



Report on CDR portfolio climate neutrality scenarios with and without overshoot including sensitivity analysis, gridding and extensions

Deliverable D1.2



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About RESCUE

The RESCUE project will improve knowledge and understanding in area c) of this call: “Climate and Earth System responses to climate neutrality and net negative emissions” by pursuing two overall objectives: 1) Quantify the climate and Earth system responses to pathways achieving climate neutrality by Carbon Dioxide Removal (CDR) deployment with and without temperature overshoot, and

2) Assess the potential role of CDR in reducing net GHG emissions, as well as its potential environmental risks and co-benefits. RESCUE will expand existing knowledge on CDR methods to design a suite of new global temperature stabilization scenarios at several target values to achieve the first objective. New model developments will deliver improved climate projections with explicit representation of CDR portfolios for these scenarios. The analyses will be devoted to finding suitable pathways to climate neutrality considering multiple aspects of the Earth system response: mean climate and extremes, sea-level rise, global carbon cycling, biodiversity, and ecosystem services. Particular attention will be paid to the reversibility of induced changes by comparing scenarios with and without temperature overshoot. The second objective will be achieved by analyses assessing various factors determining overall effectiveness,

impacts and co-benefits of CDR portfolios. These factors include CDR-specific CO₂ uptake, CDR-induced biogeophysical climate feedbacks, CDR-derived non-CO₂ radiative forcers, and the interaction between socio-economic and environmental impacts (e.g., biodiversity). Moreover, a dedicated analysis will provide key criteria for developing a monitoring system for the effectiveness of CDR portfolio deployments and their potential side effects. Stakeholders will be closely engaged throughout the project to ensure policy relevance and final update of the results which will be made freely available via existing climate services.

1 Abstract

This deliverable summarizes the future scenarios based on the Integrated Assessment model (IAM) REMIND-MAgPIE that the Earth System Models will use. The scenarios span a broad range of assumptions to embrace the uncertainty in socioeconomic development and climate policies. The scenarios with REMIND-MAgPIE extend until 2100 and cover all emissions of Greenhouse Gases and aerosols from energy, industry and the AFOLU sectors as well as the land-use dynamics, including transitions. The REMIND-MAgPIE model derives scenarios with an extended portfolio of Carbon Dioxide Removal (CDR) options structures, including Bioenergy with Carbon Capture and Storage, Afforestation, Ocean Alkalinity Enhancement, and Direct Air Capture. These options are fully integrated into the technological, political and economic model. The data is harmonized to emission and land-use datasets that are standard in Earth System Models (ESMs) and gridded to a fine grid (0.5° and 0.25° granularity) to be compatible with the input requirements of the ESMs. The scenarios were developed at different stages of the project and span the Tier 1 scenarios, which will be used by full complexity ESMs and the Tier 2 scenarios, which were derived later and incorporate stakeholder feedback and complement the Tier 1 scenarios by extending the scope of assessed policy frameworks regarding CDR, land-based climate change mitigation and equity considerations. The Tier 1 scenarios are also extended until 2300 based on an emulator that replicates REMIND-MAgPIE behaviour that was run under varying policy assumptions. Therefore, also scenarios with a very long-time horizon and vastly different overshoots with variations in the magnitude and duration of exceeding the carbon budget are provided. During the implementation period of the WP developments in the IPCC, CMIP, ISIMIP and other relevant processes and fora were actively recognized by the project partners. The work plan was flexibly adjusted to best connect the research reported here and make the outcomes of the research as relevant as possible.

2 Executive Summary

The purpose of the deliverable is to introduce, describe and analyze the new scenarios for the RESCUE project. They comprise the following key characteristics:

1. Two sets of core scenarios are developed for use in ESMs using the state-of-the-art IAM developed and operated by the PIK team called REMIND-MAgPIE.
2. The first set of scenarios (called Tier 1 scenarios) is fully usable for CMIP6-type ESMs and comprises 1.5°C and well-below 2°C scenarios with no/low and high overshoot.
3. The second set of scenarios (called Tier 2 scenarios) is fully usable for Earth System Model of Intermediate Complexity (gridding of data was omitted, since full complexity ESMs will not run Tier 2 scenarios) and comprises 1.5°C scenarios with no/low and high overshoot with varied assumptions on CDR, land-based mitigation and equity considerations, while incorporating latest data and model updates (particularly improving the near-term realism).
4. The harmonized data of Tier 1 scenarios is gridded to 0.25° and 0.5° grid cells.
5. The Tier 1 scenarios are extended at the global level for the period 2100 to 2300.

