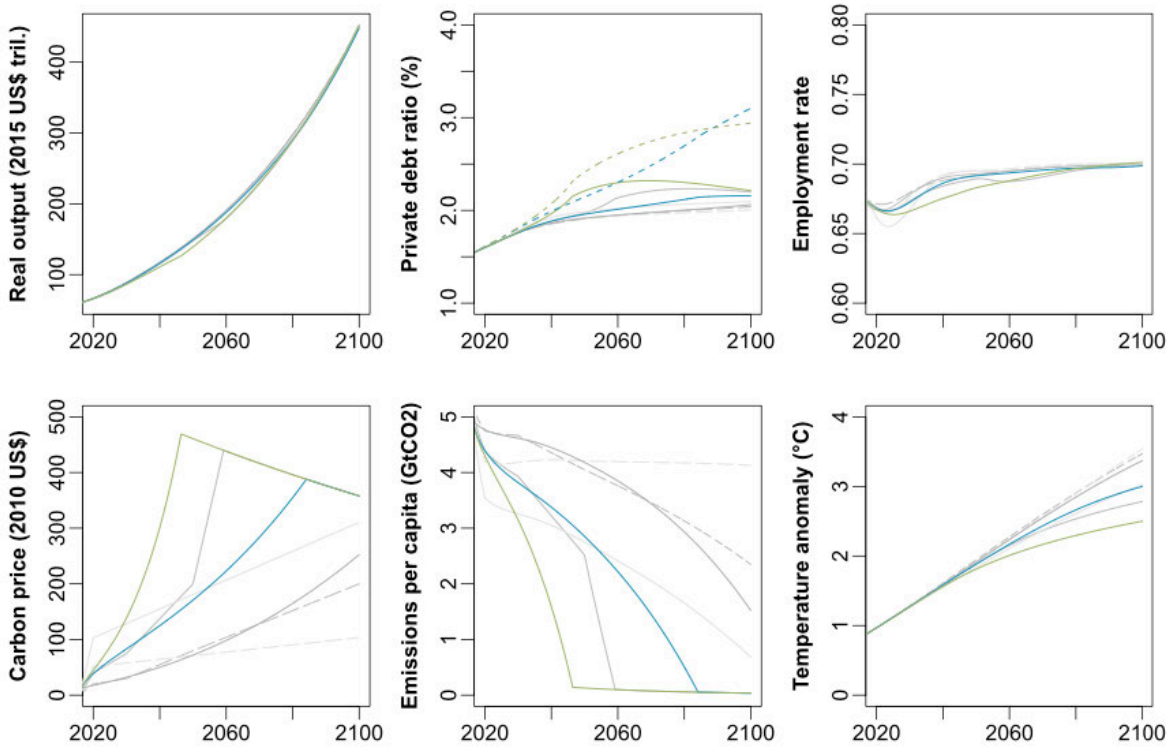


Figure: Outcomes with Nordhaus damages and different carbon prices.

Example 4: Sensitivity analysis - Bovari et al (2018b)

