Can we bet on negative emissions to stabilize at 2°C even under strong carbon cycle feedbacks?

Katsumasa Tanaka

National Institute for Environmental Studies (NIES), Tsukuba, JAPAN

Contributed by **Yoshiki Yamagata, Daniel Johansson, Tokuta Yokohata**
Seita Emori, Tatsuya Hanaoka

SDWG, Boulder, Colorado, US (8 February 2016)

INTRODUCTION

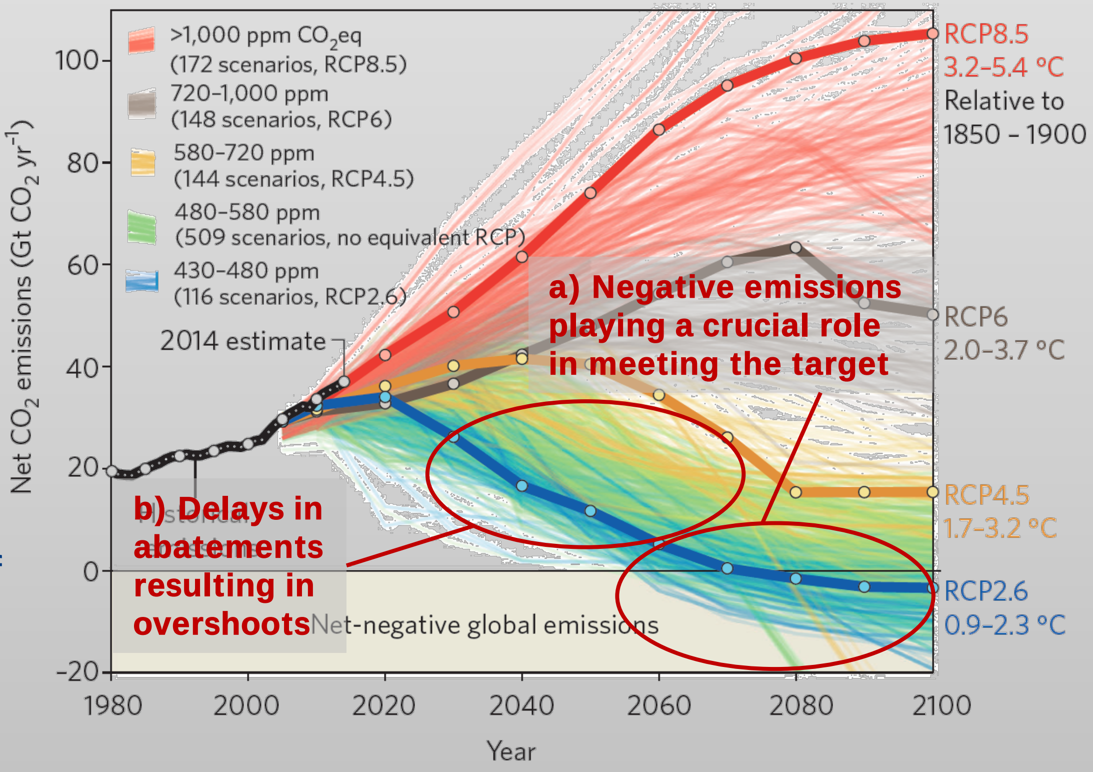
Are we on a pathway toward the 2°C stabilization target?

- 2°C stabilization target endorsed by the Paris Agreement
- Narrowing windows of opportunities to stay below 2°C due to the insufficient INDC pledges
- 2°C stabilization would be more feasible if:

  a. Negative emission technologies are deployable at a sufficiently large scale,

  and

  b. Overshoot does not entail a high risk of reinforcing itself through carbon cycle feedbacks (→ *addressed in this study*).



a) Negative emissions playing a crucial role in meeting the target

b) Delays in abatements resulting in overshoots

After Fuss et al. (2014, *Nature Climate Change*)

INTRODUCTION

Research questions

- **Is it a good strategy to bet on negative emissions to the 2^{o}C target?**

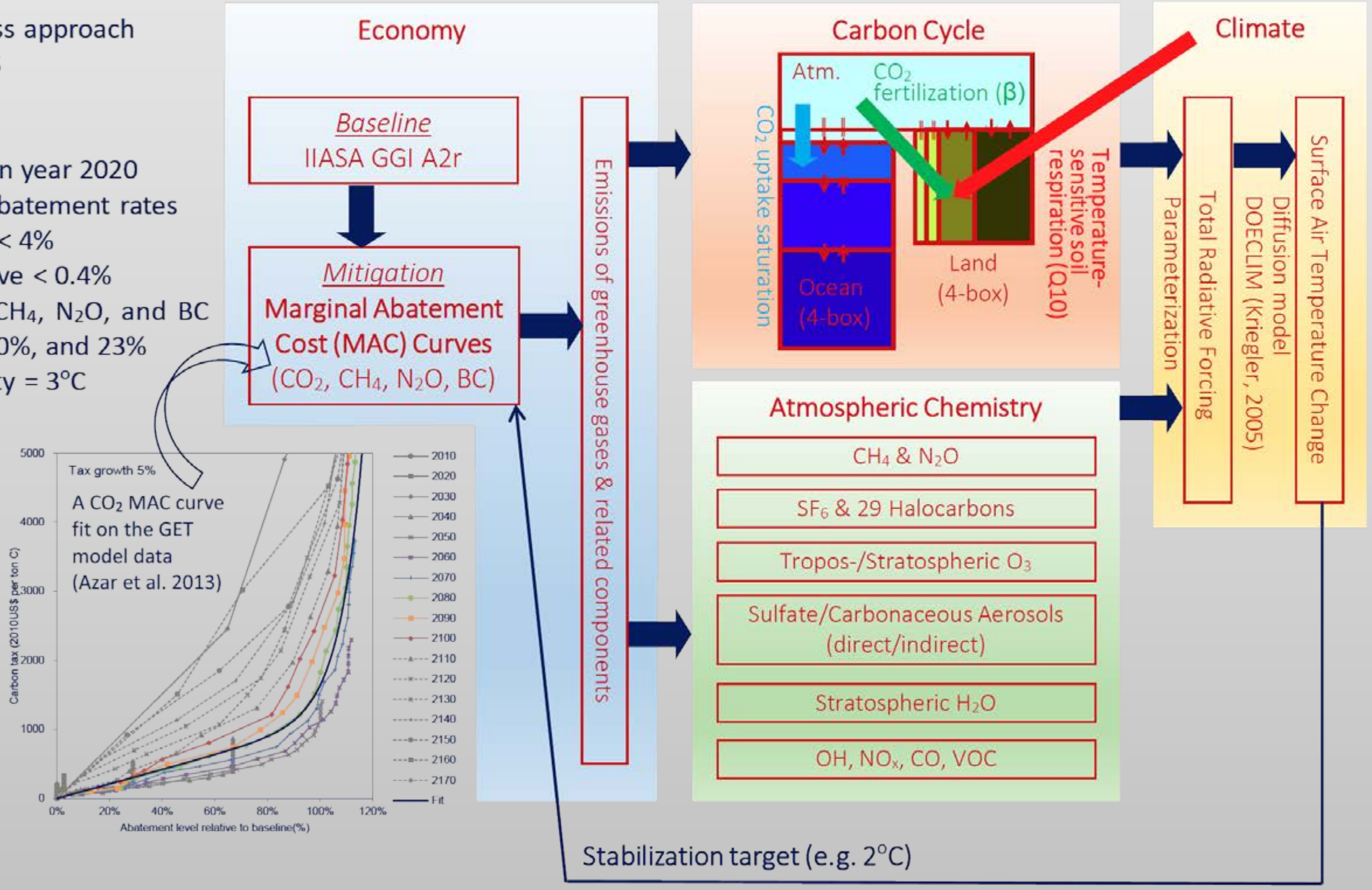
- How are 2^{o}C overshoot pathways and mitigation costs influenced by carbon cycle feedbacks?

METHOD

Setup to compute least-cost stabilization pathways (ACC2 model)

- Cost-effectiveness approach
- Written in GAMS

- 4% discount rate
- Mitigation start in year 2020
- Constraints for abatement rates
  - First derivative < 4%
  - Second derivative < 0.4%
  - Max. for CO_2, CH_4, N_2O, and BC = 112%, 70%, 50%, and 23%
- Climate sensitivity = 3°C



Economy

Baseline
IIASA GGI A2r

Mitigation
Marginal Abatement Cost (MAC) Curves
(CO_2, CH_4, N_2O, BC)

Emissions of greenhouse gases & related components

Carbon Cycle

Atm.

CO_2 fertilization (β)

CO_2 uptake saturation

Ocean (4-box)

Land (4-box)

Temperature-sensitive soil respiration (Q10)

Atmospheric Chemistry

- CH_4 & N_2O
- SF_6 & 29 Halocarbons
- Tropos-/Stratospheric O_3
- Sulfate/Carbonaceous Aerosols (direct/indirect)
- Stratospheric H_2O
- OH, NO_x, CO, VOC

Climate

Parameterization

Total Radiative Forcing

Diffusion model DOECLIM (Kriegler, 2005)

Surface Air Temperature Change

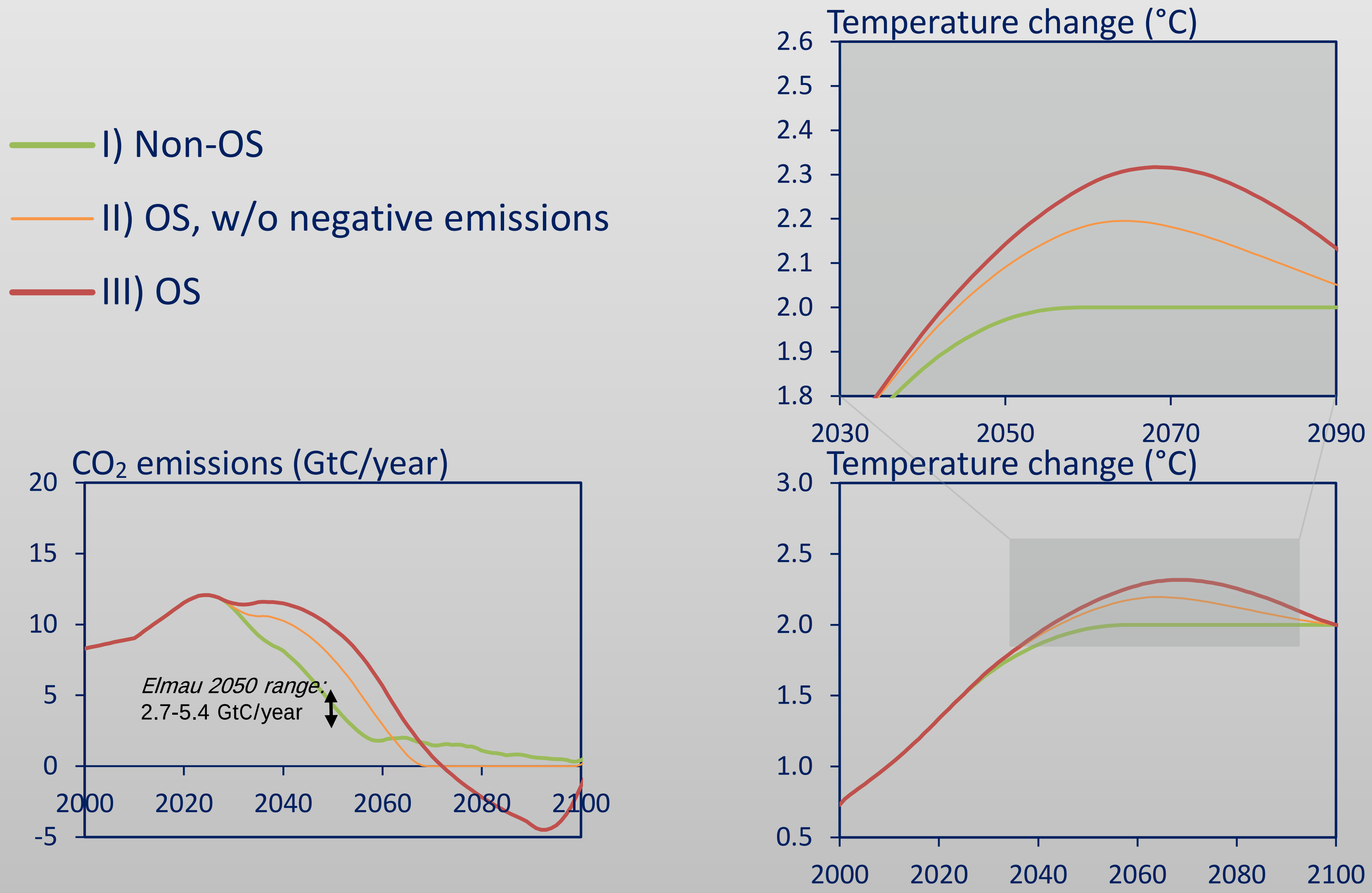
Stabilization target (e.g. 2°C)

A CO_2 MAC curve fit on the GET model data (Azar et al. 2013)

Tanaka, Johansson, O'Neill, Fuglestvedt (2013, *Climatic Change*)

RESULTS I

Characteristics for overshoot pathways (no carbon cycle feedbacks)

