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[MEXT-Program] SENTAN 気候変動予測先端研究プログラム

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Developing an Integrated Assessment Model to Explore Optimal Cost-Benefit Paths for Shared Socioeconomic Pathways Scenarios

Xuanming Su, Kiyoshi Takahashi, Tokuta Yokohata, Katsumasa Tanaka, Shinichiro Fujimori, Jun'ya Takakura, Rintaro Yamaguchi and Weiwei Xiong: Developing an integrated assessment model to explore optimal cost-benefit paths for Shared Socioeconomic Pathways scenarios, EGUsphere [preprint], https://doi.org/10.5194/egusphere-2024-1640, 2024.

1. Introduction

- Climate change researchers and policymakers use **Integrated Assessment Models (IAMs)** to investigate the intricate connections between socioeconomic systems and Earth's climate system.
- The CB-IAMs address **primarily reductions of CO_2 emissions or integrated GHG emissions**. However, the SSP variations are crucial for determining the optimal emissions pathway because they affect the potential, ease, and costs of reducing emissions of GHGs as well as aerosols and pollutants.
- To illustrate the effects of climate change on human society, the DICE model uses **a highly simplified damage function** built from current surveys and estimates. However, there are obvious differences of impacts among SSPs in specific areas such as occupational health costs and hydropower generation.
- To comprehensively represent the reaction of the climate to anthropogenic activities **over medium and very long periods of time**, the CB-IAM employs a projection horizon of 2450.
- In this study, we developed a CB-IAM by combining **a socioeconomic module with a Reduced-Complexity Module (RCM)**.

Assumptions of reference scenarios

Table 1: Main socioeconomic and climate-related indicators in 2100 for SSP reference scenarios and the DICE model.

Scenarios	Population (Millions)	GDP (Trillions USD)	Industrial CO_2 (GtC/year)	CO_2 concentration (ppm)	Radiative forcing (Wm^{-2})	Global temperature change (°C)
DICE2013R	10167.4	511.41	28	858.3	6.9	3.9
DICE2016R	11069.3	908.51	19.3	826.4	6.8	4.1
DICE2023	10534.3	839.22	24.3	842.9	7.4	3.8
SSP1	6886.8	855.4	5.3	577.7	5.3	3.7
SSP2	8960	726.5	16.0	752.2	6.9	4.6
SSP3	12639.4	417.6	25.3	866.6	7.6	5.0
SSP4	9263.3	493.2	7.8	617.1	5.5	3.7
SSP5	7393.3	1448.6	21.9	849.8	7.7	5.1

Su et al., 2017: Emission pathways to achieve 2.0 and 1.5 °C climate targets

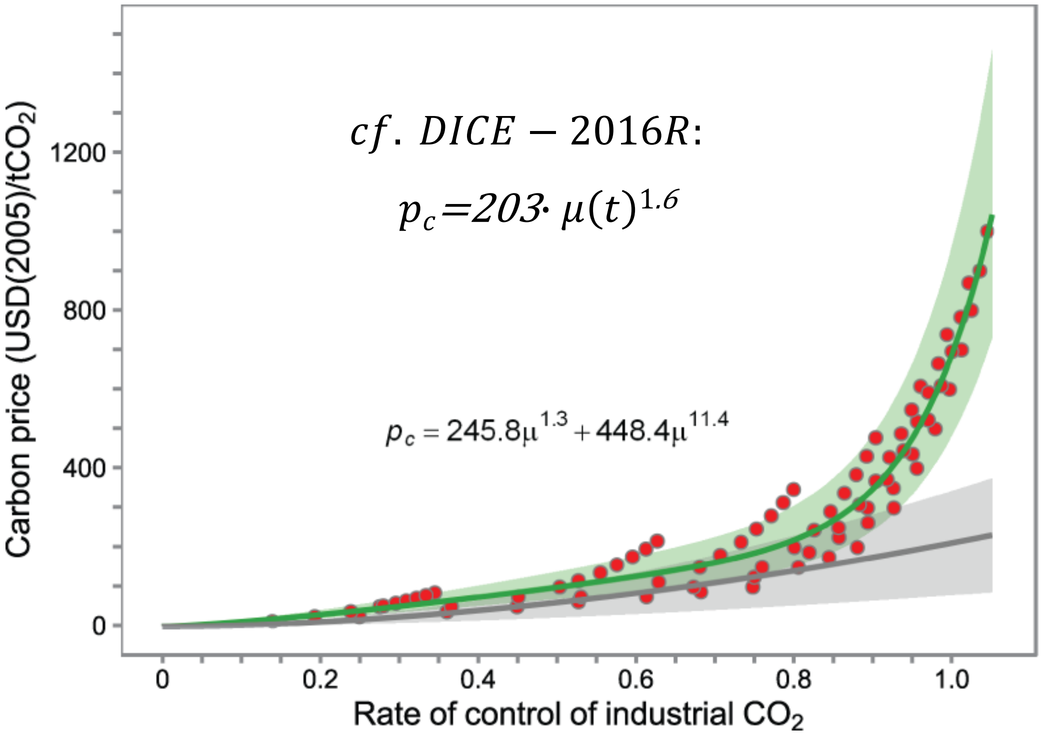
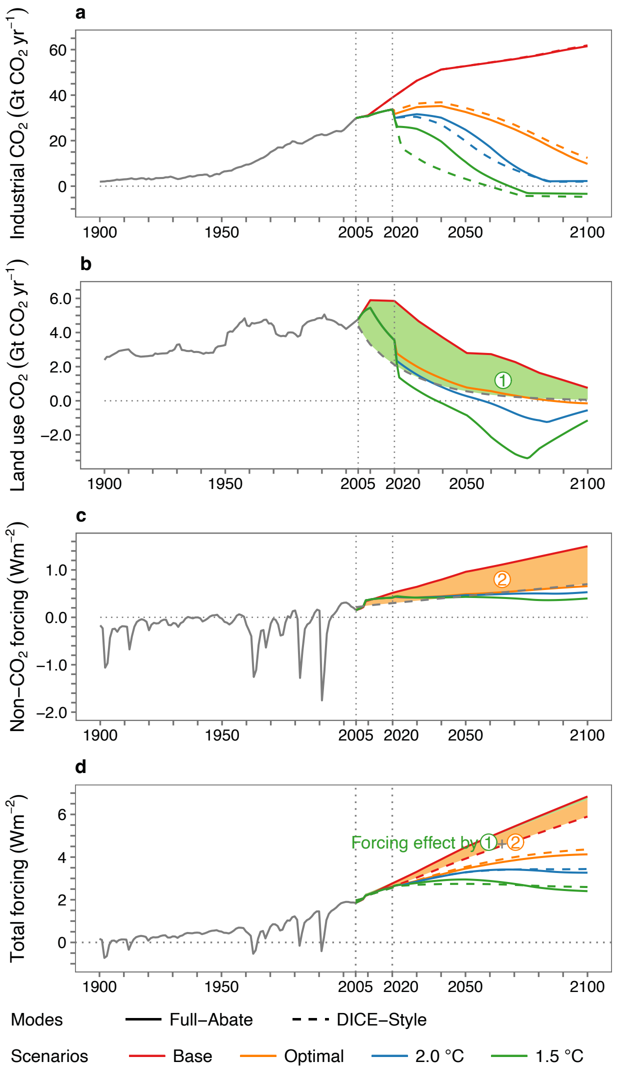


Fig. 1: Marginal abatement cost (MAC) curve for the Shared Socioeconomic Pathways 2 scenario. The red points represent sensitivity data relating the rate of control of industrial CO_2 to the carbon price. The green line (equation) and band represent the MAC curve considered in this study, and the gray line and band represent the MAC curve of DICE-2013R. The upper bound is the MAC in 2005, and the lower bound is the MAC in 2300.



Su, X., Takahashi, K., Fujimori, S., Hasegawa, T., Tanaka, K., Kato, E., … Emori, S. (2017). Emission pathways to achieve 2.0 °C and 1.5 °C climate targets. *Earth's Future*, *5*(6), 592–604. https://doi.org/10.1002/2016EF000492.

Fig. 2: Comparison between the DICE-Style and Full-Abate assessments.