Keywords

Integrated Assessment Modeling, Earth System Modeling, Model Interfacing, Climate Change Mitigation, Temperature Overshoot, Energy System, Land-Use System

3 Introduction

3.1 Scope and structure of the report

The following report discusses the results of the climate change mitigation scenarios that were derived within the RESCUE project (chapter 4), the downscaling and harmonization process to produce ESM-ready emissions and land-use data (chapter 5) and the extension of the scenarios beyond 2100 (chapter 6).

The Deliverable introduces the achievements reached in the context and with the support of the RESCUE project. The objectives of RESCUE for WP1 have been accomplished, the outputs are available and contribute to the broader scientific process. The scientific publishing process is in progress. Several papers have been published, are in the review process or in preparation. The software tools (T1.4) are available on open source platforms and scenarios (T1.3) will be made available to the broader community in the process of review and publication.

The improvements of the REMIND-MAGPIE model as well as the improved interfacing with the Earth System Models contributed to the development of scenarios that are used in the ScenarioMIP/CMIP process. The methods and tools developed for data harmonization and gridding (T1.3) are currently used to support the ScenarioMIP/CMIP7 process that aims to contribute to WG1 of the Seventh Assessment Report of the IPCC. The methods for scenario extensions (T1.4) are explored for their applicability for ScenarioMIP/CMIP7. The tools for geo-spatial explicit climate forcings (T1.2) are also planned to be used for the integration of IAMs with Impact modelers (WG2 of the IPCC).

These improvements have been achieved along with the OptimESM project that pursued similar objectives. Two main features distinguish both projects. First, the scenarios in RESCUE are guided by research questions and were designed with the project partners in the context of the RESCUE project, while scenarios in OptimESM contribute more specifically to the ScenarioMIP/CMIP7 process; these scenarios are derived in a broader scientific context and aim to address more general research questions than RESCUE. Second, climate forcing data for RESCUE is consistent with CMIP6, while OptimESM is consistent with data used in CMIP7/ScenarioMIP.

3.2 Development and scope of Tier 1 and Tier 2 scenarios

The development of the Tier 1 and the Tier 2 scenarios happened at different stages of the project and differ somewhat with respect to their purpose. Tier 1 scenarios had to be provided early such that the full complexity ESMs with large run-times can start running them quickly. One of the focus research topics that should be addressed within the RESCUE project is the question on reversibility of earth system variables. The Tier 1 scenarios were thus designed in a way that maximizes their “usefulness” towards the subsequent ESM simulations. To that end, the scenarios had to fulfill two main objectives:

1. There had to be a pair of two matching scenarios with and without temperature overshoot, such that the response of the earth system to anthropogenic emissions in a world with and a world without temperature overshoot can be compared meaningfully. In particular that meant that the cumulative CO₂ emissions in 2100 had to be equal in the OS and the no-OS scenarios.
2. Given the internal variability of climate change (i.e., natural fluctuations within the Earth’s climate system, independent of external forcings), the differences in climate drivers between the OS and the no-OS scenarios need to be sufficiently large to detect a distinguishable difference in the earth system response. In other words, the cumulative CO₂ emissions at the peak of the overshoot

scenario had to be sufficiently larger than the cumulative emissions in the non-OS scenario at the same time.

To maximize the difference between OS and no-OS scenarios, we designed the Tier 1 no-OS scenario such that a very ambitious carbon budget of 500 Gt CO₂ from 2020 must not be exceeded at any point in time. However, due to system inertia and the very fast ramp-up of CDR until the peak-year, there will be some level of net negative emissions in the years after the peak, reducing the cumulative emissions by about 100 Gt CO₂. Thus, in order to again match the cumulative emissions of the OS scenario in 2100, the GHG price has to be relaxed, such that emissions rise again to 500 Gt CO₂ in 2100 (compare Figure 3.1).