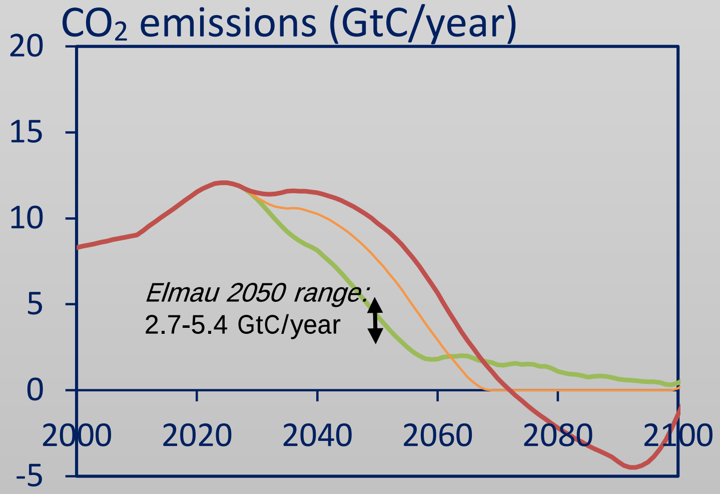


RESULTS I

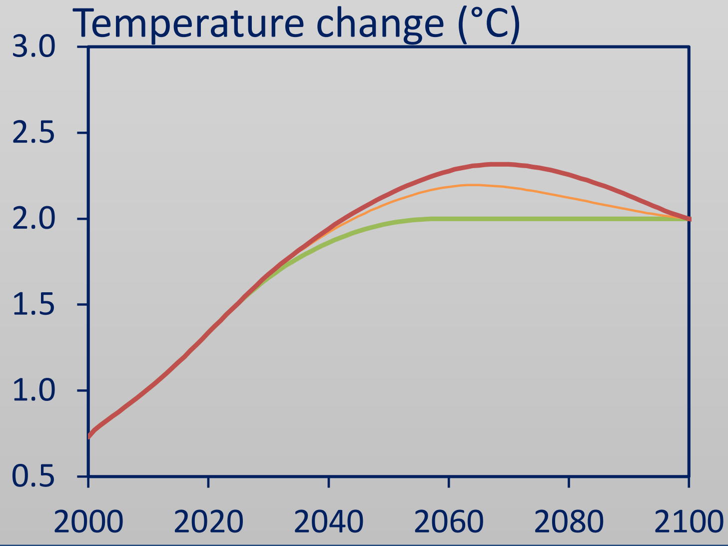
Characteristics for overshoot pathways (no carbon cycle feedbacks)

CONSEQUENCES							
Cumulative CO_2 emissions till 2100 (GtC)	*Costs till 2100 (trillion US$)*					*Intergenerational equity ratio (after 2050/till 2050)*	
	CO_2	N_2O	CH_4	BC	Total	Cumulative CO_2 emissions	Annual costs
— 542	88.8%	1.3%	9.5%	0.3%	36.1	71.1/471	1.78
— 573	88.6%	1.8%	9.4%	0.2%	32.1	59.9/513	3.19
— 566	90.0%	1.5%	8.4%	0.2%	30.3	26.6/540	4.76

— I) Non-OS
— II) OS, w/o negative emissions
— III) OS


CO_2 emissions (GtC/year)

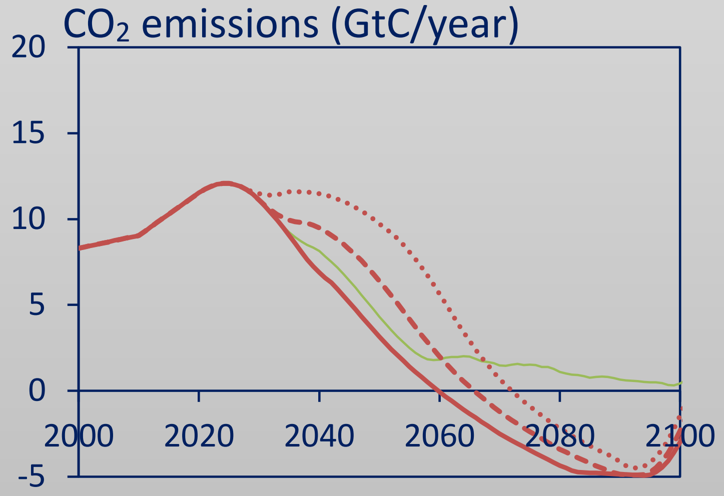
Elmau 2050 range:
2.7-5.4 GtC/year

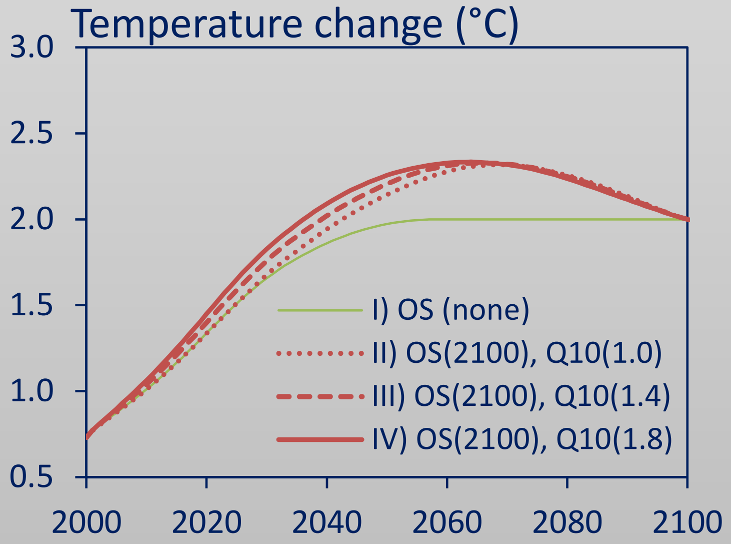

Temperature change (°C)

RESULTS II

Influences of carbon cycle feedbacks on the pathways and costs

Cumulative CO_2 emissions till 2100 (GtC)	*Costs till 2100 (trillion US$)*					*Intergenerational equity ratio (after 2050/till 2050)*			
	CO_2	N_2O	CH_4	BC	Total	Cumulative CO_2 emissions	CH_4 costs fraction	Annual costs	
—— 542	88.8%	1.3%	9.5%	0.3%	36.1	71.1/471	9.9%/8.4%	1.78	—— I) OS (none)
········ 566	90.0%	1.5%	8.4%	0.2%	30.3	26.6/540	8.9%/3.9%	4.76	········ II) OS(2100), Q10(1.0)
- - - - 429	90.2%	1.5%	8.0%	0.2%	40.4	(-68.2)/497	8.9%/3.7%	3.24	- - - - III) OS(2100), Q10(1.4)
━━ 326	90.2%	1.6%	8.0%	0.2%	50.7	(-128.6)/455	9.1%/3.6%	2.34	━━ IV) OS(2100), Q10(1.8)





RESULTS III
Can we bet on negative emissions to stabilize the warming at 2°C?

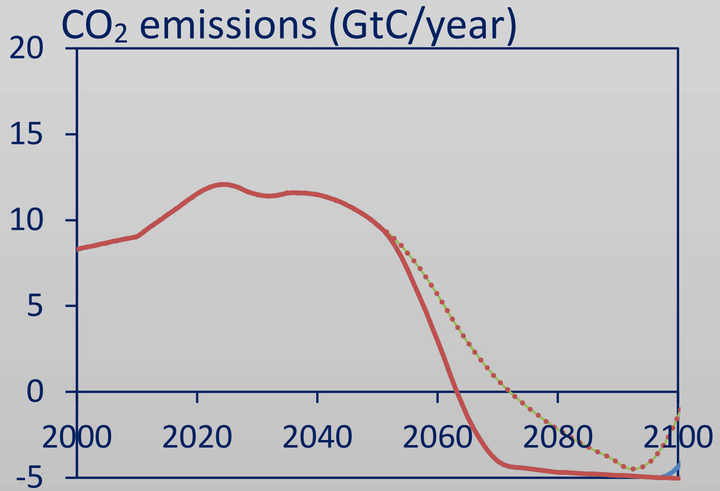
- We actually do not know how strong the carbon cycle feedbacks can be.
- To plan a pathway now, we need to assume a certain feedback strength.
- Then our course of action will be adjusted as the reality unfolds.
- We formulate this problem as a *learning* exercise below.

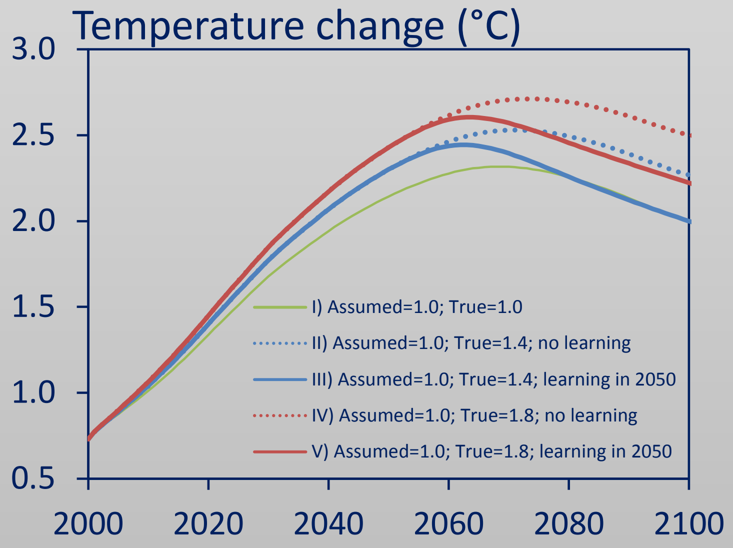
CASES	**Q10**		
	Assumed estimate	*True estimate*	*Correction in 2050*
I	1.0	1.0	No
II	1.0	1.4	No
III	1.0	1.4	Yes
IV	1.0	1.8	No
V	1.0	1.8	Yes

RESULTS III

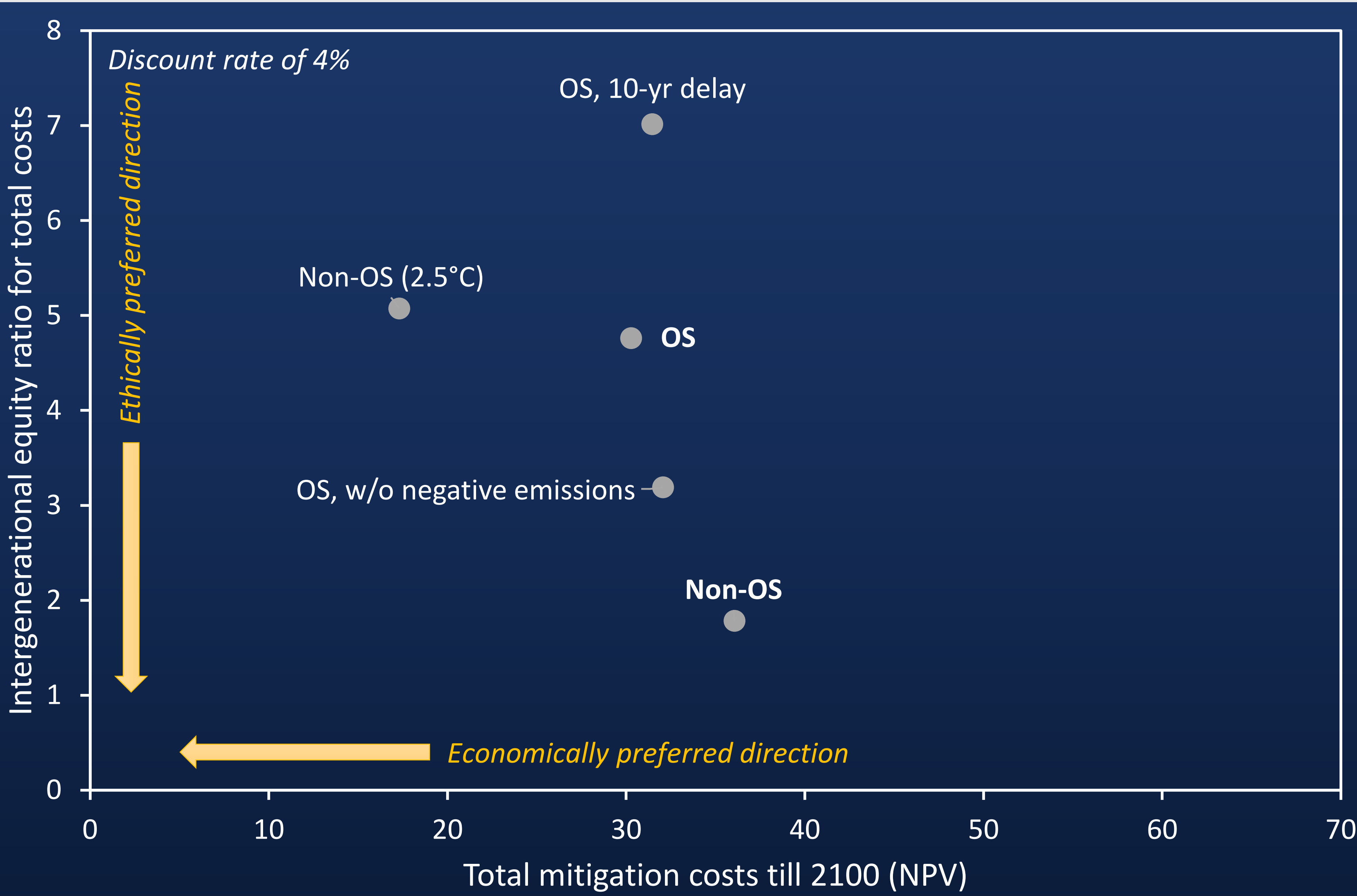
Can we bet on negative emissions to stabilize the warming at 2°C?