2. Methods

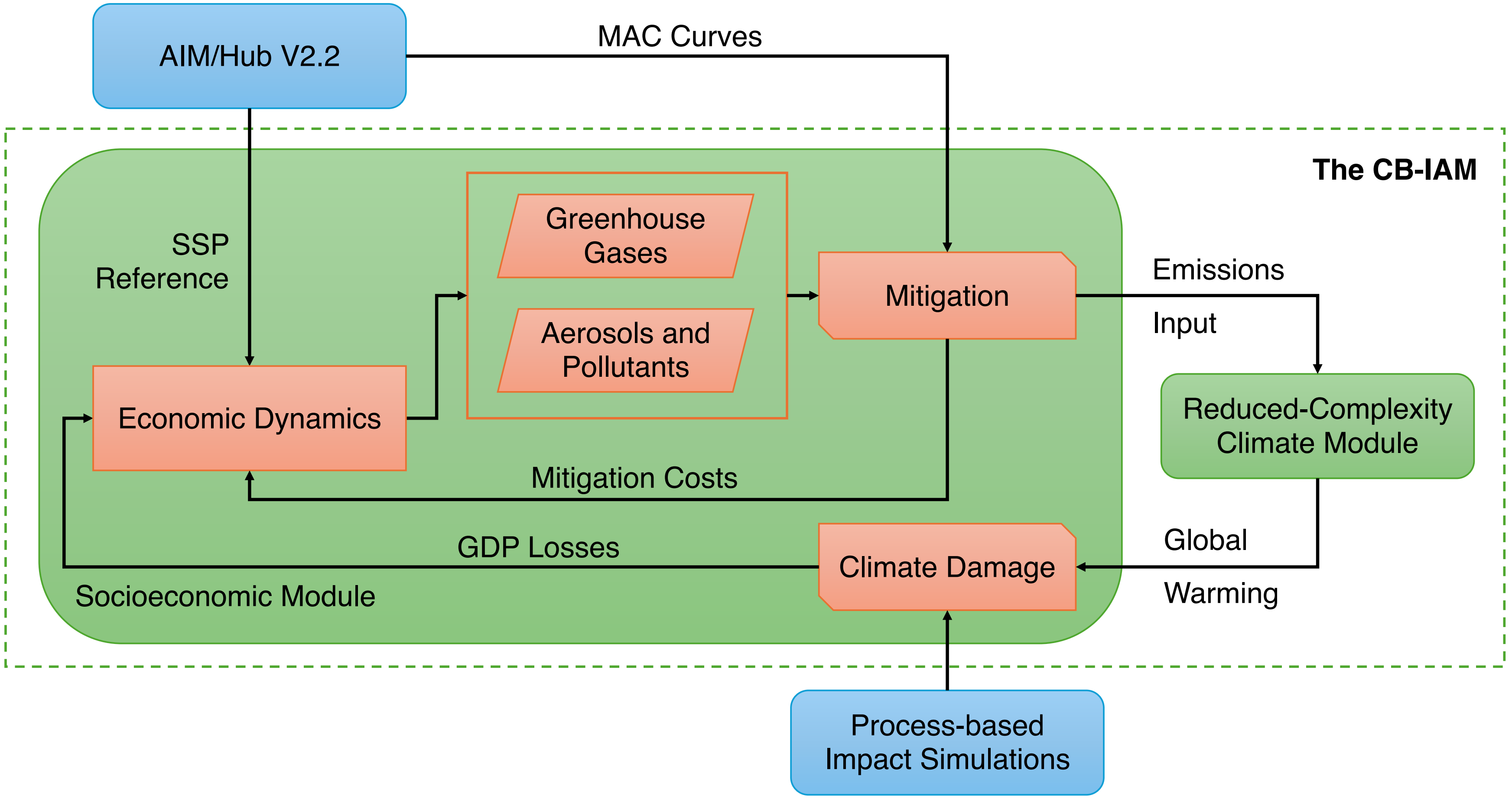


Fig. 3: Diagram of the modules for development of the cost-benefit Integrated Assessment Model (CB-IAM). Colored areas show modules or their connected components. Black arrows represent the interactions between modules and components. The dashed line encloses the components of the CB-IAM. AIM/Hub V2.2 is taken from Fujimori et al. (2017, 2023; Fujimori, Masui, and Matsuoka 2017). The process-based impact simulations are from Takakura et al. (2021).

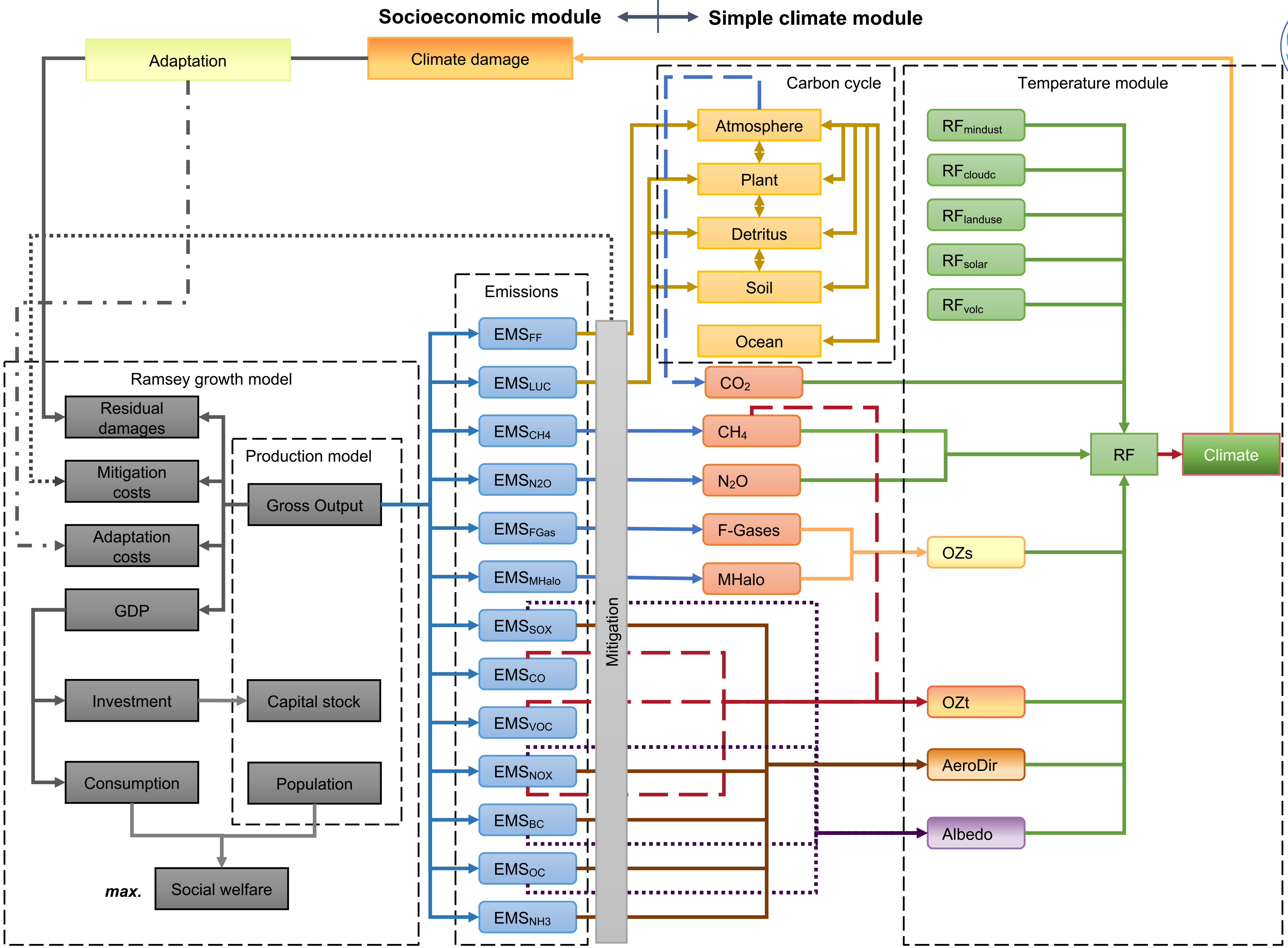
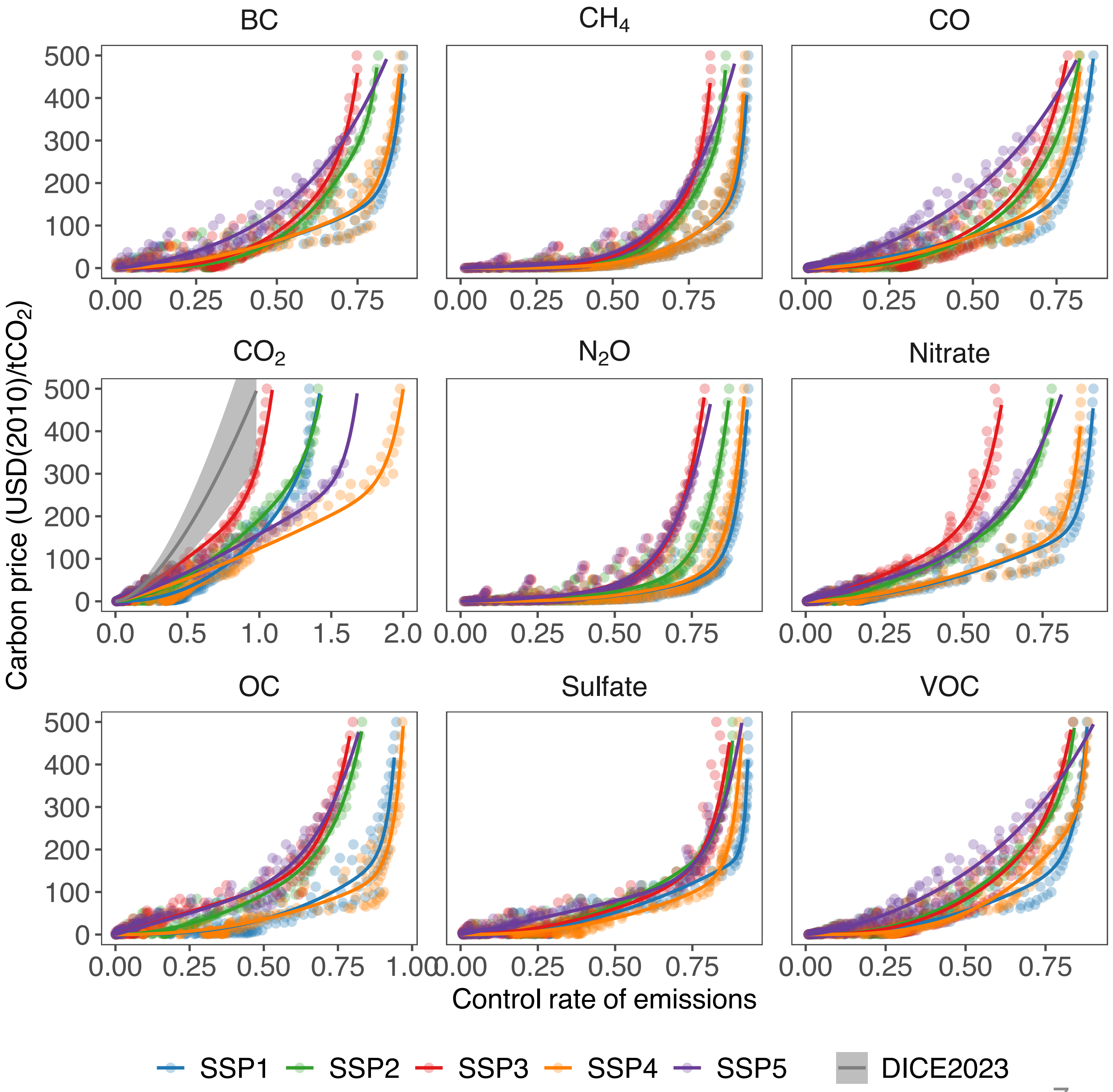