While these scenarios are well suited to analyze questions regarding reversibility of the earth system, they are not ideal for discussing policy implications of the transformation pathways of the energy and land-use system. In stakeholder workshops that were carried out in 2024 we received the feedback that the no-OS scenario was not strictly compatible with the wording of the Paris Agreement (PA), due to the increase of emissions in the last third of the century. Furthermore, the by now extremely ambitious climate target of not exceeding 500 Gt of CO₂, which requires a very strong near-term mitigation - for example reducing coal use between 2020 and 2030 already by 67% (see section 4.2.3) - was perceived as implausible.

To address these concerns, we adopted the scenario design of the Tier 2 scenarios. In particular, we updated the REMIND model version, which comes with a major update of input data, particularly affecting near term emission trends from currently implemented and planned national policies. Since international climate action in the past few years has not been sufficiently stringent, there is less room for GHG emissions reductions until 2030 in the new model, rendering the non-overshoot 500 Gt CO₂ budget virtually infeasible. We therefore changed the target seeking approach in such a way that a small overshoot of about 150 Gt CO₂ is allowed also in the no-OS scenario and the 500 Gt CO₂ cumulative emissions only need to be achieved by 2100 (i.e., equally to the OS scenario, see Figure 3.1). The “no-OS” scenario is therefore called “no/low OS scenario”. Incorporating the stakeholder feedback on equity concerns in the 1.5°C OS scenario, we now also apply differentiated carbon prices in these scenarios. Another concern that was raised during the stakeholder workshop was the excessive amount of energy-intensive DACCS in some regions, particularly in the reforming economies (REF) in the high OS scenarios. In the new REMIND version, a constraint was introduced that limits the amount of energy that can be used for CDR activities to 10% of the total final energy use in each region.