Cumulative CO_2 emissions till 2100 (GtC)	*Costs till 2100 (trillion US$)*					*Intergenerational equity ratio (after 2050/till 2050)*			
	CO_2	N_2O	CH_4	BC	Total	Cumulative CO_2 emissions	CH_4 costs fraction	Annual costs	
—— 566	90.0%	1.5%	8.4%	0.2%	30.3	26.6/540	8.9%/3.9%	4.76	—— I) Assumed=1.0; True=1.0
········ —	—	—	—	—	—	—	—	—	········ II) Assumed=1.0; True=1.4; no learning
—— 449	84.4%	2.9%	12.5%	0.1%	43.4	(-90.5)/540	13.2%/3.9%	7.09	—— III) Assumed=1.0; True=1.4; learning in 2050
········ —	—	—	—	—	—	—	—	—	········ IV) Assumed=1.0; True=1.8; no learning
—— ~~448~~	~~84.1%~~	~~3.0%~~	~~12.7%~~	~~0.1%~~	~~43.7~~	~~(-91.6)/540~~	~~13.4%/3.9%~~	~~7.13~~	—— V) Assumed=1.0; True=1.8; learning in 2050

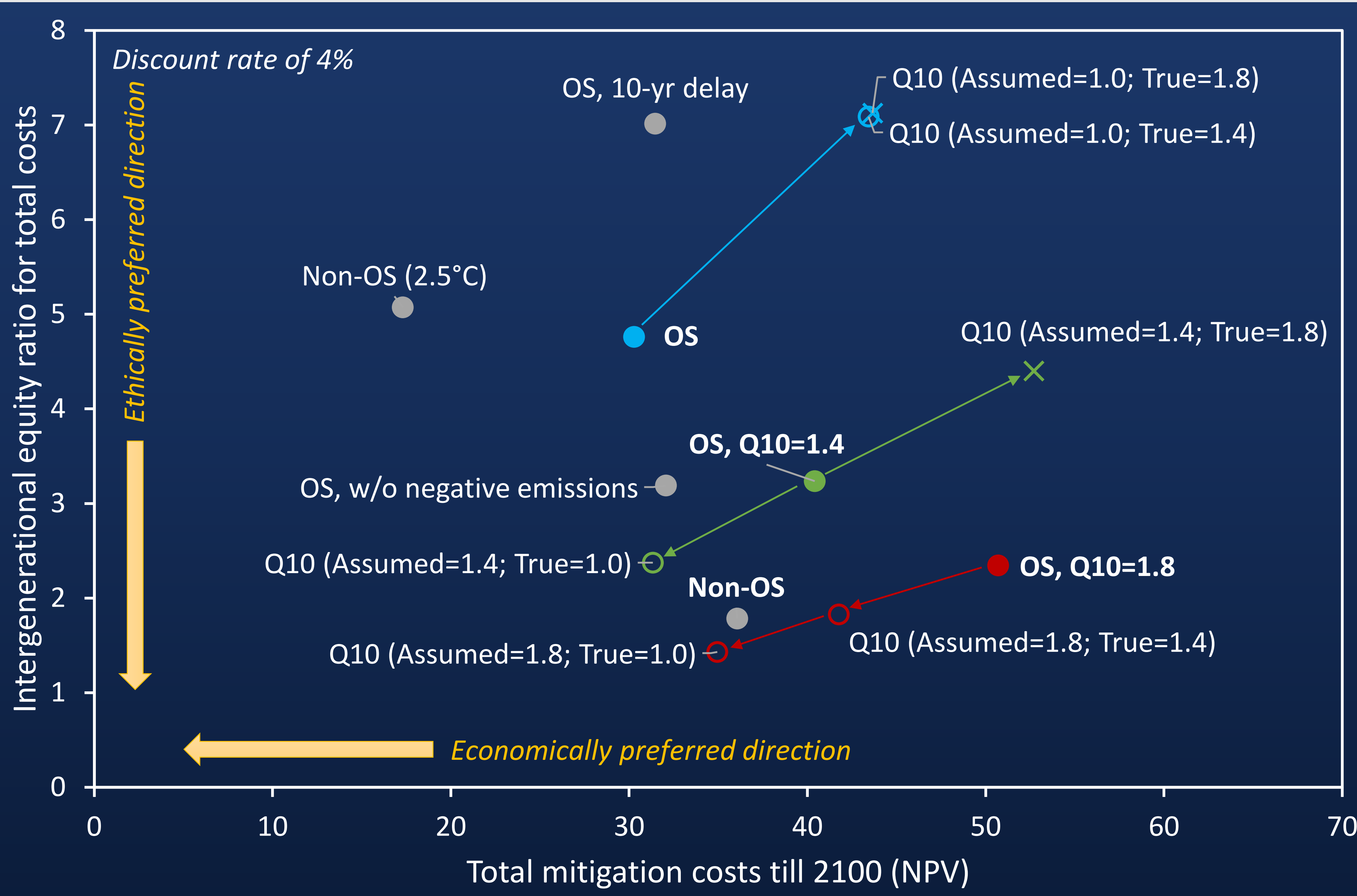




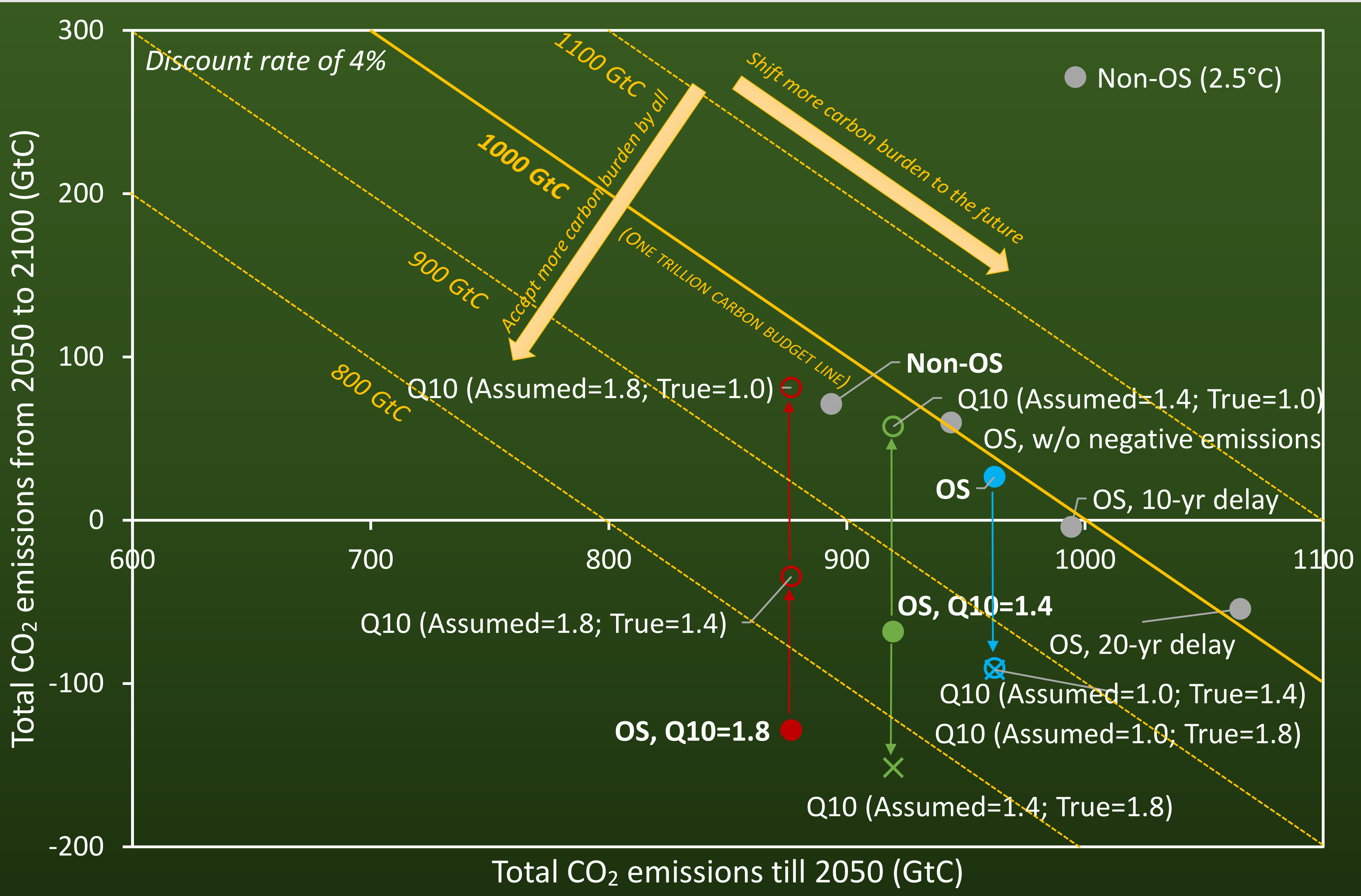
COST EQUITY CHART: Which strategy makes sense? (w/o C-CC feedbacks)



COST EQUITY CHART: Which strategy makes sense? (w/ C-CC feedbacks)



EMISSION EQUITY CHART: Which strategy makes sense?



CONCLUDING REMARKS

- Given the narrowing windows of opportunities to stay below 2°C, allowing overshoot gives more flexibility to reach the target.
- Accepting overshoot reduces the costs to achieve the stabilization target. This, however, came at the expense of future generations. Overshoot shifts the burden to the future.
- Can we bet on negative emissions to achieve the 2°C target? It depends.
    - If carbon cycle feedbacks are known to be weak, it makes sense to aim for a non-overshoot pathway.
    - If the feedback strength is a priori unknown, it is fair to assume strong feedbacks. It is inevitable to accept an overshoot pathway.

      (It may end up with the same costs and degree of inequality with a non-overshoot case if the feedbacks turn out to be insignificant.)

WAYS FORWARD

- While our simple and transparent approach captures first-order processes and feedbacks and allows one to explore ideas with minimal time and costs, it misses out more detailed aspects of the problem: namely, damage, adaptation, spatial heterogeneity, land constraint, and competition with food.

- Our study highlights the importance of considering “learning” when one evaluates strategic options and their consequences under uncertainty.

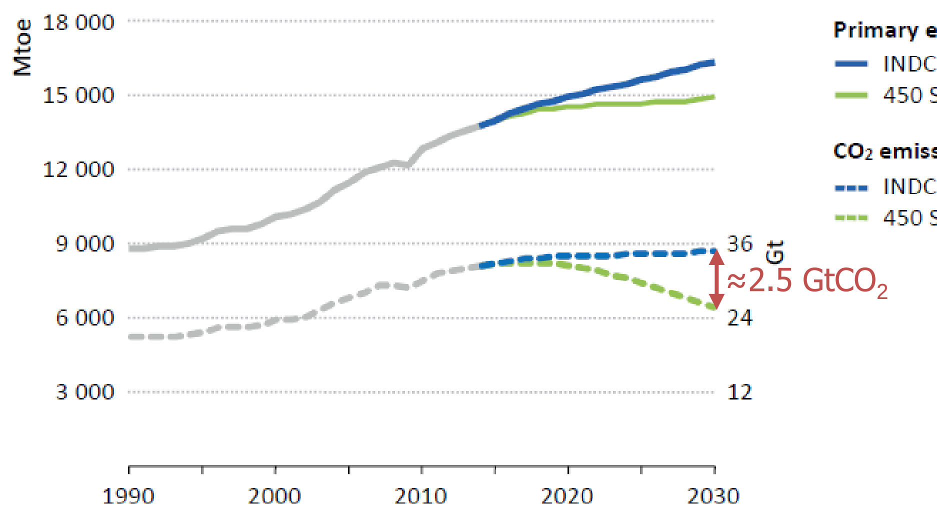
- Our *simple* approach illuminates a need for investigating this issue further by using a range of models including coupled Earth System Model (ESM)-Integrated Assessment Models (IAMs).

Appendix

SIDELINE

INDCs and their implications to global emissions

Figure 2.1 ▷ **Global primary energy demand and related CO_2 emissions by scenario**



An indication:
If we aim for 2°C stabilization, it must go through an overshoot?

Figure 2.3 ▷ **Global energy-related CO_2 emissions in the INDC Scenario and remaining carbon budget for a >50% chance of keeping to 2 °C**

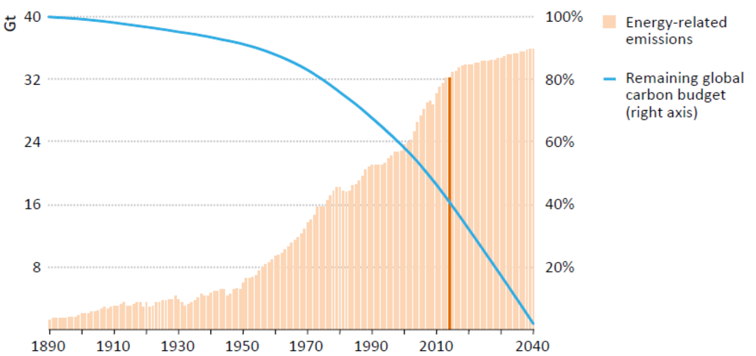
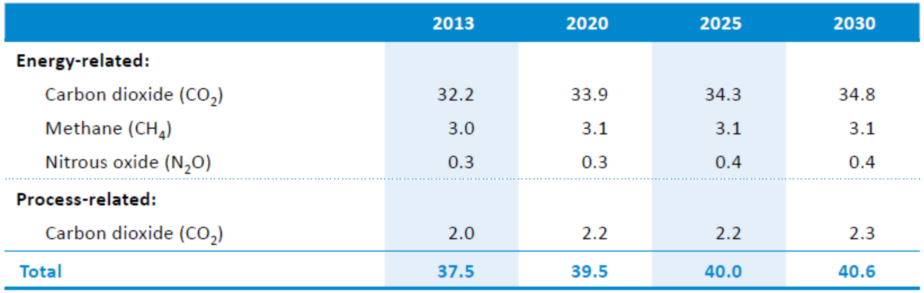


Table 2.1 ▷ **Global energy- and process-related greenhouse-gas emissions in the INDC Scenario** (Gt CO_2-eq)