Fig. 4: The framework of SCM4OPT v3.3.

Estimating a new set of MAC curves

Fig. 5: Marginal abatement cost (MAC) curves for the SSP1-5 scenarios. Colored points show sensitivity data relating the rates of control of emissions to carbon prices based on AIM/Hub V2.2. Colored lines reflect the MAC curves. Note that for GHG emissions, reductions of land-use-related emissions are not covered; for aerosols and pollutants, reductions of emissions from land use, the energy sector (commercial, residential, and industrial use), industrial processes, and waste are not included. The gray line and range on the CO_2 panel indicate the DICE2023 MAC curve.



SSP-dependent damage functions

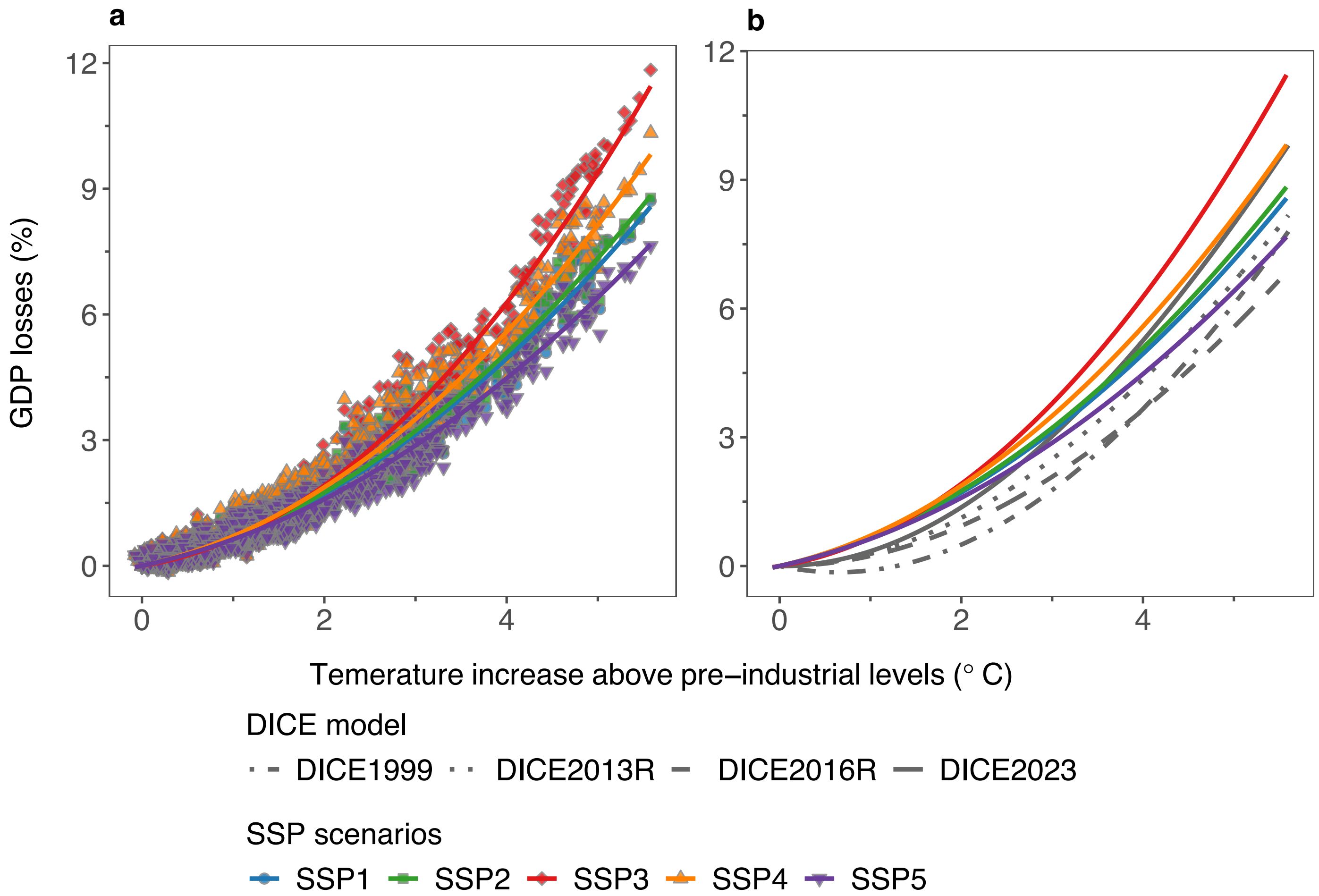


Fig. 6: Damage functions in the DICE model and this study. a Sensitivity data derived from the process-based impact simulation results (Takakura et al. 2021), and the estimated SSP-dependent damage functions. Colored points show the relationship between GDP losses and temperature increases above pre-industrial levels. Colored lines indicate the estimated damage functions. **b** The estimated SSP-dependent damage functions in relation to various versions of the DICE model. Colored lines denote the estimated damage functions, and the gray lines show the MAC curves used in the DICE model.