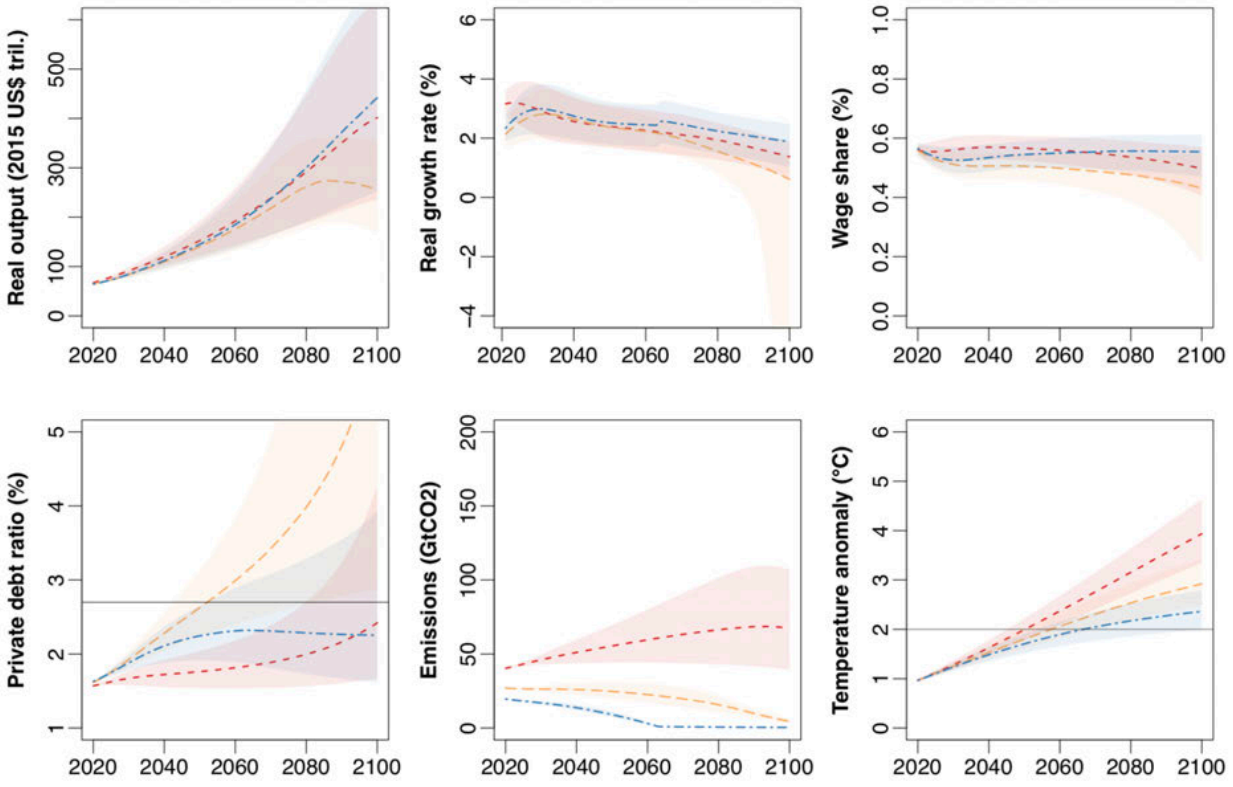


Figure 3: $[0.05; 0.95]$ probability interval of the *No policy*, *Carbon tax*, and *Carbon tax and subsidy* scenarios with a damage allocation to the stock of physical capital of $f_K = 33\%$ respectively in red, orange and blue shades (medians in small, long and mixed dashes)

Inflation revisited

- Recall the price dynamics

$$i = \frac{\dot{p}}{p} = \eta(\xi c - 1)$$

- In Coping (2018) the cost was assumed to be

$$c = \left(\frac{1}{(1-A)(1-\mathbf{D}^Y)}\right)\left[\frac{w}{pa} + \nu\left(\frac{rD + \Delta(\pi)pY}{pK}\right) + p_c\sigma(1-n)\right]$$

- In Debt and Damages (2018), this was changed to the simpler form $c = \omega$.
- Accordingly, the parameters (η, ξ) changed from $(0.5, 1.3)$ to $(0.192, 1.875)$.
- But what are plausible ranges for these parameters?

Relaxation parameter - Grasselli and Maheshwari (2018)