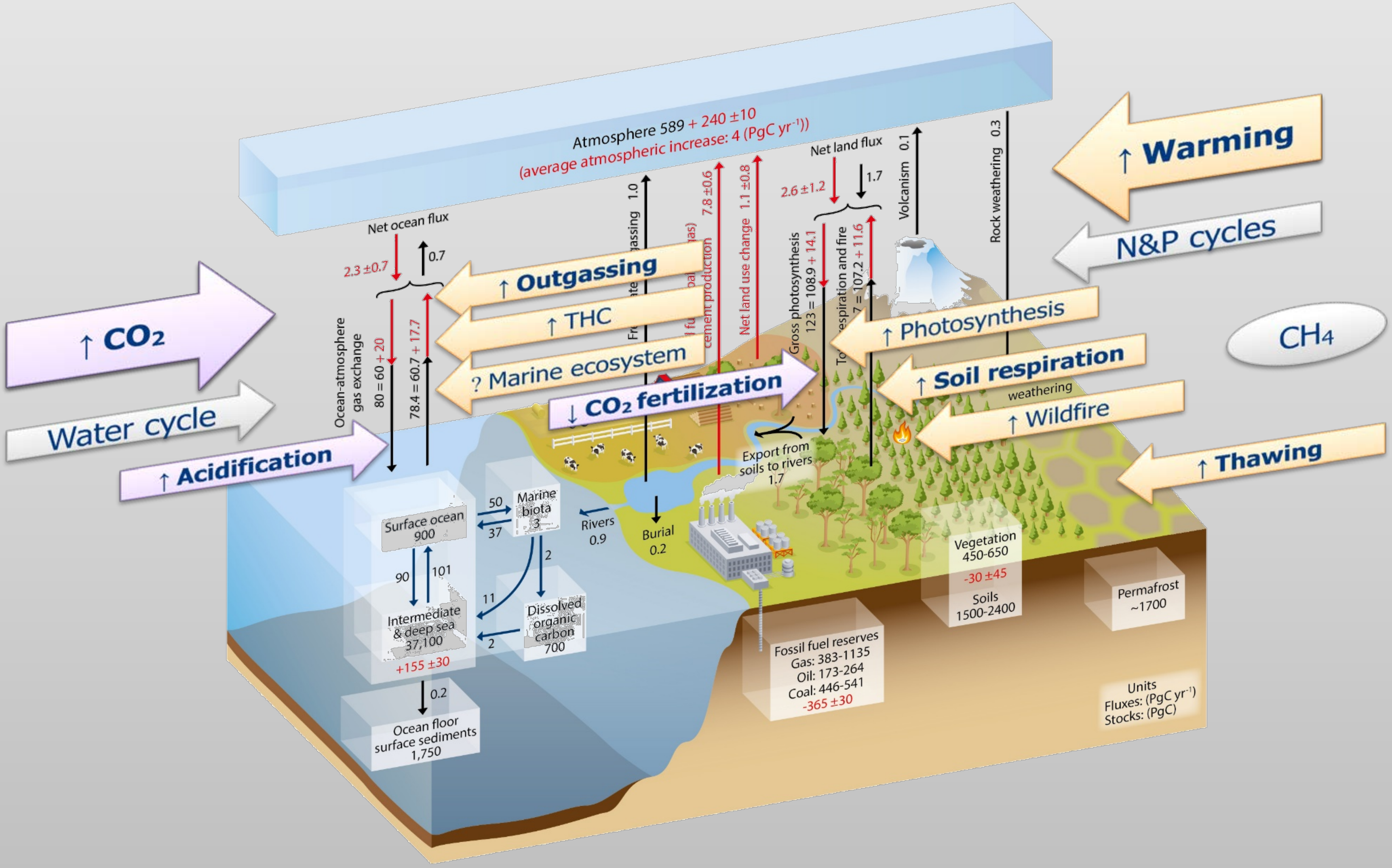


	2013	2020	2025	2030
Energy-related:				
Carbon dioxide (CO_2)	32.2	33.9	34.3	34.8
Methane (CH_4)	3.0	3.1	3.1	3.1
Nitrous oxide (N_2O)	0.3	0.3	0.4	0.4
Process-related:				
Carbon dioxide (CO_2)	2.0	2.2	2.2	2.3
Total	**37.5**	**39.5**	**40.0**	**40.6**

IEA Energy and Climate Change
(2015, Table 2.1 and Figures 2.1 and 2.3)

BACKGROUND II: CARBON CYCLE FEEDBACKS

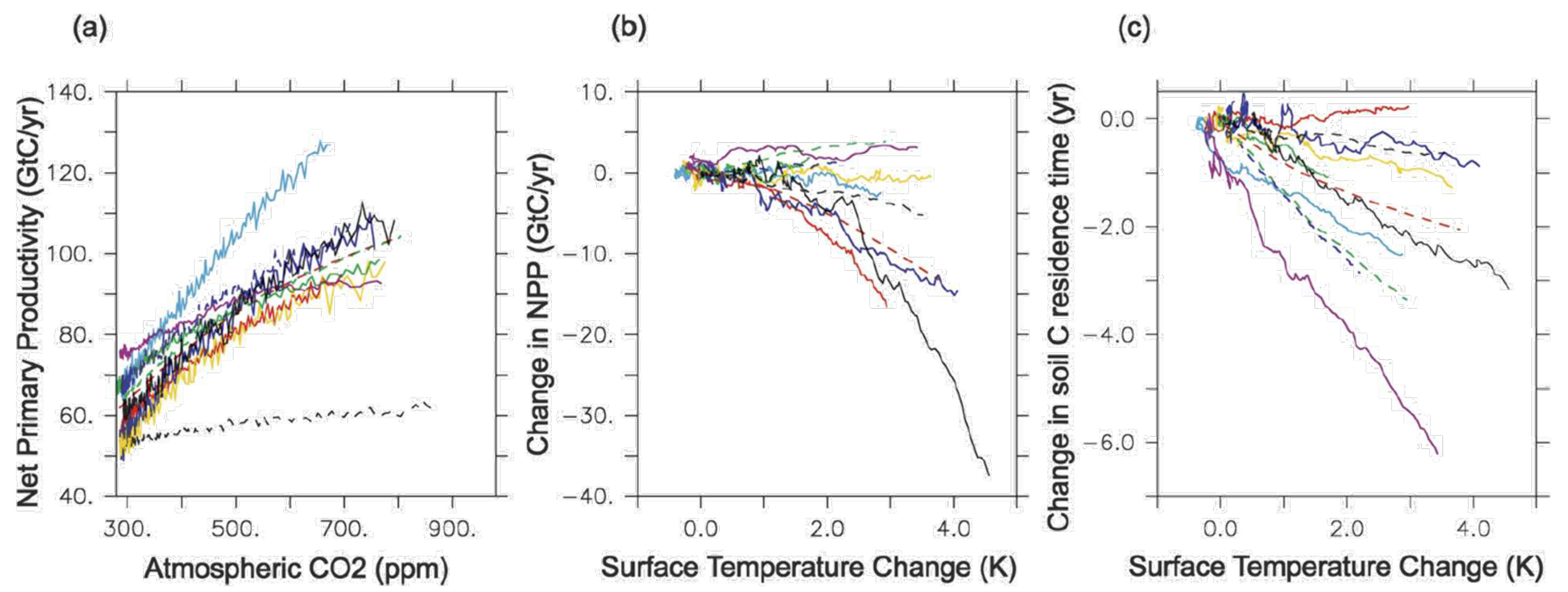
Global carbon cycle and associated feedbacks



BACKGROUND II: CARBON CYCLE FEEDBACKS

Terrestrial carbon cycle feedbacks

- The overshoot in the mid-century might amplify itself by strengthening climate-carbon cycle feedbacks.
- Such feedbacks are known to be positive albeit with large uncertainties.



Friedlingstein et al. (2006, *Journal of Climate*)

Parameter estimation

- Simulation length: year 1750 – 2000, annual time step
- Parameters (e.g. CO_2 emissions, beta factor, Q10, climate sensitivity)
- Data (e.g. Atmospheric CO_2/CH_4/N_2O concentration, temperature)
- Minimize squared deviations weighted by prior uncertainties

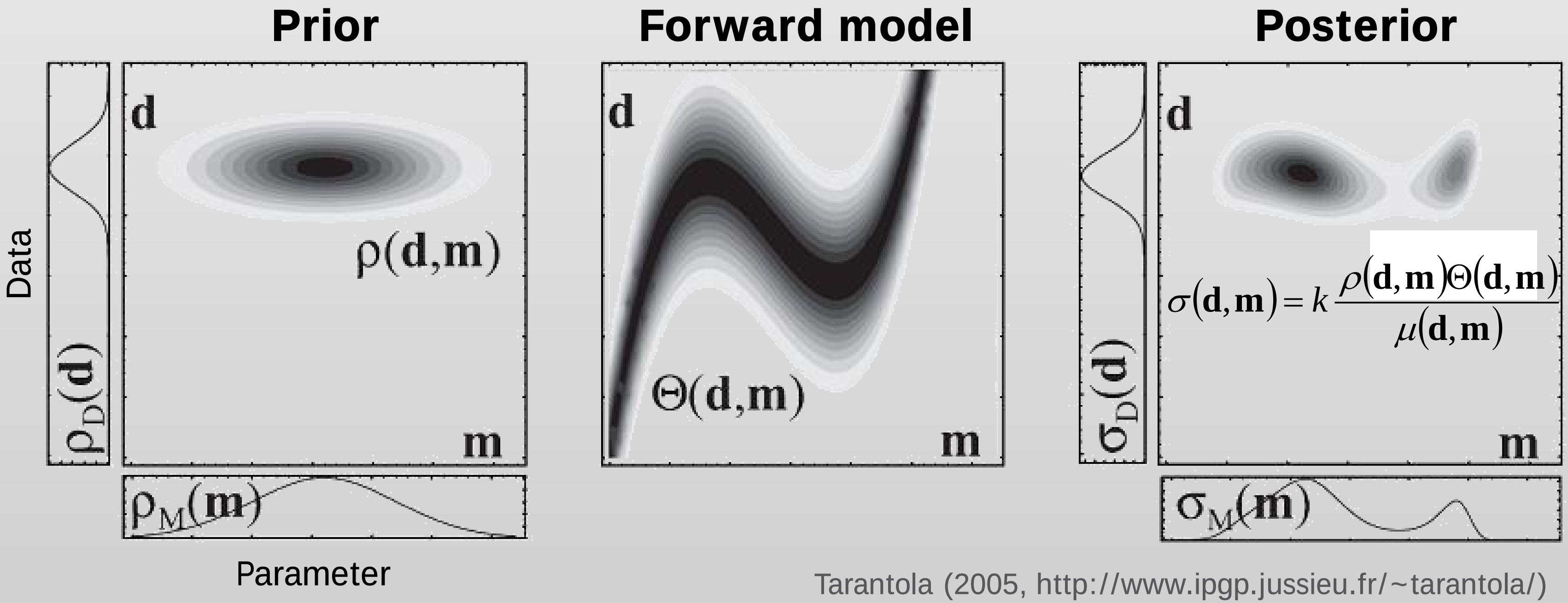
$$S(\mathbf{m}) = \frac{1}{2}\left(\sum_{i=1}^{a} \left(\frac{g_i(\mathbf{m}) - d_{mes,i}}{\sigma_{d,i}} \right)^2 + \sum_{j=1}^{b} \left(\frac{m_j - m_{prior,j}}{\sigma_{m,j}} \right)^2 \right)$$

- Major assumptions
  - Gaussian errors
  - Independent errors
  - No structural uncertainty

- Parameters estimated in the inversion are used for future projections.

Tanaka, Raddatz, O'Neill, and Reick (2009, *Geophysical Research Letters*)

Probabilistic Inverse Estimation Theory



Tarantola (2005, http://www.ipgp.jussieu.fr/~tarantola/)

$$\sigma_{\mathrm{M}}(\mathbf{m}) = \int_{\mathcal{D}} k \frac{\rho(\mathbf{d},\mathbf{m})\sigma(\mathbf{d},\mathbf{m})}{\mu(\mathbf{d},\mathbf{m})} d\mathbf{d}$$

$\Downarrow$ *Gaussian errors, no structural uncertainties*

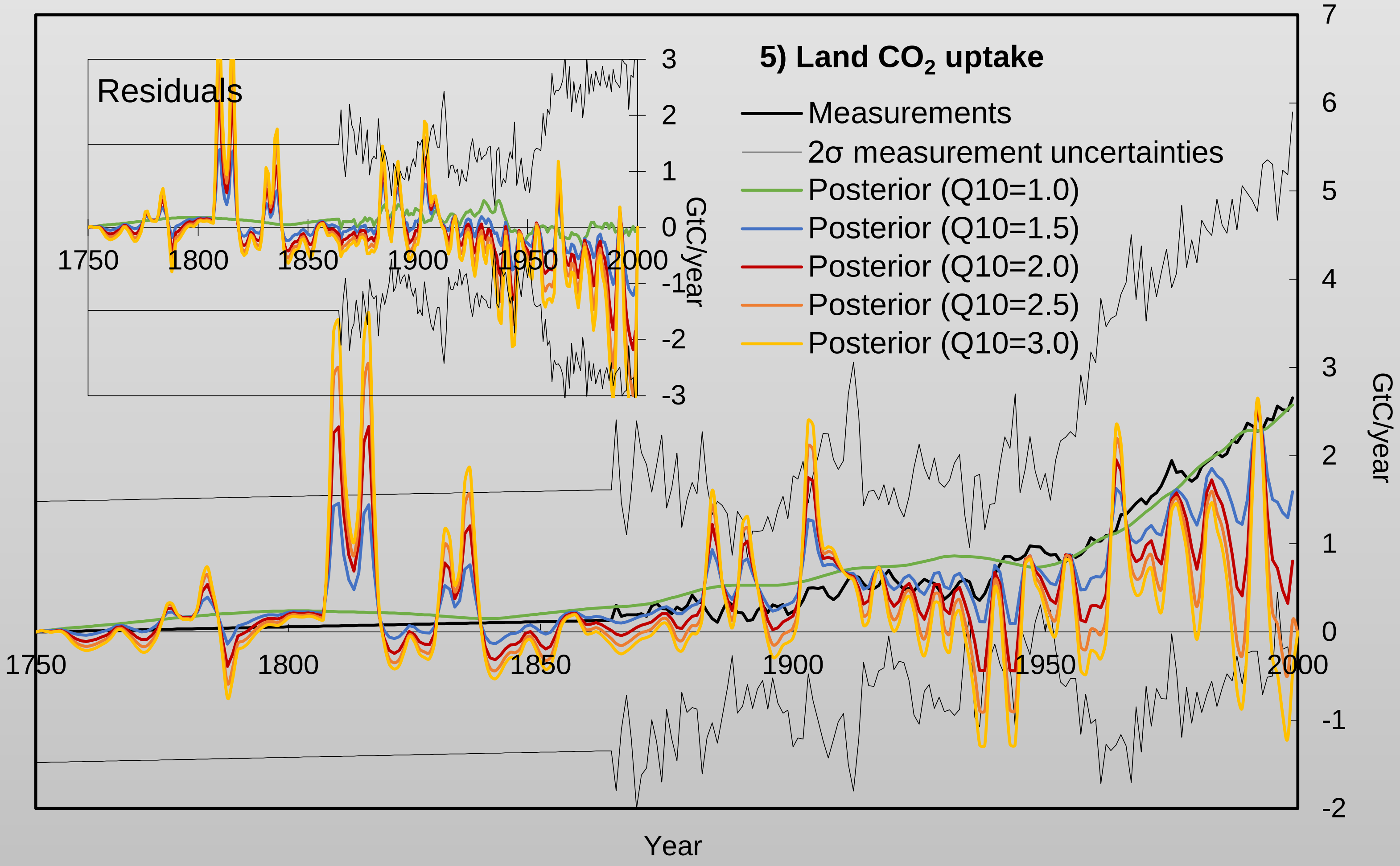
$$\sigma_{\mathrm{M}}(\mathbf{m}) = k' \exp(-S(\mathbf{m})) \quad \text{where} \quad S(\mathbf{m}) = \frac{1}{2}\left(\left(\mathbf{g}(\mathbf{m}) - \mathbf{d}_{mes}\right)^T \mathbf{C}_{\mathrm{D}}^{-1}\left(\mathbf{g}(\mathbf{m}) - \mathbf{d}_{mes}\right) + \left(\mathbf{m} - \mathbf{m}_{prior}\right)^T \mathbf{C}_{\mathrm{M}}^{-1}\left(\mathbf{m} - \mathbf{m}_{prior}\right)\right)$$