Assumptions of population and GDP

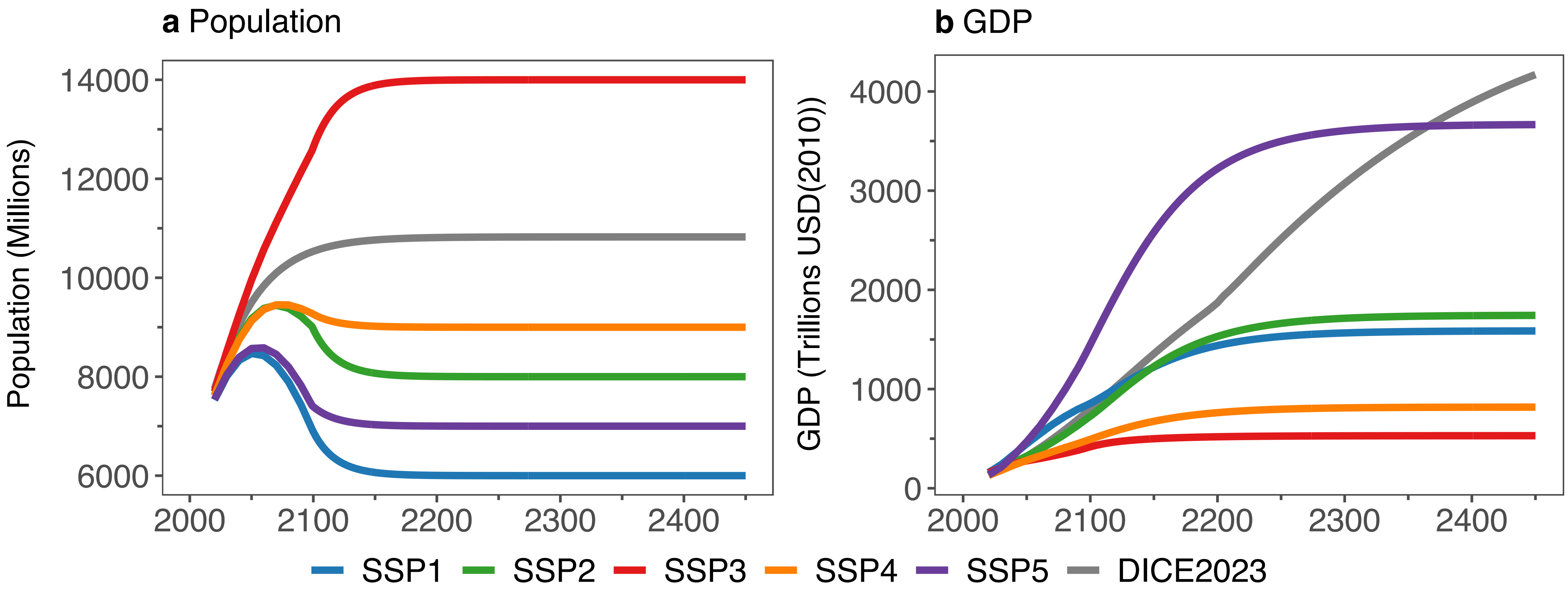


Fig. 7: Assumptions on (a) population and (b) GDP. The population is assumed to stabilize after 2150 (Su et al. 2017, 2018). Colored lines show the SSP projections, and the gray line reflects the assumption of DICE2023.

Emission assumptions

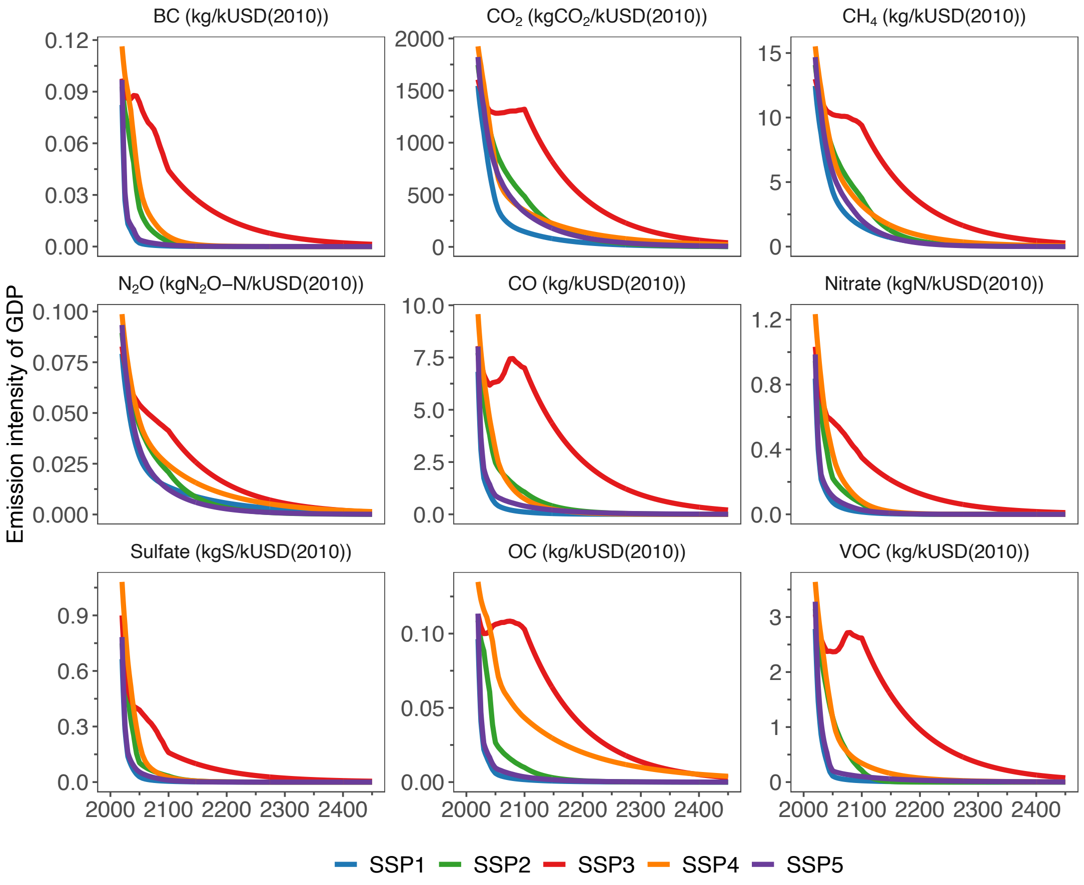


Fig. 8: Emission intensity for the reference scenarios of the SSPs. Colored lines show the SSP projections. The values before 2100 are estimated based on output of the AIM/Hub V2.2.