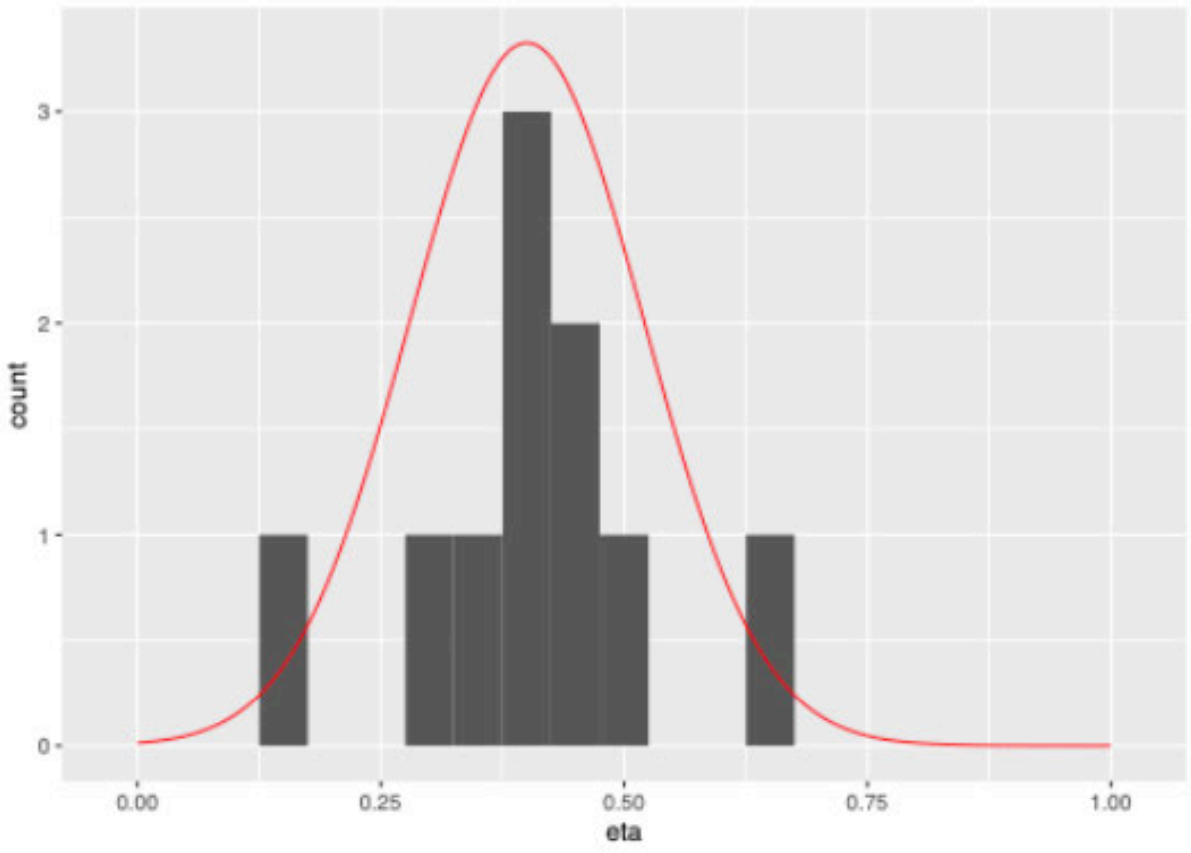


Figure: Fitted $N(0.40, 0.12)$ distribution.

Markup parameter - Grasselli and Maheshwari (2018)