$\Downarrow$ *Independent errors*

$$\sigma_{\mathrm{M}}(\mathbf{m}) = k' \exp(-S(\mathbf{m})) \quad \text{where} \quad S(\mathbf{m}) = \frac{1}{2}\left(\sum_{i=1}^{a}\left(\frac{g_i(\mathbf{m}) - d_{mes,i}}{\sigma_{d,i}}\right)^2 + \sum_{j=1}^{b}\left(\frac{m_j - m_{prior,j}}{\sigma_{m,j}}\right)^2\right)$$

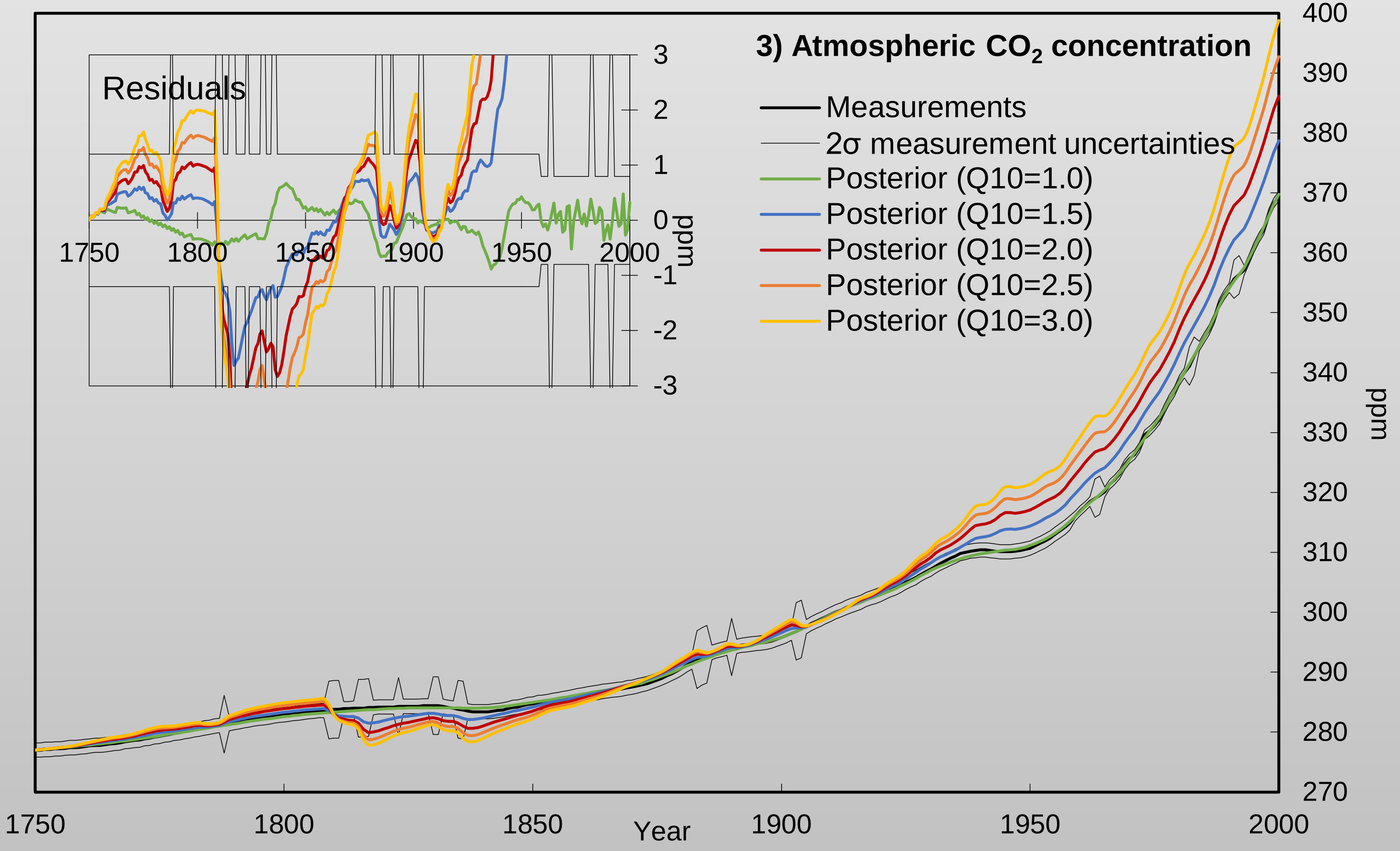
BACKGROUND II: CARBON CYCLE FEEDBACKS

Q10=3.0 means net CO_2 outgassing from land (if all the others intact).



BACKGROUND II: CARBON CYCLE FEEDBACKS

Q10=3.0 means net CO_2 outgassing from land (if all the others intact).



Background II: Carbon cycle feedbacks
Only relatively small overshoots considered before

- We consider larger overshoots to explore what carbon cycle feedbacks might play out.

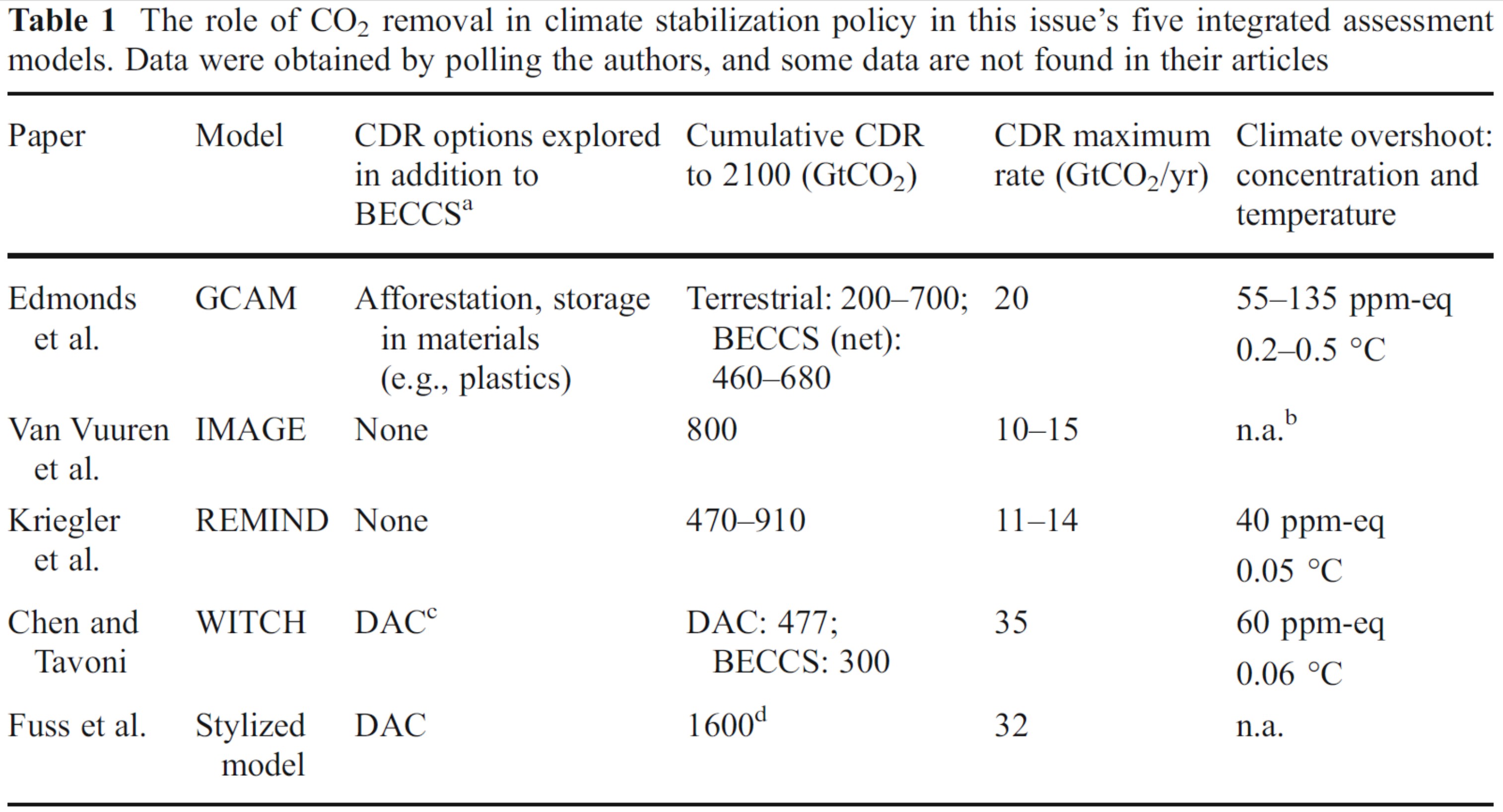
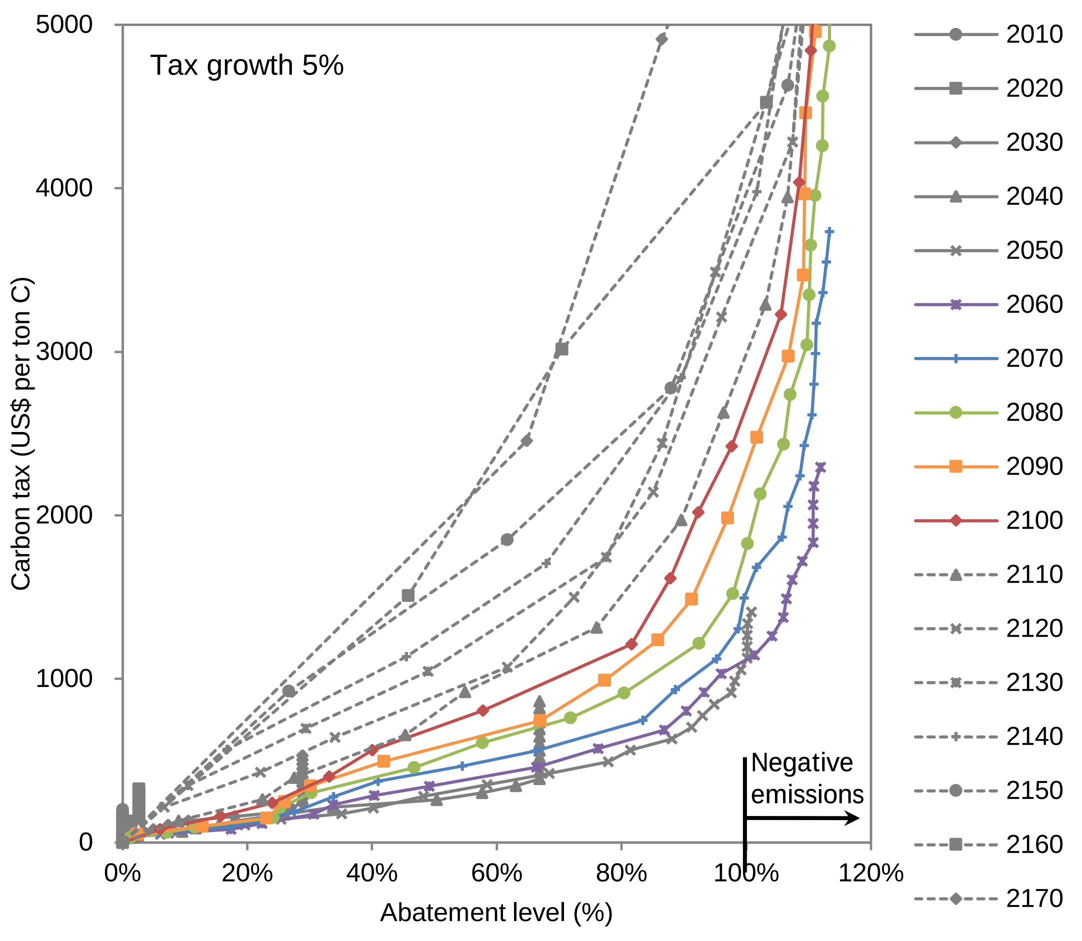


Table 1 The role of CO_2 removal in climate stabilization policy in this issue's five integrated assessment models. Data were obtained by polling the authors, and some data are not found in their articles

Paper	Model	CDR options explored in addition to BECCS[a]	Cumulative CDR to 2100 ($GtCO_2$)	CDR maximum rate ($GtCO_2$/yr)	Climate overshoot: concentration and temperature
Edmonds et al.	GCAM	Afforestation, storage in materials (e.g., plastics)	Terrestrial: 200–700; BECCS (net): 460–680	20	55–135 ppm-eq 0.2–0.5 °C
Van Vuuren et al.	IMAGE	None	800	10–15	n.a.[b]
Kriegler et al.	REMIND	None	470–910	11–14	40 ppm-eq 0.05 °C
Chen and Tavoni	WITCH	DAC[c]	DAC: 477; BECCS: 300	35	60 ppm-eq 0.06 °C
Fuss et al.	Stylized model	DAC	1600[d]	32	n.a.