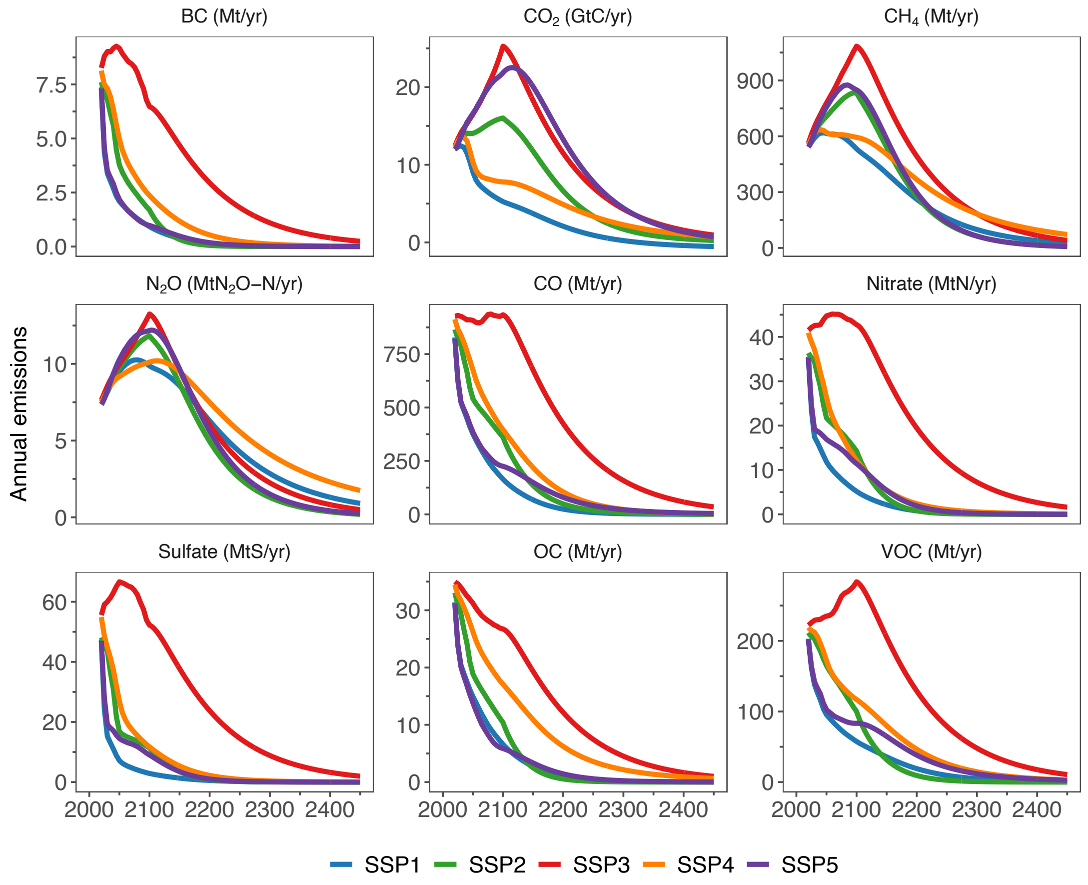


Fig. 9: Emissions of GHGs, aerosols, and pollutants for the reference scenarios of the SSPs. Colored lines show the SSP projections.

Simple climate module

- The Simple Climate Model for Optimization version 3.3 (SCM4OPT v3.3) (Nicholls et al. 2020; Su et al. 2022) is **a radiative forcing and global temperature simulation model** that uses a full suite of GHG, aerosol, and pollutant emissions, as well as land-use albedo, as input.
- To be employed in long-term optimization, the SCM4OPT v3.3 was revised to
  - depict the carbon cycle using **an impulse response function** (Barrage and Nordhaus 2023);
  - switch to a **one-year time step** from a biweekly time period.
- The RCM uses **a default set of parameters** to reproduce the average global temperature increase.
- To reduce complexity, we considered climate-related uncertainty using a temperature **sensitivity range of 2 °C to 5 °C** (Forster et al. 2021).

3. Results

- We ran simulations for two scenarios for each SSP:
  - **the reference scenario**, which calls for no future mitigation, and
  - **the optimal scenario**, which balances the present values of the costs associated with mitigation with the present values of climate damages under the SSP projections and the related extensions.
- To further illustrate how the optimal emission pathways would develop under the SSP assumptions, three sensitivity tests were also conducted:

  a. **mitigation occurs in CO_2 only** as opposed to the scenario with full mitigation in all available emissions;

  b. a comparison is made between the use of **the new damage function** and that used in the DICE2023 model;

  c. a cross-sensitivity test is conducted regarding **population, total productivity level, and MACs** to highlight the important factors influencing the long-term stabilized temperature and the optimal climate policies.

Global temperature change

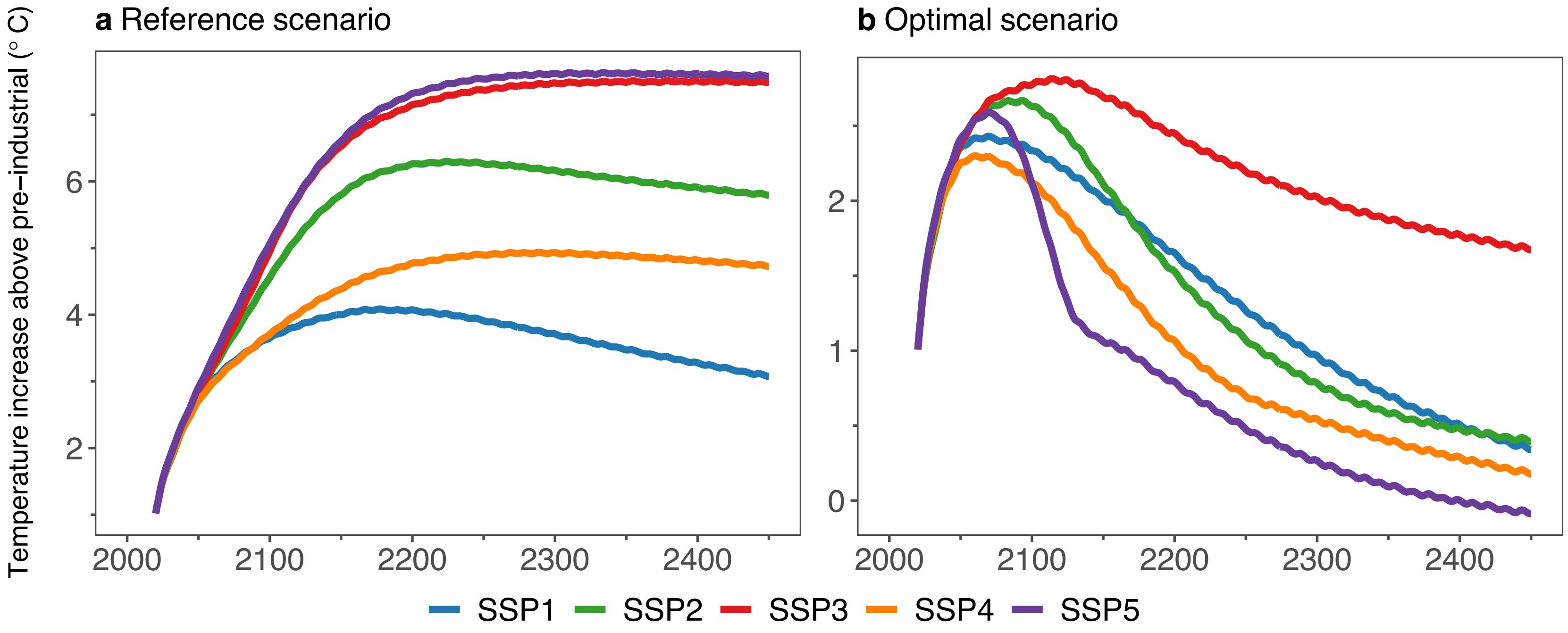


Fig. 10: Global temperature changes for the SSPs in the (a) reference scenario and the (b) optimal scenario. Colored lines show the SSP projections.

- For the reference scenarios, there were significant temperature increases for **SSP3 and SSP5**, and the temperature increase was smallest for **SSP1** in the long run.
- The **SSP3** scenario led to both the highest optimal temperature, namely the maximum temperature under optimal conditions, and the highest stabilized temperature, most likely because of the large emissions and the difficulty in reducing those emissions.
- The optimal scenarios for **SSP1, SSP2, and SSP4** all had similar stabilized temperatures at the end of the assessment period. However, **SSP2** had a higher optimal temperature than the other two because it assumed comparatively high emissions in the near term.