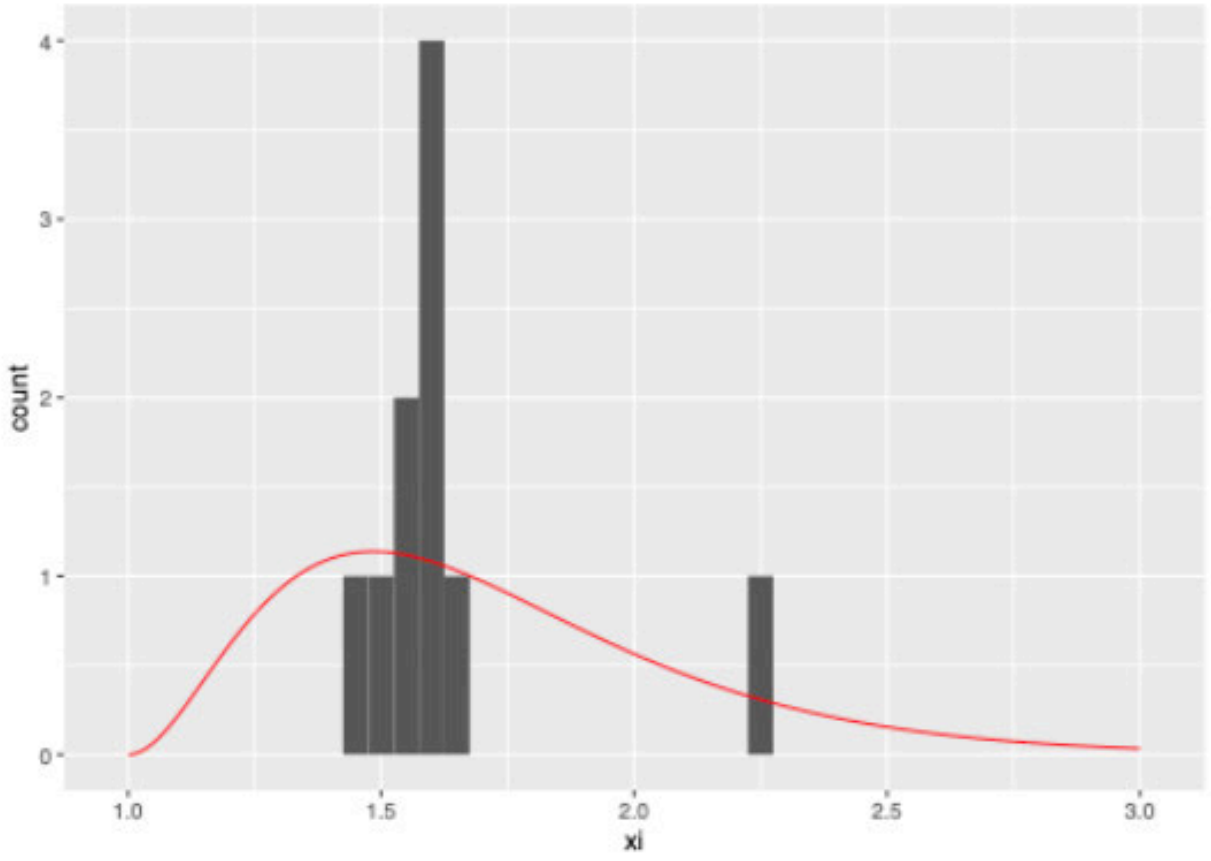


Figure: Fitted generalized Gamma distribution with mean 1.64.

Money illusion parameter - Grasselli and Maheshwari (2018)

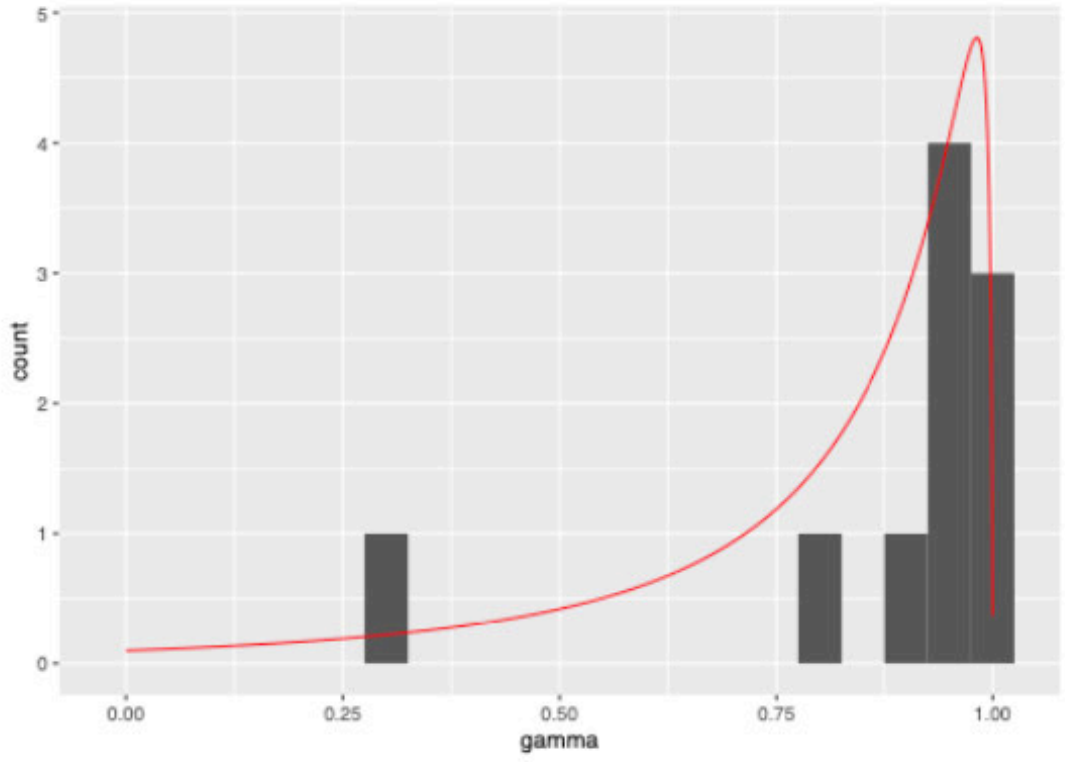
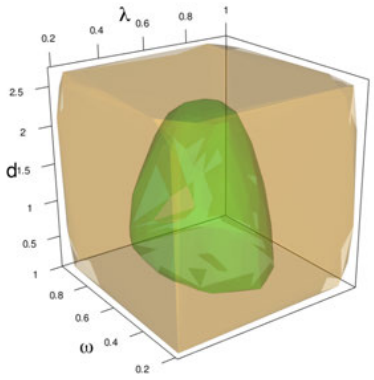
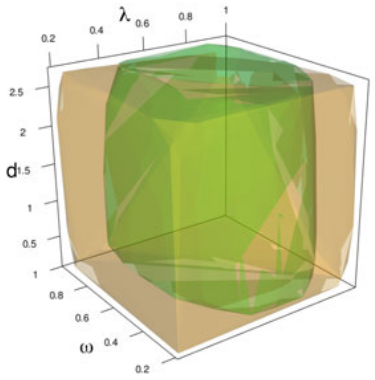


Figure: Fitted generalized Gamma distribution with mean 0.88.