Tavoni and Socolow (2013, *Climatic Change*)

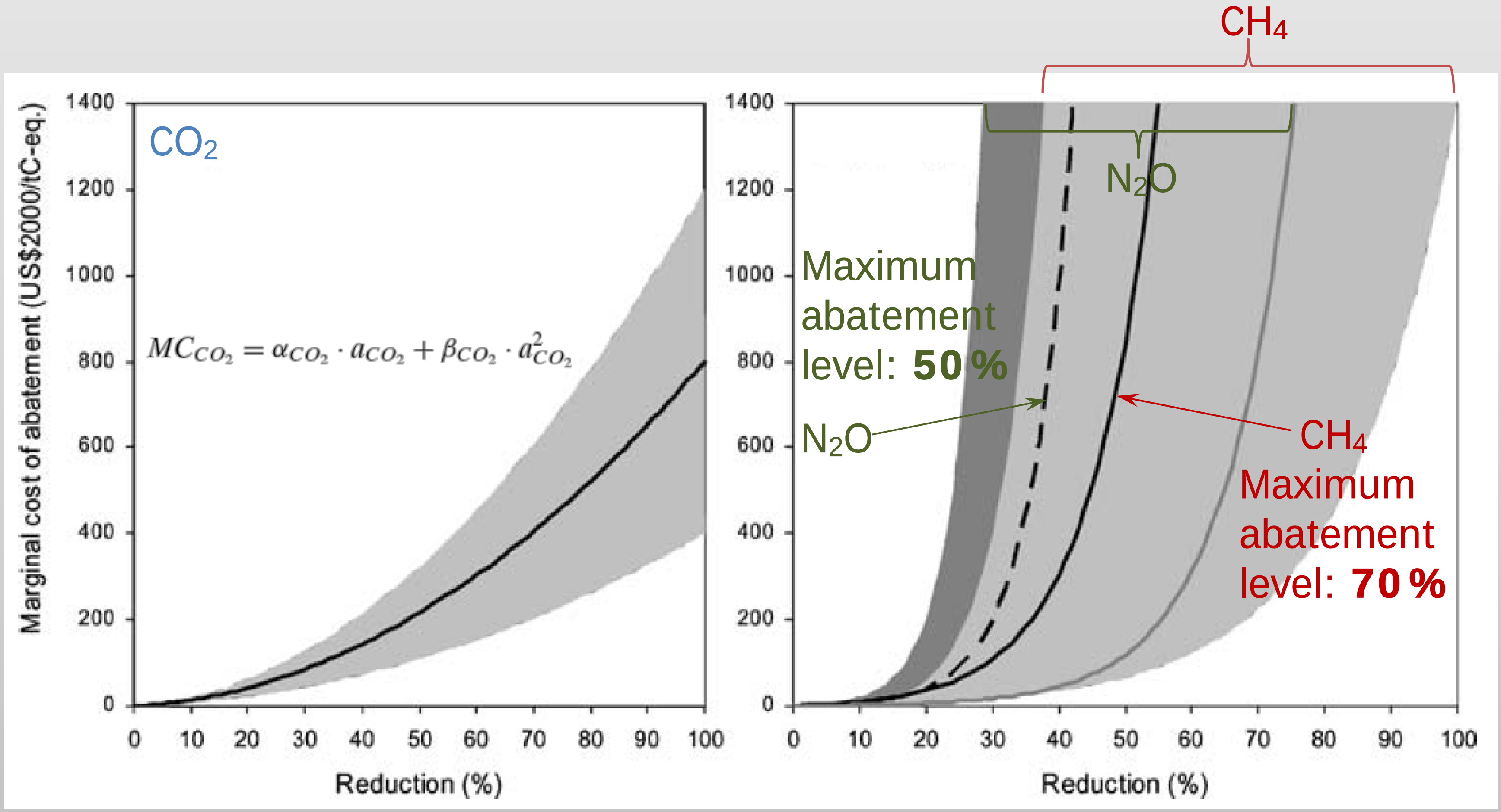
METHOD
Marginal Abatement Cost (MAC) curve: model-based derivation



Tanaka et al. (*unpublished*); Based on Azar et al. (2013, *Environmental Research Letters*)

METHOD

Marginal Abatement Cost (MAC) curves for CO_2, CH_4, and N_2O



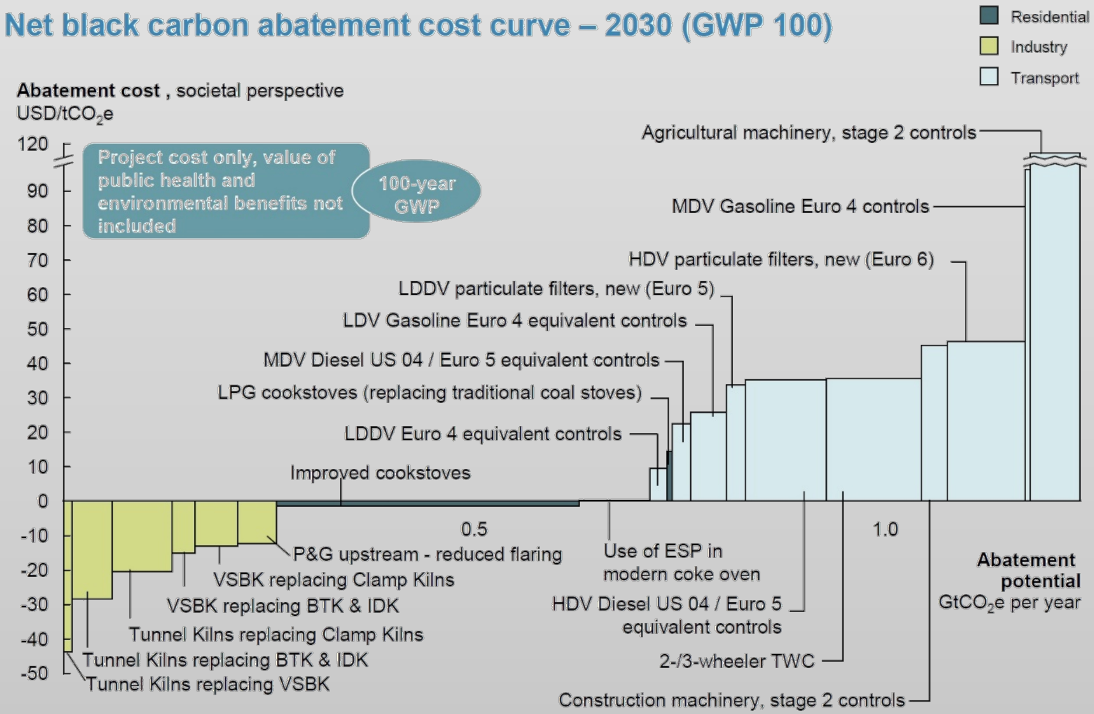
Maximum abatement level: **50%**

Maximum abatement level: **70%**

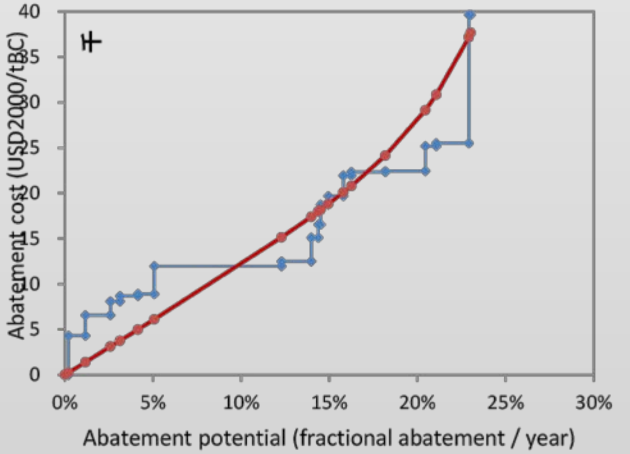
Johansson et al. (2006, *Climatic Change*)
Daniel Johansson (*personal communication*, 31 March 2015)

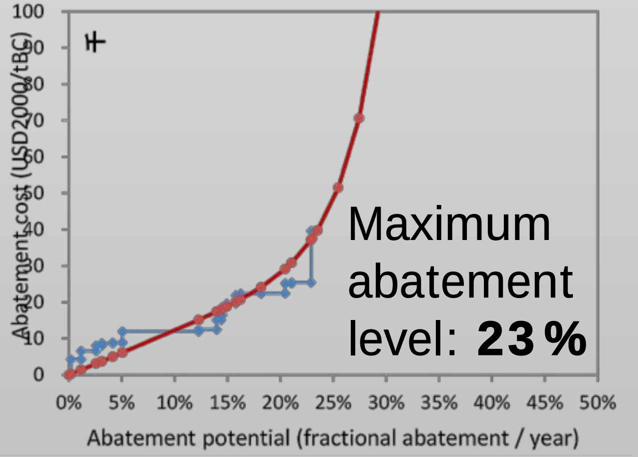
METHOD

Marginal Abatement Cost (MAC) curves for BC



Climate Works (2011, Exhibit 23)

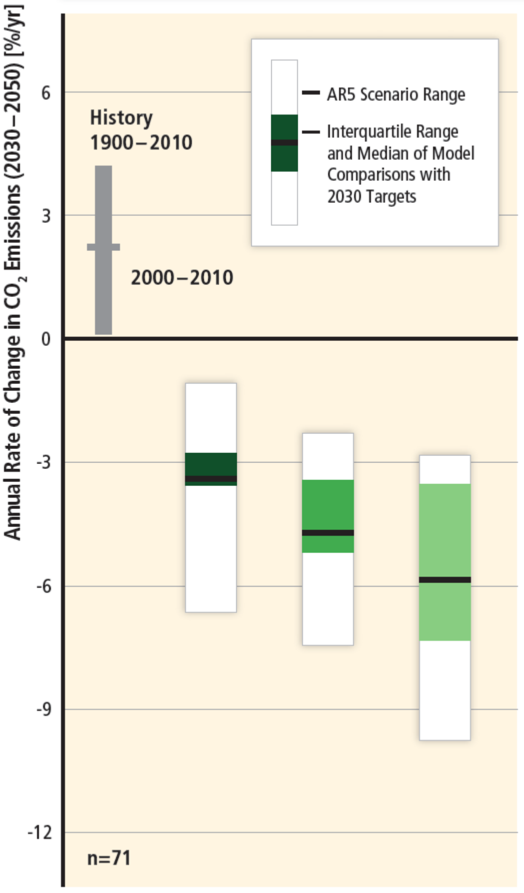


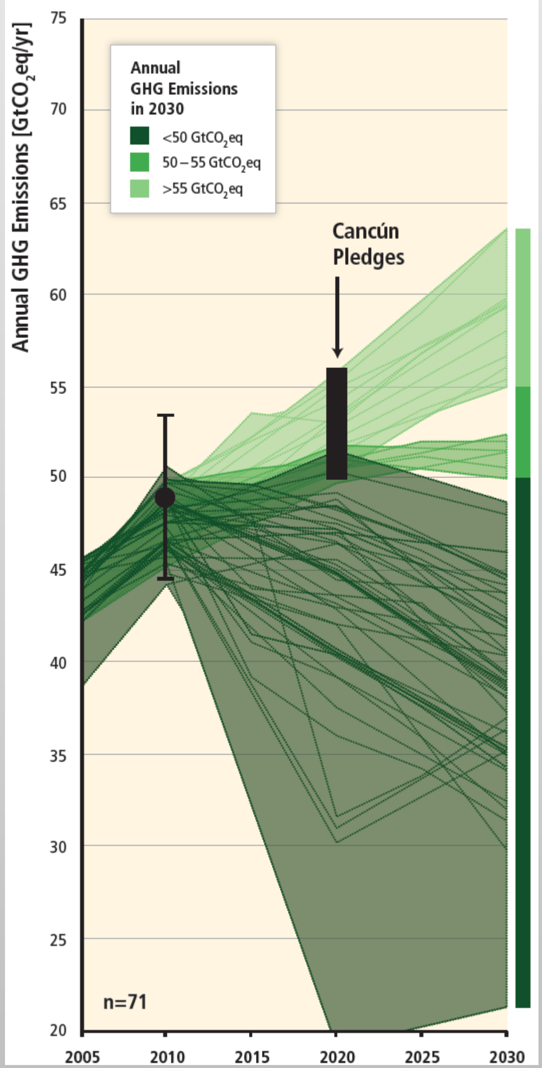


Maximum abatement level: **23 %**

METHOD
Maximum change in the abatement rate

- Assumed maximum change in the abatement rate:
  - **4% per year** (default)
  - 6% per year (sensitivity case)
  - 8% per year (sensitivity case)