Mitigation of emissions of GHGs, aerosols and pollutants

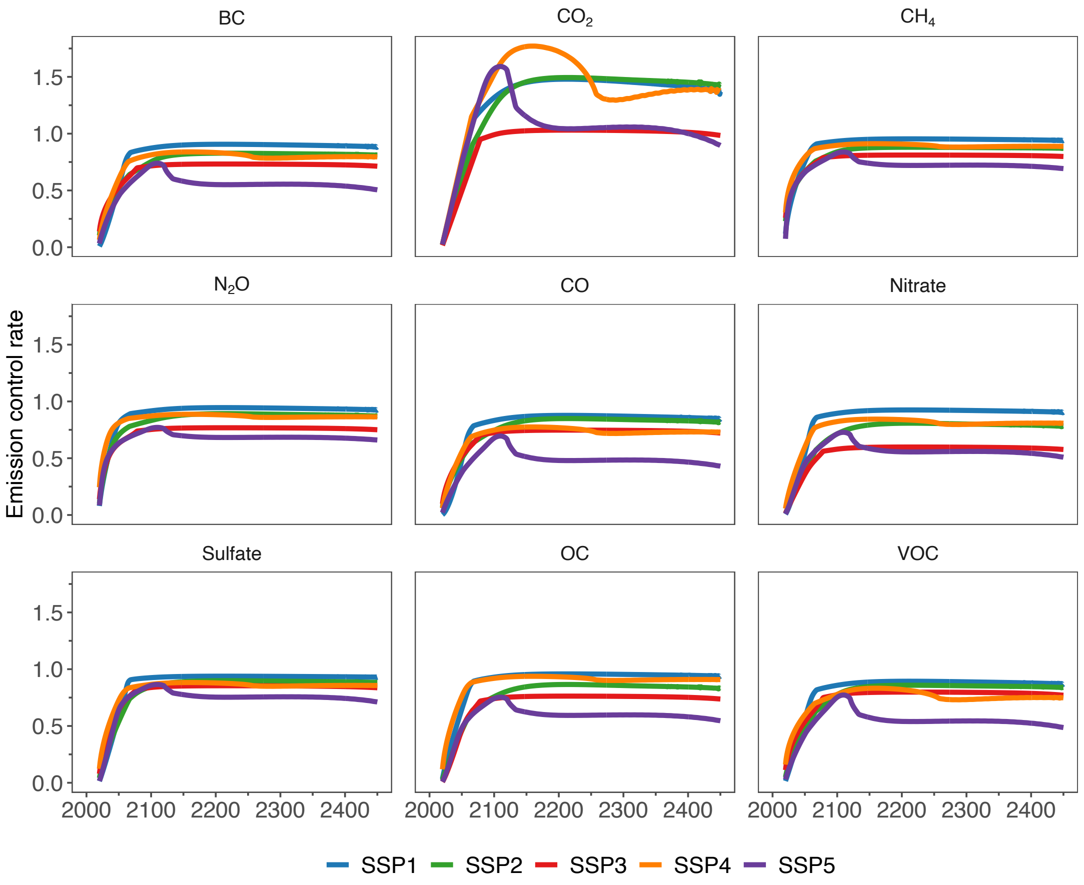


Fig. 11: Control rates of optimal scenarios. Colored lines show the SSP projections.

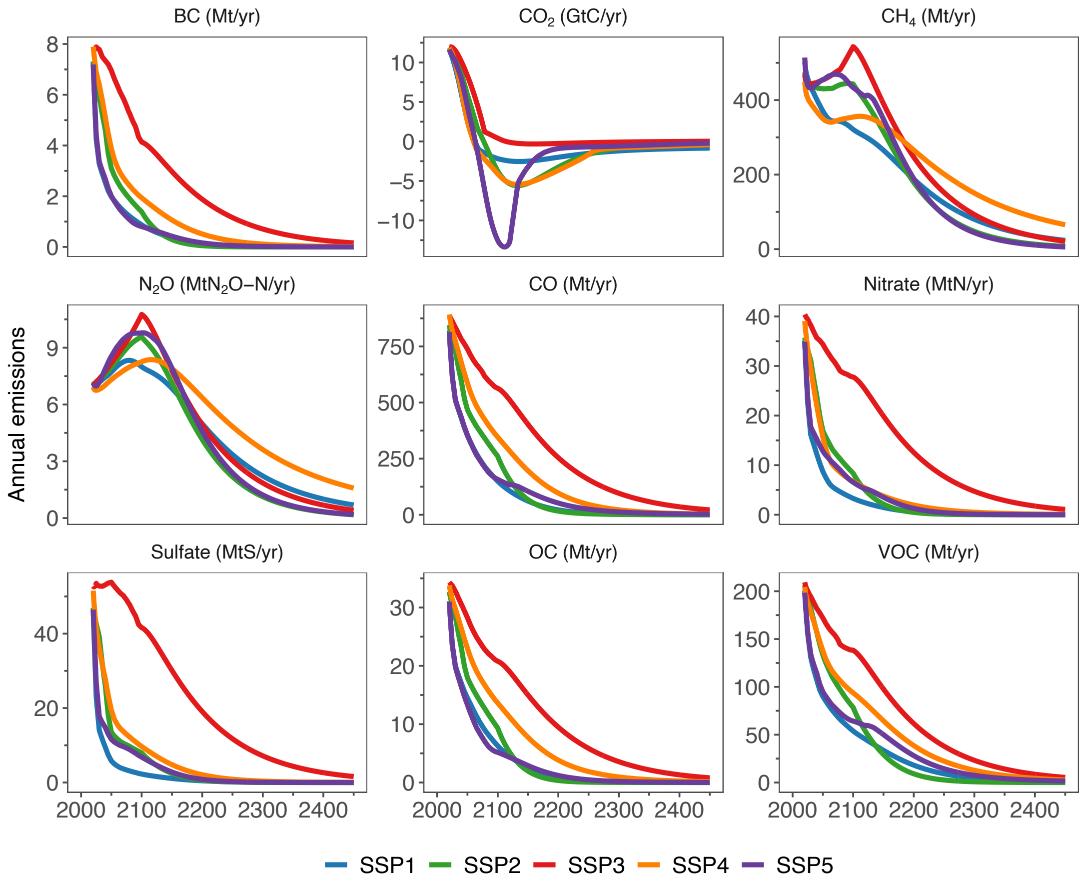
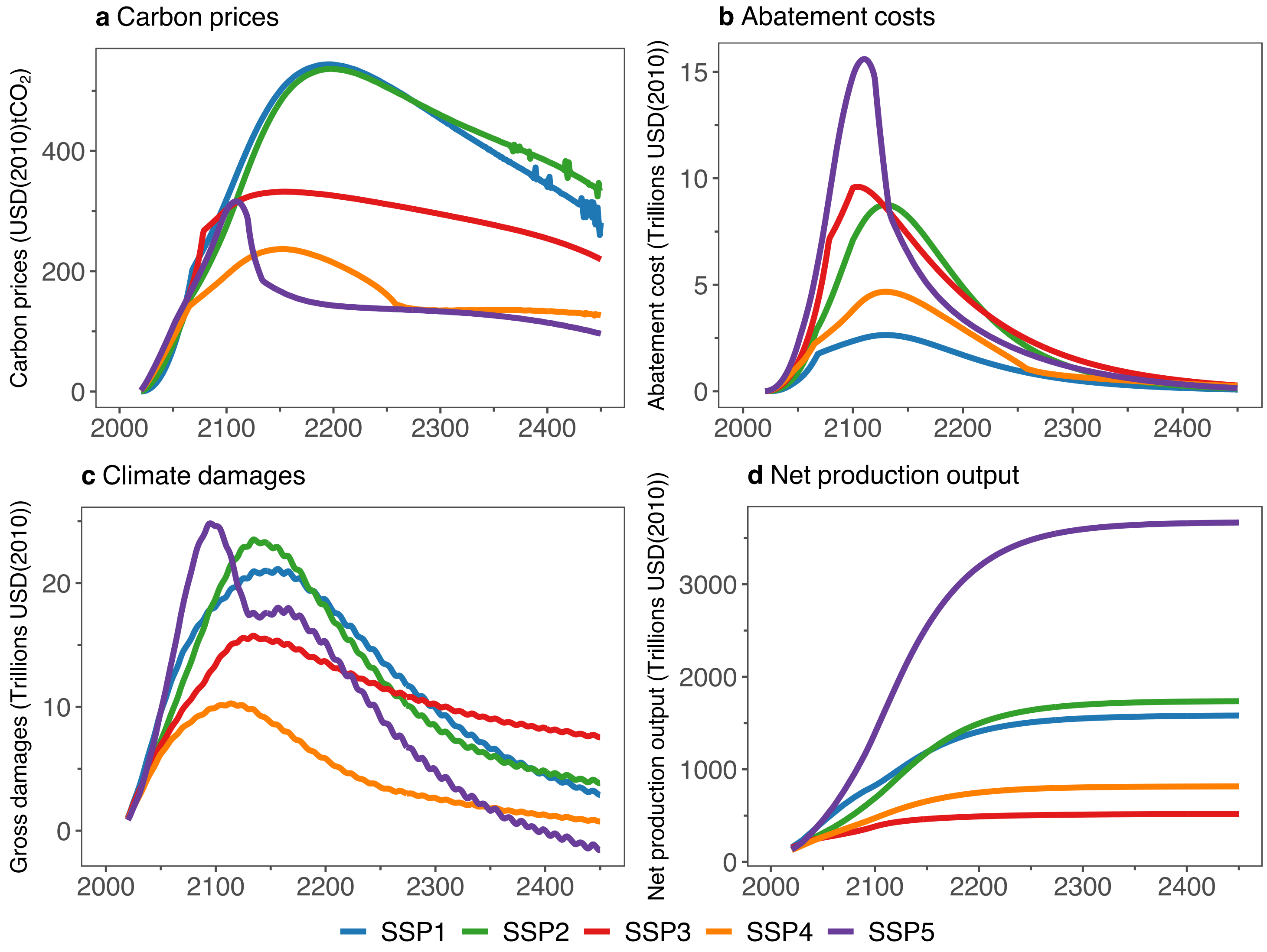