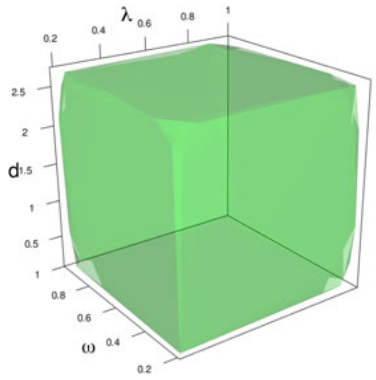
Basin of attraction of interior equilibrium - BGH (2021)



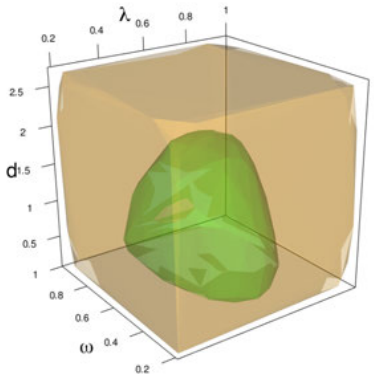
(a) $\bar{\xi} = 1.18$

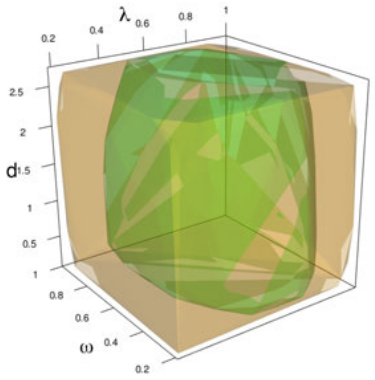


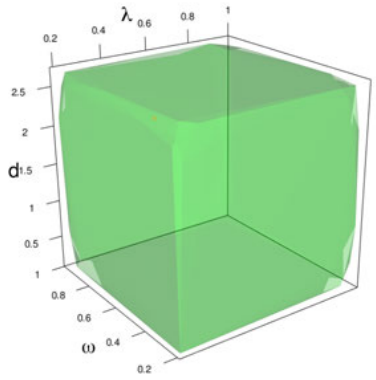
(b) $\bar{\xi} = 1.3$

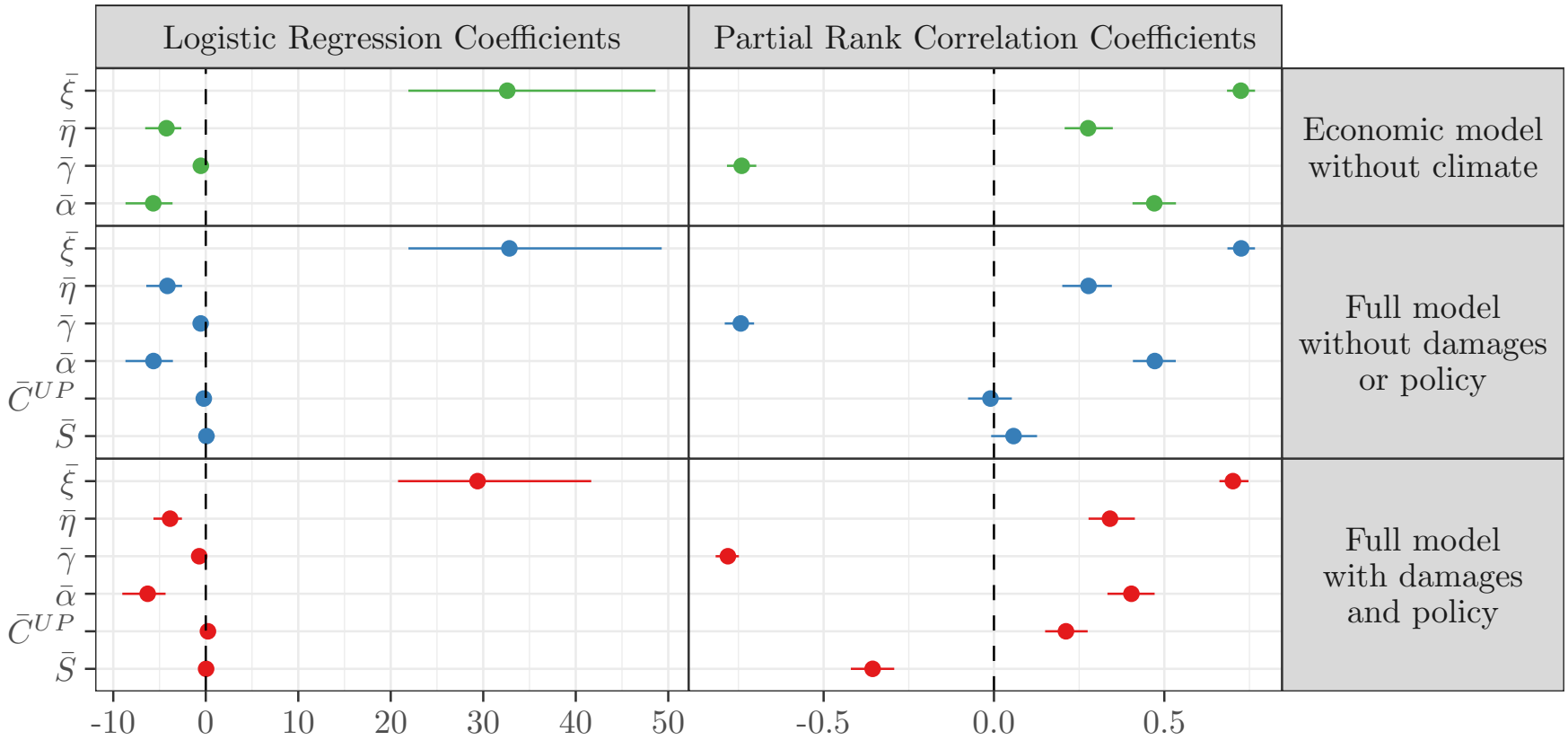


(c) $\bar{\xi} = 1.875$

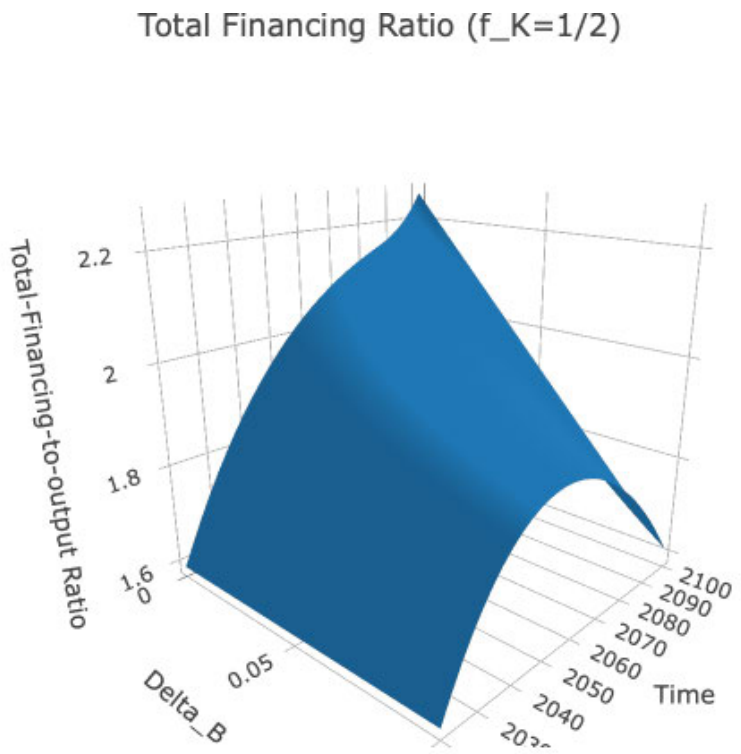




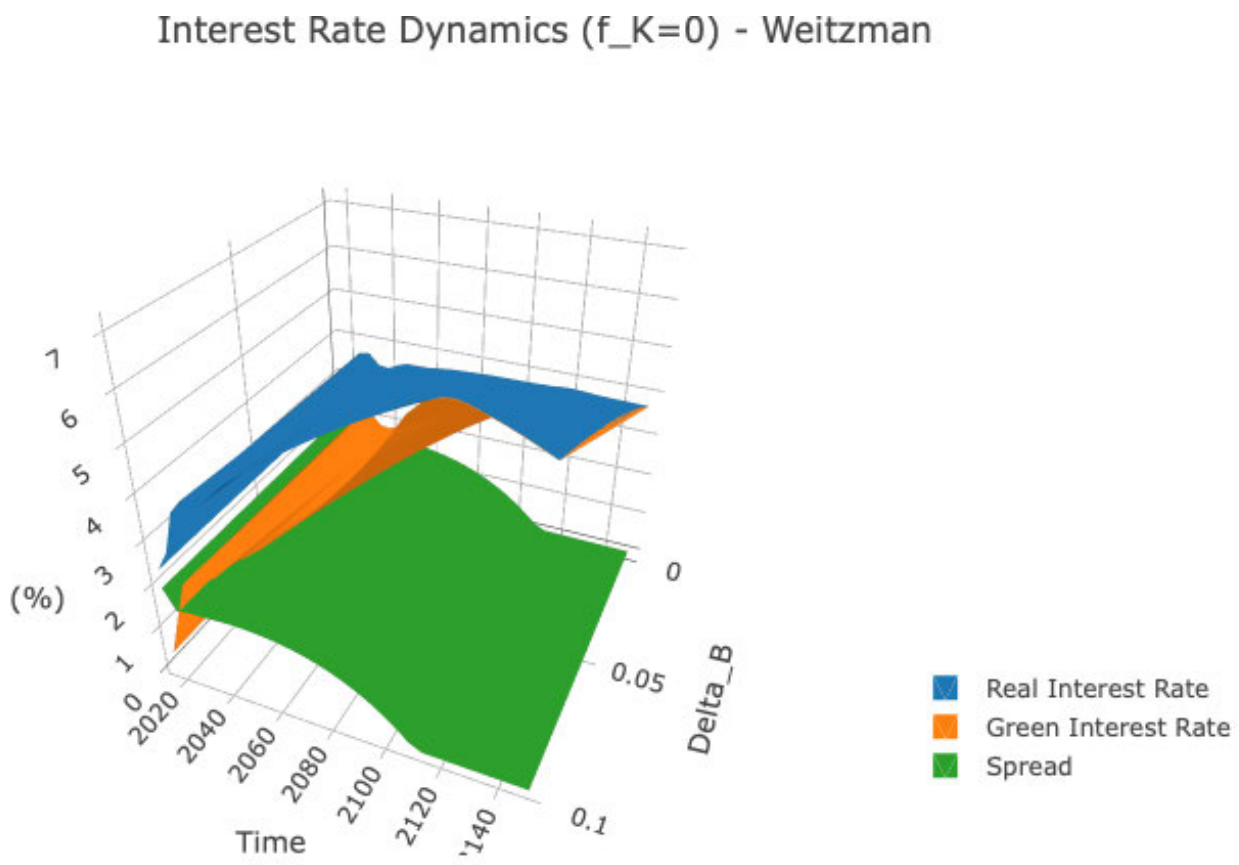



Logistic Regression Coefficients
Partial Rank Correlation Coefficients
$\bar{\xi}$
$\bar{\eta}$
$\bar{\gamma}$
$\bar{\alpha}$
$\bar{C}^{UP}$
$\bar{S}$
Economic model without climate
Full model without damages or policy
Full model with damages and policy
-10
0
10
20
30
40
50
-0.5
0.0
0.5

Green bonds


Total Financing Ratio (f_K=1/2)
Total-Financing-to-output Ratio
2.2
2
1.8
1.6
Delta_B
0.05
Time
2100
2090
2080
2070
2060
2050
2040

Green loans


Interest Rate Dynamics (f_K=0) - Weitzman
(%)
7
6
5
4
3
2
1
0
2020
2040
2060
2080
2100
2120
Time
0
0.05
0.1
Delta_B
Real Interest Rate
Green Interest Rate
Spread

Conclusions

- Climate change is the most formidable challenge faced by the human race
- Traditional macroeconomics is ill-equipped to contribute to it
- Integration of *dynamic* models with *disequilibrium* and *slowly adjusting variables* is needed
- Finance is likely to play a fundamental role in the low-carbon transition
- Should try *everything* that is available: carbon tax, subsidies, green bonds, green securitization, green central banking, etc
- We need a Green Bubble

Thank you!