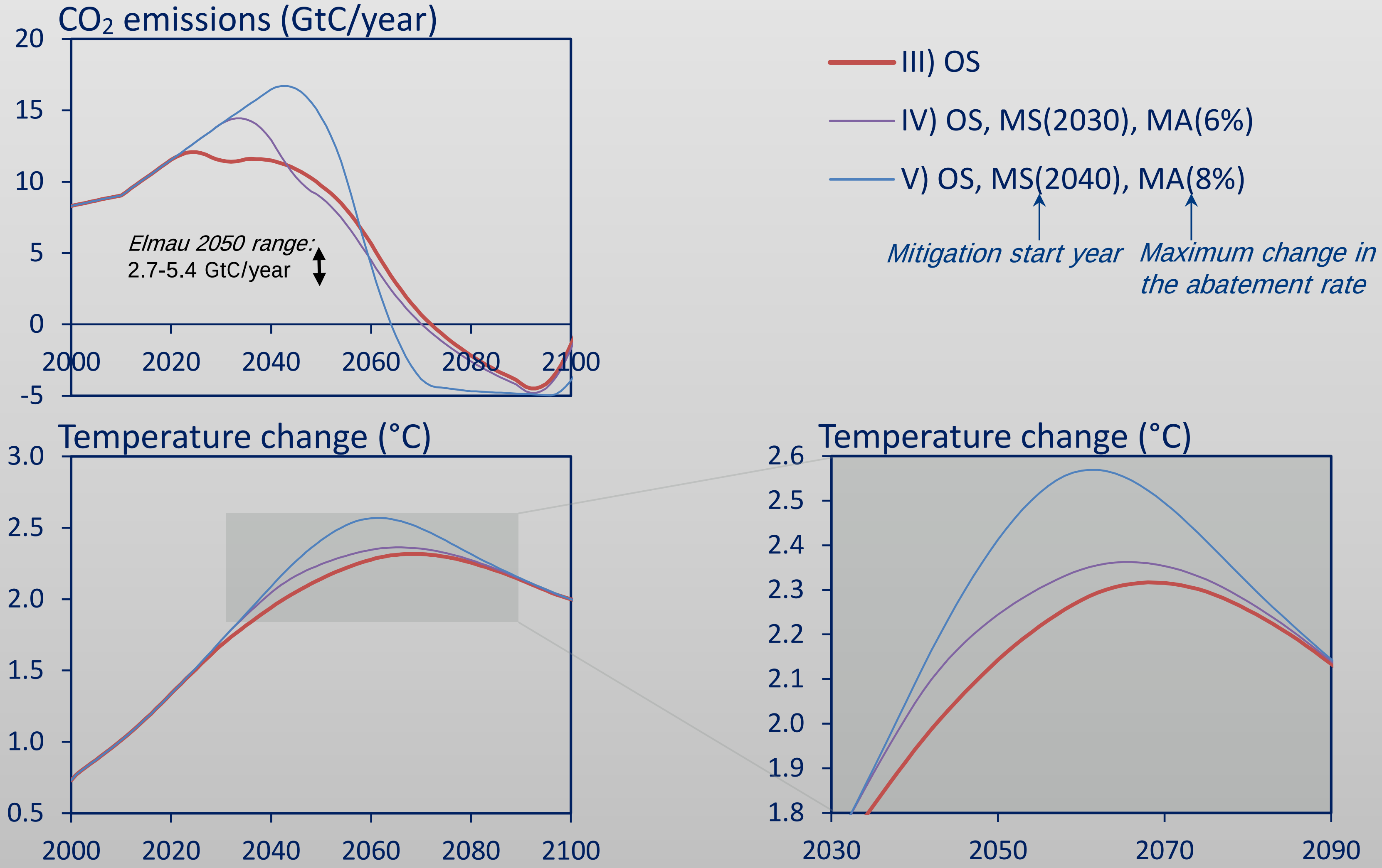




After Figure SPM.5 of IPCC AR5 WG3 (2014)

RESULTS I

Advantages and disadvantages for negative emissions



Elmau 2050 range:
2.7-5.4 GtC/year

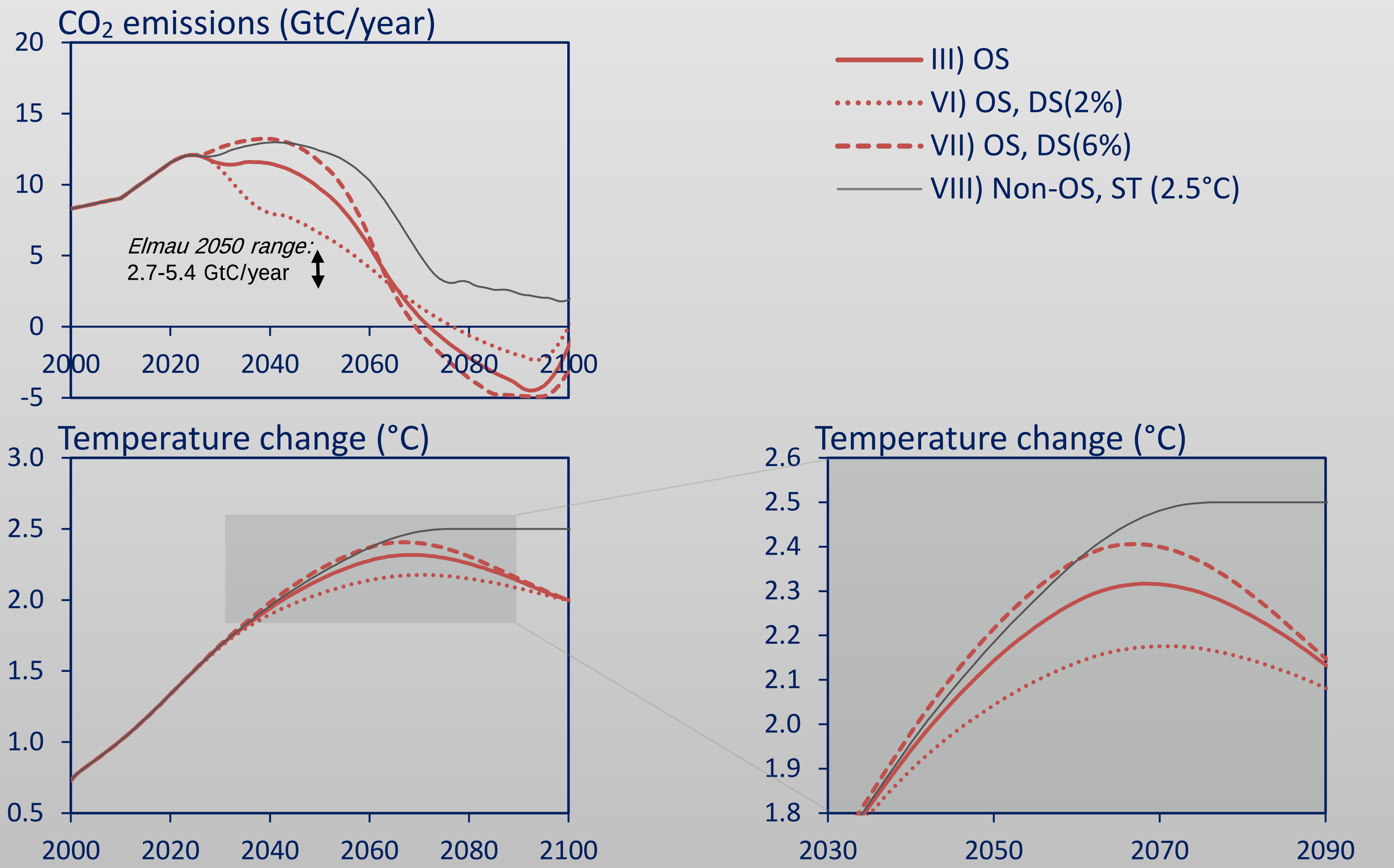
III) OS
IV) OS, MS(2030), MA(6%)
V) OS, MS(2040), MA(8%)

Mitigation start year

Maximum change in the abatement rate

RESULTS I

Advantages and disadvantages for negative emissions



CO$_2$ emissions (GtC/year)

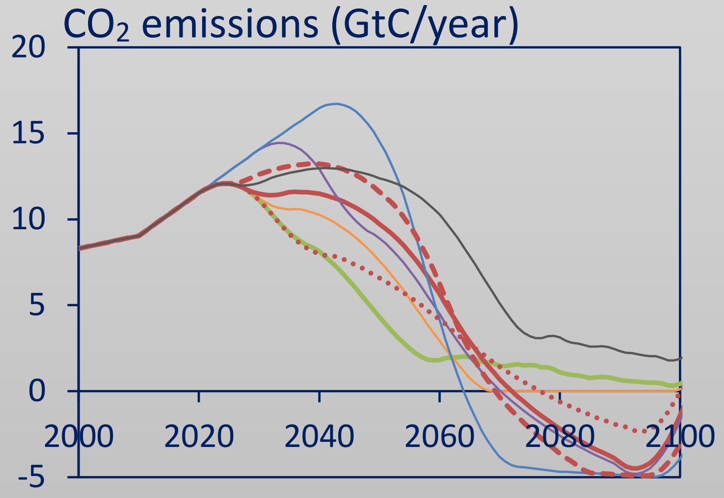
Elmau 2050 range:
2.7-5.4 GtC/year

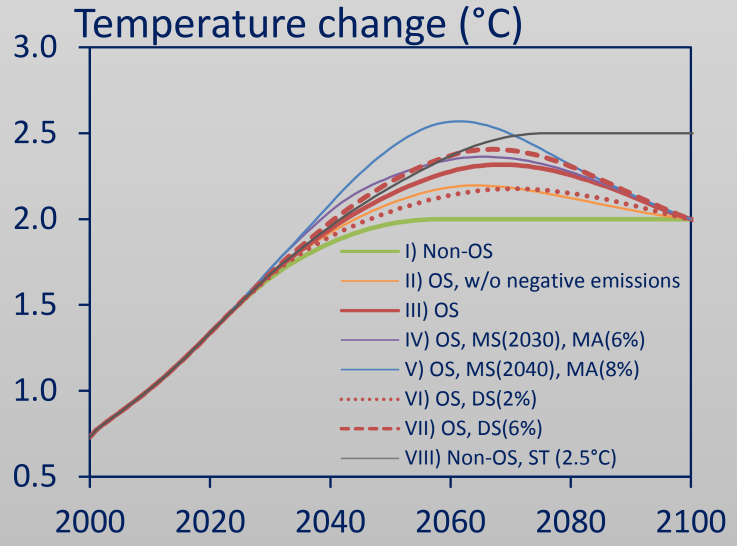
Temperature change (°C)

Temperature change (°C)

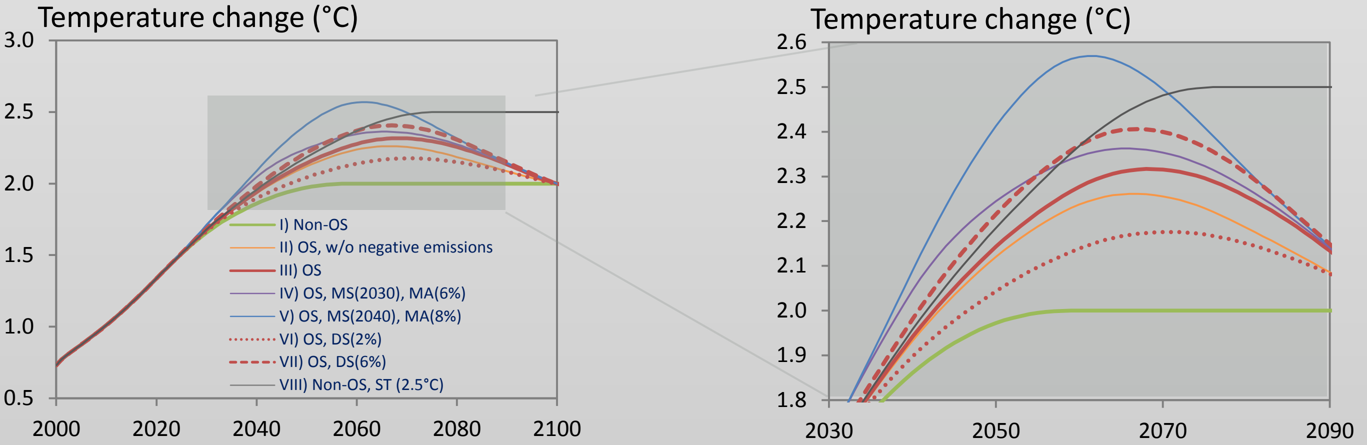
RESULTS I
Advantages and disadvantages for negative emissions

Stabilization year	*Cumulative CO₂ emissions till 2100 (GtC)*	*Costs till 2100 (trillion US$)*					*Intergenerational equity ratio (after 2050/till 2050)*			
		CO₂	N₂O	CH₄	BC	Total	Cumulative CO₂ emissions	CH₄ costs fraction	Annual costs	
2060	542	88.8%	1.3%	9.5%	0.3%	36.1	71.1/471	9.9%/8.4%	1.78	I) Non-OS
2100	573	88.6%	1.8%	9.4%	0.2%	32.1	59.9/513	10.5%/3.4%	3.19	II) OS, w/o negative emissions
2100	566	90.0%	1.5%	8.4%	0.2%	30.3	26.6/540	8.9%/3.9%	4.76	III) OS
2100	568	90.0%	1.4%	8.4%	0.2%	31.5	(-4.2)/572	8.9%/3.7%	7.01	IV) OS, MS(2030), MA(6%)
2100	589	84.9%	2.6%	12.4%	0.1%	37.1	(-54.4)/643	12.4%/2.4%	143.94	V) OS, MS(2040), MA(8%)
2100	534	92.6%	1.3%	5.9%	0.2%	124.5	51.0/482	6.5%/2.2%	3.84	VI) OS, DS(2%)
2100	578	89.4%	1.8%	8.6%	0.2%	7.7	0.7/577	9.0%/5.7%	5.58	VII) OS, DS(6%)
2078	845	88.4%	1.7%	9.6%	0.3%	17.3	271/574	9.8%/8.3%	5.07	VIII) Non-OS, ST (2.5°C)

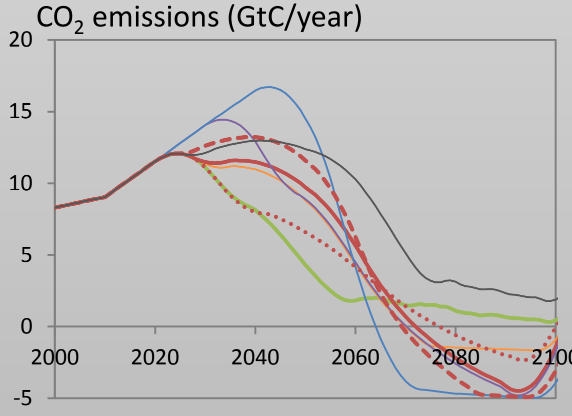

CO₂ emissions (GtC/year)