Fig. 12: Optimal emission pathways. Colored lines show the SSP projections.

Mitigation costs and climate damages

Fig. 13: (a) Carbon prices, (b) mitigation costs, (c) climate damages, and (d) net production outputs for the SSPs. Colored lines show SSP projections.



4. Discussion

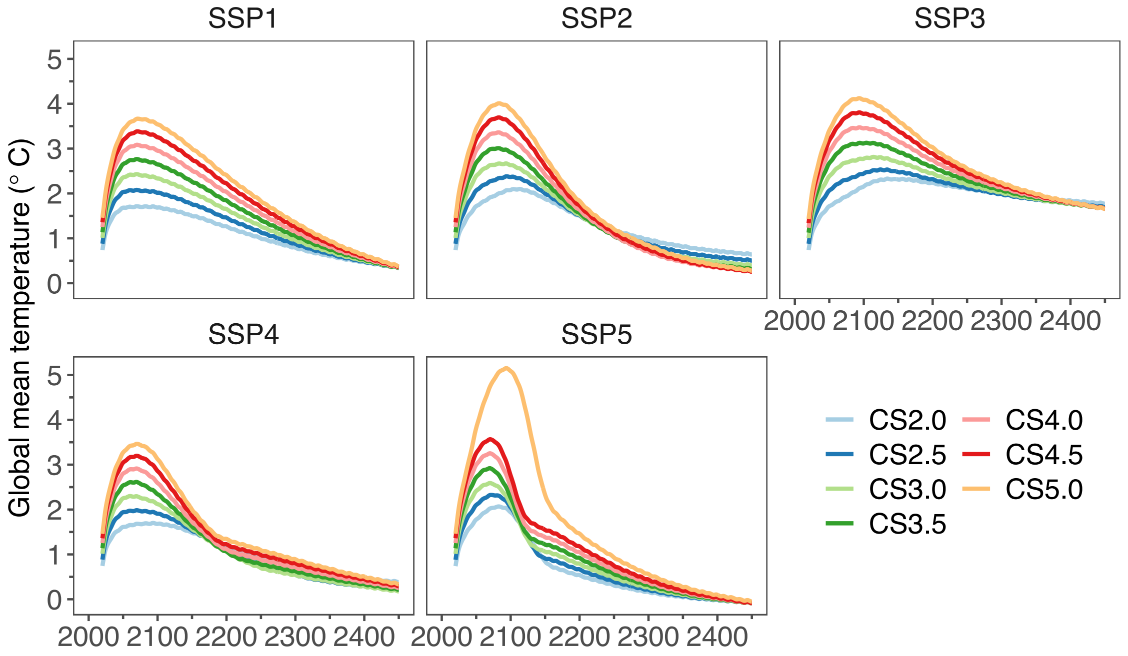


Fig. 14: Climate sensitivity test. Colored lines show the SSP projections for climate sensitivity.

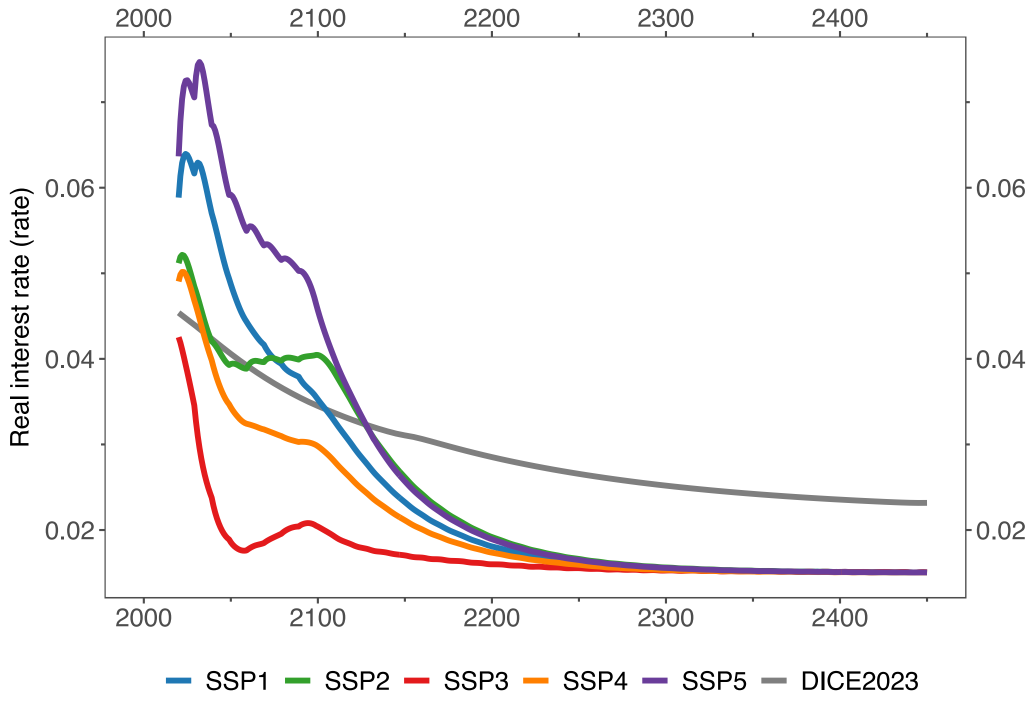
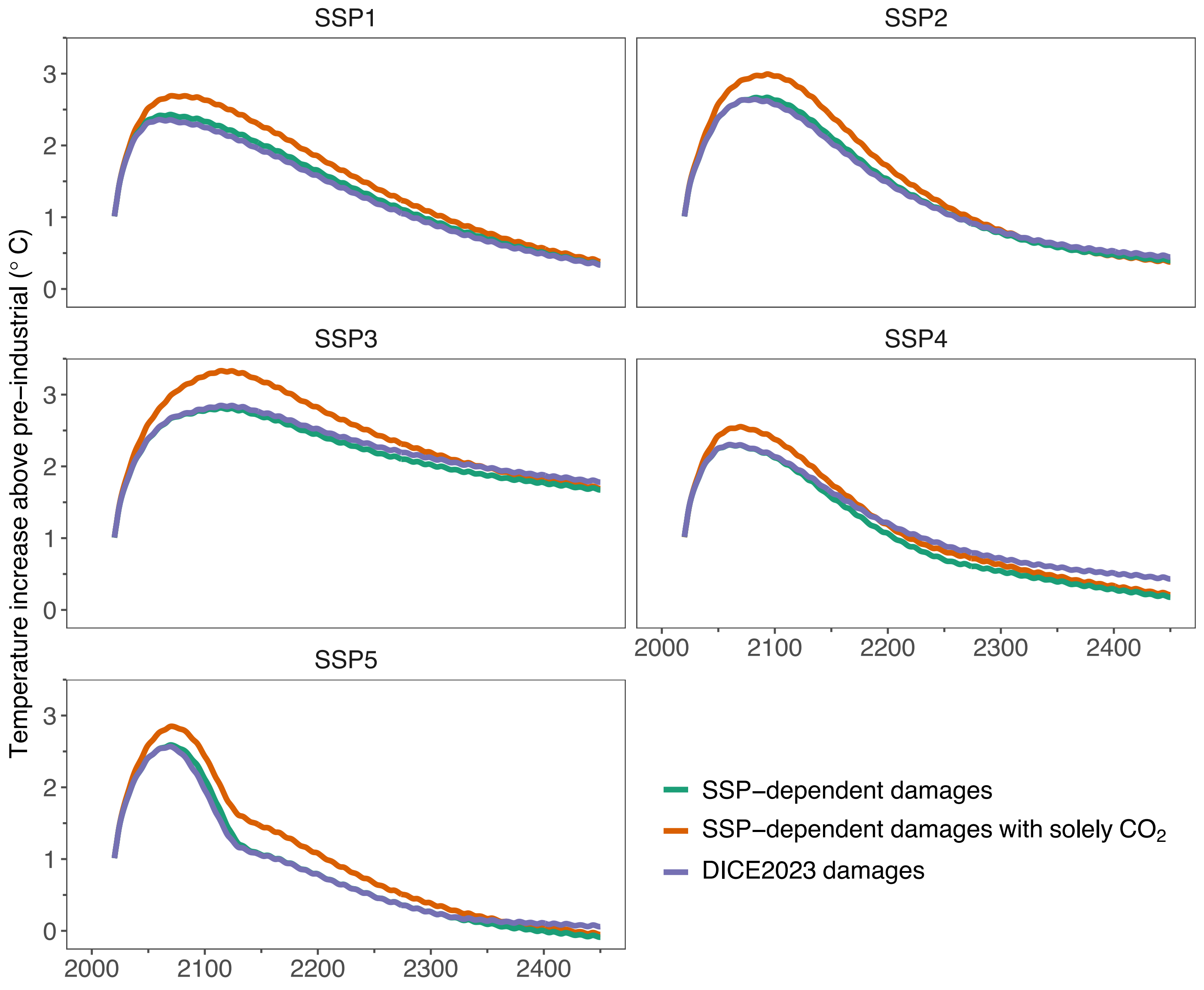


Fig. 15: Discount rates for the SSPs. Colored lines show the SSP projections, and the gray line indicates the assumption of DICE2023.

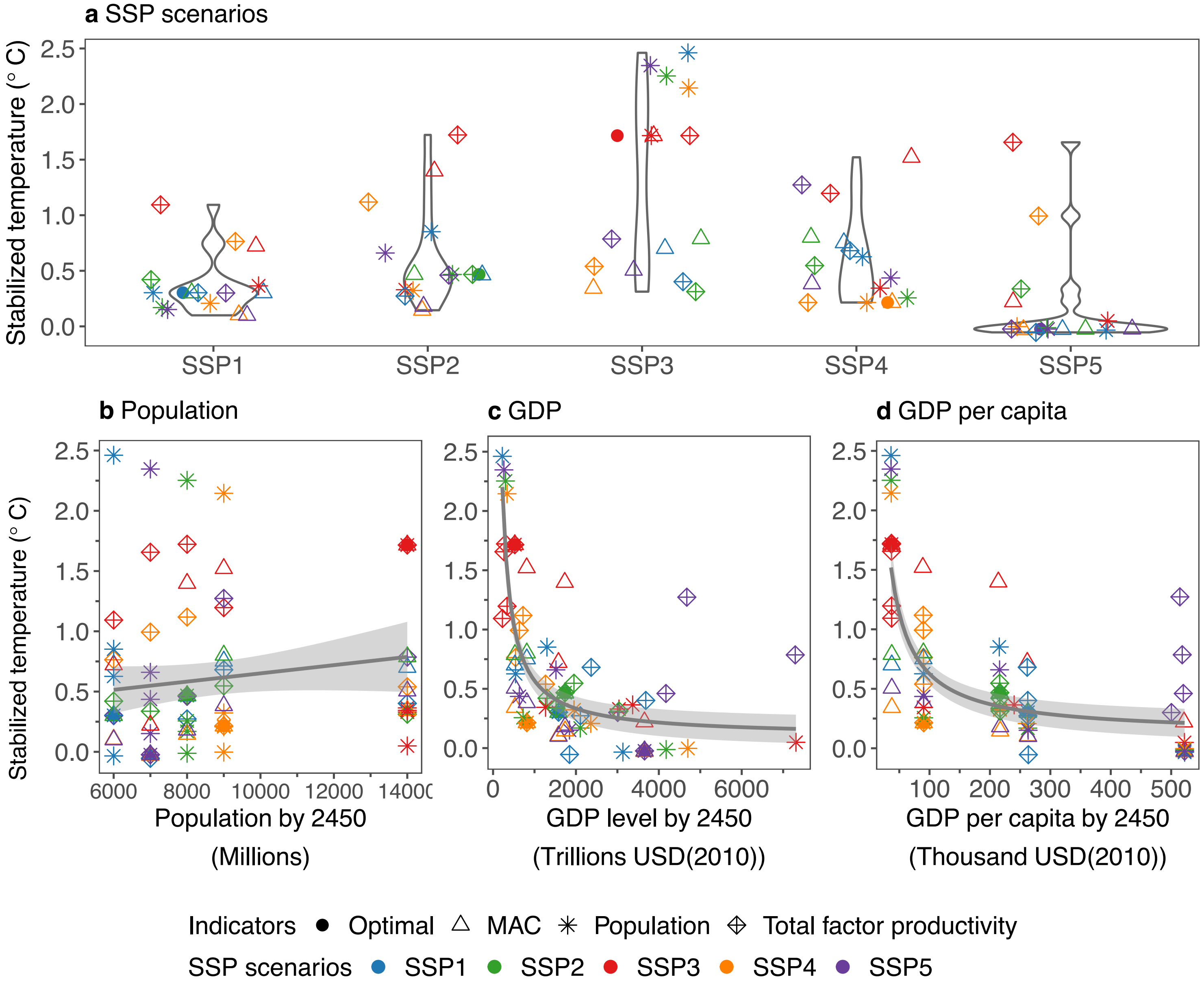
Sensitivity test using solely CO_2 emissions and SSP-dependent damage functions

Fig. 16: Temperature increases for the sensitivity scenarios. Colored lines show the SSP projections for the sensitivity scenarios of SSP-dependent damages, SSP-dependent damages with solely CO_2, and DICE2023 damages.



Indicators affecting optimization scenarios

Fig. 17: A sensitivity test with respect to the stabilized temperature: (a) SSP scenario, (b) population, (c) GPD, and (d) GDP per capita. The color of a point indicates the SSP scenario, and the shape of a point denotes the indicator used for the sensitivity test, either the population, total factor productivity, or MAC.



Limitations and future studies

- Our findings should be evaluated with caution for two reasons.
  - Our simulation results were contingent on the **SSP output of AIM/Hub V2.2 and the associated extensions**.
  - Because of a lack of mitigation cost information for such a long-term projection, the MACs created using sensitivity data for times **up to the year 2100** were extended to the year 2450.
- In this study, we created a **CB-IAM** that combined a socioeconomic module and an RCM module to represent long-term projections for SSP1–5.
- The result was **diverse patterns of optimal temperatures**, including maximum temperature achieved and stabilized temperature by the end of the evaluation period.
- The model simulations showed the importance of **distinguishing options for reducing emissions of greenhouse gases based on distinct socioeconomic growth scenarios**.
- We also show an example of **a long-term socioeconomic projection** spanning several centuries as well as a variety of socioeconomic assumptions for assessing climate change policies with long-term consequences.
- Possible future studies:
  - With this tool, we could generate estimates of **socioeconomic and climate factors in the long run** while taking into account the limitations imposed by climate policies
  - The tool can be **used to estimate the uncertainties that arise in various socioeconomic contexts and in the long-term climate system**, both of which are crucial considerations for policymakers who formulate climate change strategies.

Thank you for listening.