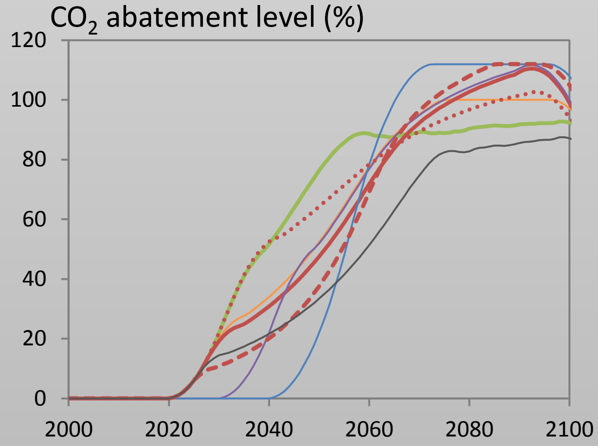

Temperature change (°C)

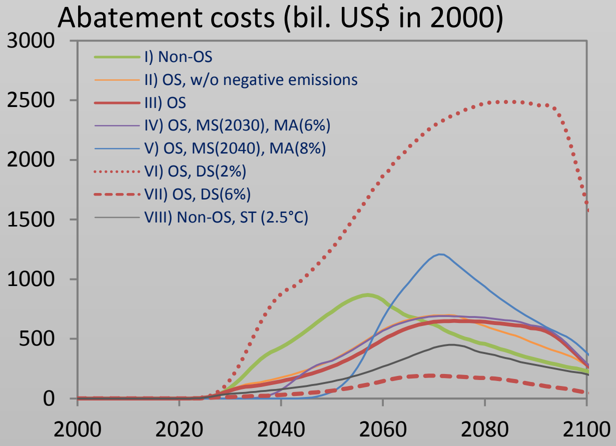
Stabilization year	*Cumulative CO_2 emissions till 2100 (GtC)*	*Costs till 2100 (trillion US$)*					*Intergenerational equity ratio (after 2050/till 2050)*			
		CO_2	N_2O	CH_4	BC	Total	Cumulative CO_2 emissions	CH_4 costs fraction	Annual costs	
— 2060	542	88.8%	1.3%	9.5%	0.3%	36.1	71.1/471	9.9%/8.4%	1.78	— I) Non-OS
— 2100	573	88.6%	1.8%	9.4%	0.2%	32.1	59.9/513	10.5%/3.4%	3.19	— II) OS, w/o negative emissions
— 2100	566	90.0%	1.5%	8.4%	0.2%	30.3	26.6/540	8.9%/3.9%	4.76	— III) OS
— 2100	568	90.0%	1.4%	8.4%	0.2%	31.5	(-4.2)/572	8.9%/3.7%	7.01	— IV) OS, MS(2030), MA(6%)
— 2100	589	84.9%	2.6%	12.4%	0.1%	37.1	(-54.4)/643	12.4%/2.4%	143.94	— V) OS, MS(2040), MA(8%)
⋯ 2100	534	92.6%	1.3%	5.9%	0.2%	124.5	51.0/482	6.5%/2.2%	3.84	⋯ VI) OS, DS(2%)
- - - 2100	578	89.4%	1.8%	8.6%	0.2%	7.7	0.7/577	9.0%/5.7%	5.58	- - - VII) OS, DS(6%)
— 2078	845	88.4%	1.7%	9.6%	0.3%	17.3	271/574	9.8%/8.3%	5.07	— VIII) Non-OS, ST (2.5°C)


Temperature change (°C)

Temperature change (°C)

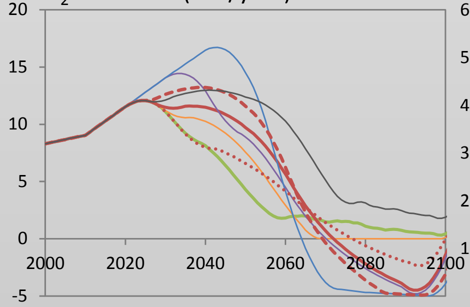

CO_2 emissions (GtC/year)


CO_2 abatement level (%)

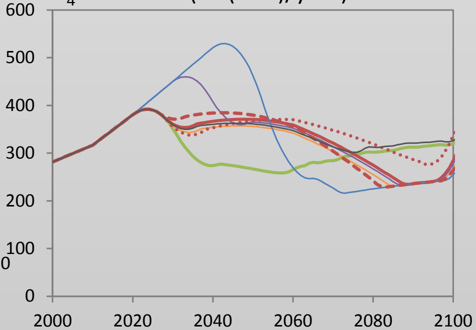

Abatement costs (bil. US$ in 2000)

Stabilization year	*Cumulative CO_2 emissions till 2100 (GtC)*	*Costs till 2100 (trillion US$)*					*Intergenerational equity ratio (after 2050/till 2050)*			
		CO_2	N_2O	CH_4	BC	Total	Cumulative CO_2 emissions	CH_4 costs fraction	Annual costs	
2060	542	88.8%	1.3%	9.5%	0.3%	36.1	71.1/471	9.9%/8.4%	1.78	I) Non-OS
2100	573	88.6%	1.8%	9.4%	0.2%	32.1	59.9/513	10.5%/3.4%	3.19	II) OS, w/o negative emissions
2100	566	90.0%	1.5%	8.4%	0.2%	30.3	26.6/540	8.9%/3.9%	4.76	III) OS
2100	568	90.0%	1.4%	8.4%	0.2%	31.5	(-4.2)/572	8.9%/3.7%	7.01	IV) OS, MS(2030), MA(6%)
2100	589	84.9%	2.6%	12.4%	0.1%	37.1	(-54.4)/643	12.4%/2.4%	143.94	V) OS, MS(2040), MA(8%)
2100	534	92.6%	1.3%	5.9%	0.2%	124.5	51.0/482	6.5%/2.2%	3.84	VI) OS, DS(2%)
2100	578	89.4%	1.8%	8.6%	0.2%	7.7	0.7/577	9.0%/5.7%	5.58	VII) OS, DS(6%)
2078	845	88.4%	1.7%	9.6%	0.3%	17.3	271/574	9.8%/8.3%	5.07	VIII) Non-OS, ST (2.5°C)

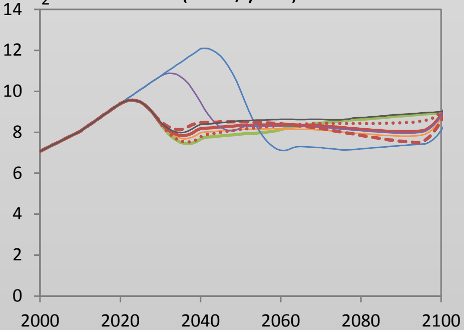
CO_2 emissions (GtC/year)



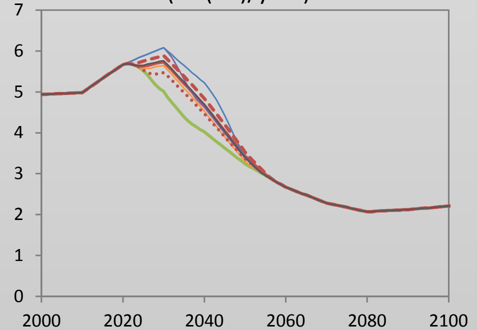
CH_4 emissions (Mt(CH4)/year)



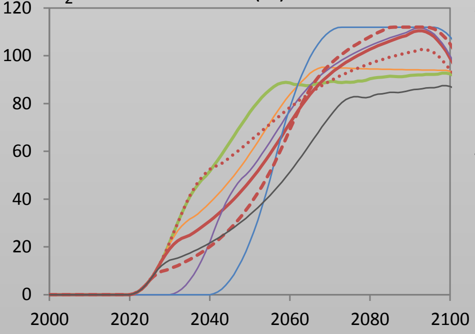
N_2O emissions (MtN/year)



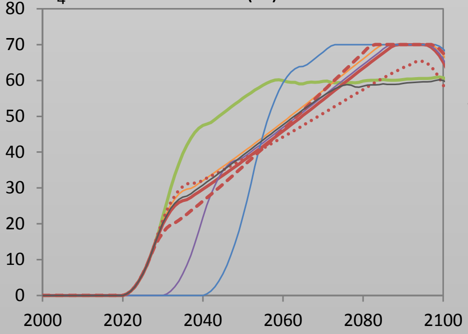
BC emissions (Mt(BC)/year)



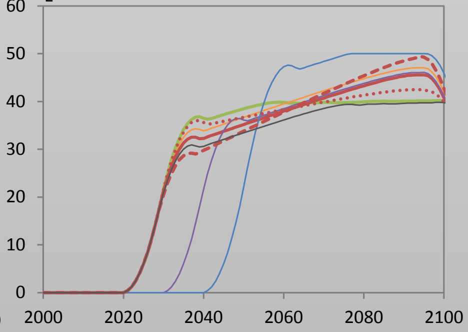
CO_2 abatement level (%)



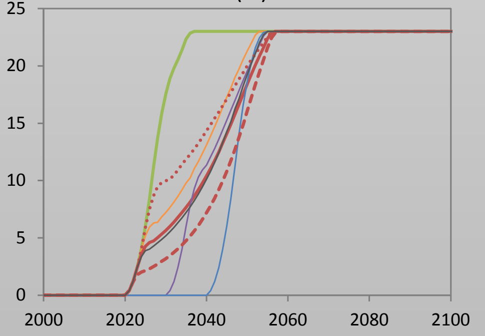
CH_4 abatement level (%)



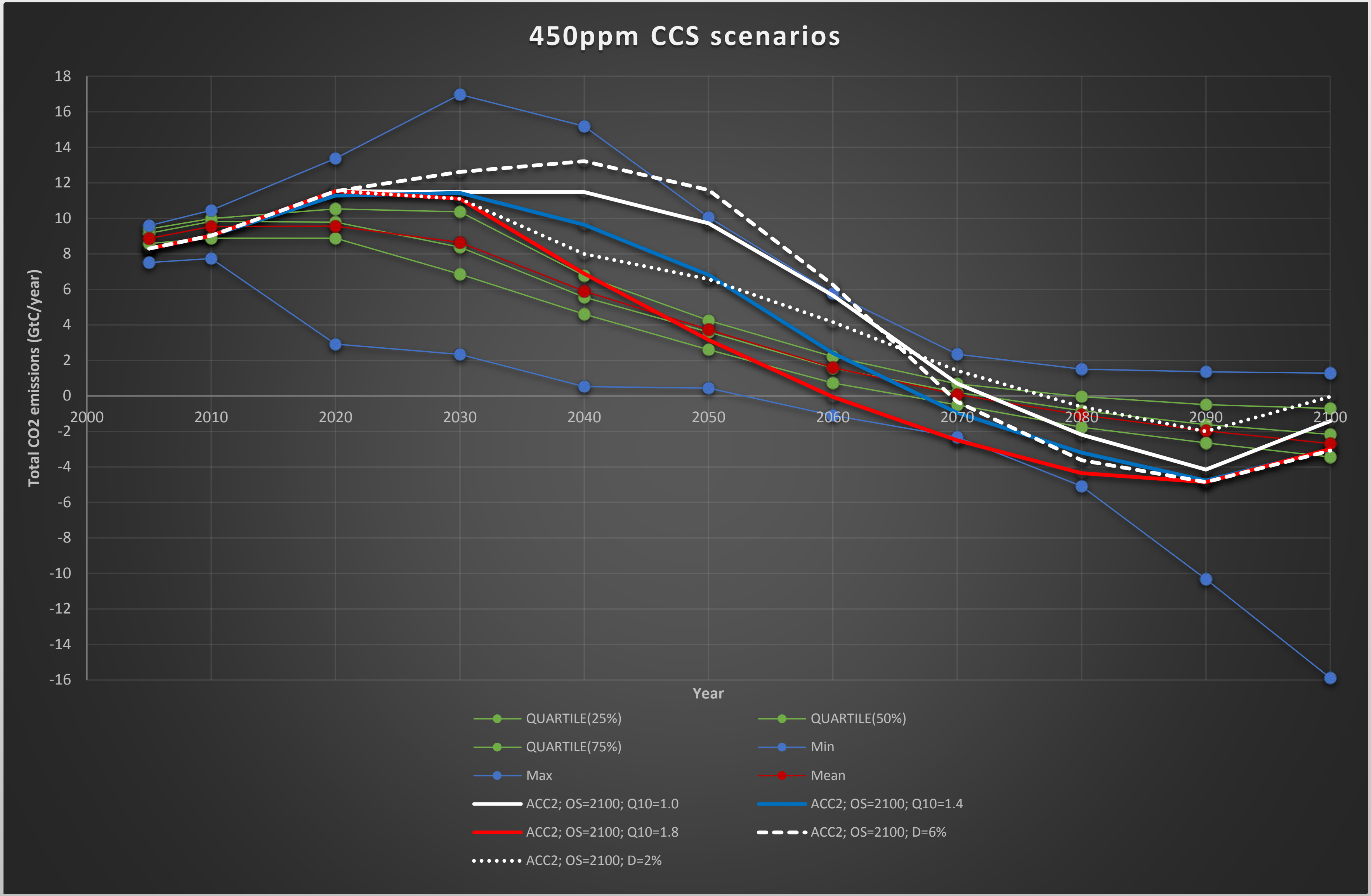
N_2O abatement level (%)



BC abatement level (%)



450ppm NoCCS scenarios


450ppm CCS scenarios
Total CO2 emissions (GtC/year)
18
16
14
12
10
8
6
4
2
0
-2
-4
-6
-8
-10
-12
-14
-16
2000
2010
2020
2030
2040
2050
2060
2070
2080
2090
2100
Year
QUARTILE(25%)
QUARTILE(50%)
QUARTILE(75%)
Min
Max
Mean
ACC2; OS=2100; Q10=1.0
ACC2; OS=2100; Q10=1.4
ACC2; OS=2100; Q10=1.8
ACC2; OS=2100; D=6%
ACC2; OS=2100; D=2%