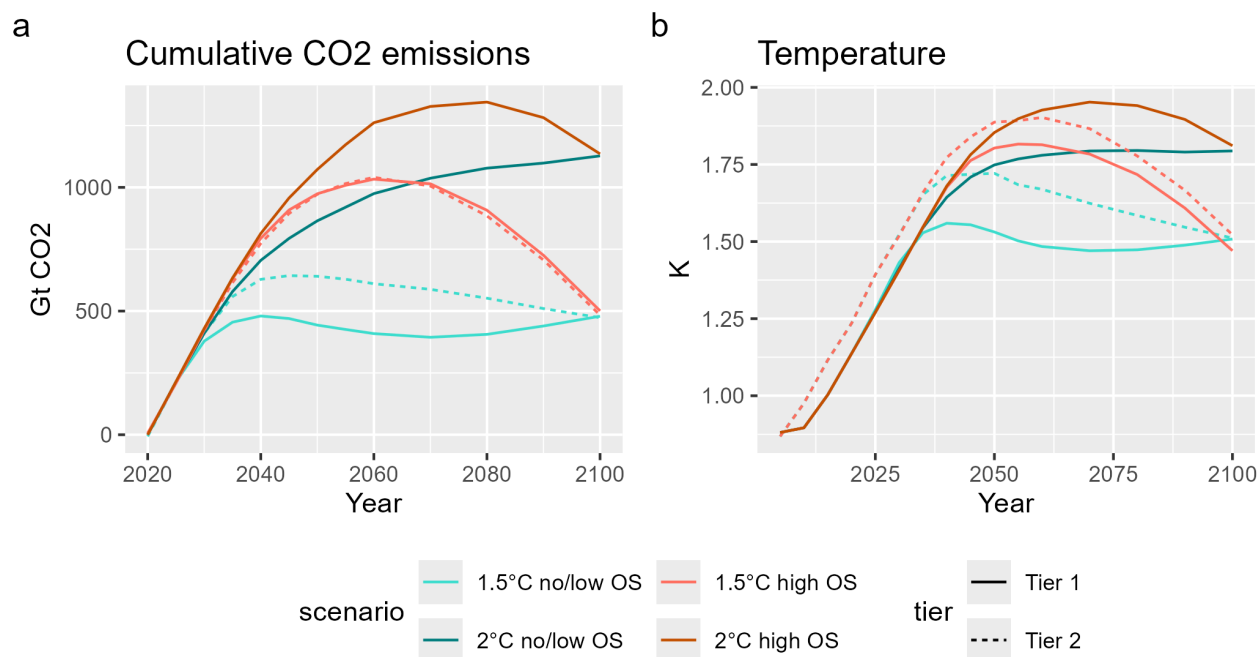


Figure 3.1. Cumulative CO2 emissions (a) and global mean temperature response (b) in Tier 1 and Tier 2 scenarios. Please note that the temperature response in the Tier 2 scenarios was created with a different version of the MAGICC model than what was used for the Tier 1 scenarios, making the temperature outcome not directly comparable. In section 4.3 more details on the comparison between Tier 1 and Tier 2 scenarios are shown.

Within the RESCUE project, the Tier 2 scenarios have a slightly different purpose than the Tier 1 scenarios. Given that the difference between the OS and the no-OS scenario is less pronounced in the Tier 2 scenarios - the maximum difference in global mean temperature between these scenarios is now less than 0.2 K - they are not suited for reversibility experiments in full complexity ESMs that feature internal variability (see point 2 above). However, they are still useful for analyses with intermediate complexity ESMs (Earth System Model of Intermediate Complexity, EMIC) without internal variability, such as the UVic model, that is represented within the RESCUE consortium via Geomar. Most of all, though, they have the great advantage that the transformation of the economy within the IAM results is more nuanced, without implausible near-term trends and without a revival of GHG emissions after 2070.

The different foci of the Tier 1 and Tier 2 scenarios reveal the tension between rather idealized Tier 1 scenarios serving the needs of the ESMs and the more nuanced Tier 2 scenarios that are better suited for addressing research questions regarding the impacts on the socio-economic systems within and overshoot and a no overshoot world. The consequence of this two-staged approach is that Tier 1 and Tier 2 scenarios are not directly comparable, i.e. the results of the reversibility analysis that is based on the Tier 1 scenarios, does not perfectly match the results of the economic consequences of an overshoot that can be better analyzed with the Tier 2 scenarios. In order to still be able to connect these two strands of research, we present a comparison of the Tier 1 and the Tier 2 scenarios in section 4.3.

Additionally to the model update and sharpening of the scenario design, the scope of potential future climate change mitigation pathways is widened in the Tier 2 scenarios by the addition of sensitivity scenarios. In these sensitivity scenarios, we alter the assumptions on three different domains:

- A. The scenarios now have Enhanced Weathering of rocks (EW) and carbon storage in long-lived materials as CDR options available. Furthermore, the impact of the availability of CDR options is tested, by adding scenarios
 - a. without Direct Air Carbon Capture and Storage (DACCS) and EW and
 - b. without afforestation and reforestation (AR).
- B. We added scenarios, in which there is no protection of land carbon pools such as forests (by deactivating the CO₂ price on land) to assess the impact of different mitigation strategies on unprotected ecosystems. We include these scenarios because the protection of land carbon pools is lagging behind and we found substantial variations of the land-use patterns due to deforestation.
- C. We added scenarios addressing equity concerns, in which we prolong the period of regionally-differentiated carbon prices from 2050 to 2070. These scenarios were adopted after feedback from stakeholders at one of the RESCUE science-policy interface workshops.

4 Scenarios with and without overshoot with a broad CDR portfolio

In the following we introduce 18 different climate change mitigation scenarios (8x Tier 1, 10x Tier 2) derived with the Integrated Assessment Model (IAM) REMIND-MAGPIE and discuss the results of overshoot and non-overshoot pathways in detail. These scenarios are designed to be used as an input for Simple Climate Models (SCMs) and Earth System Models (ESMs). Additionally to these 18 different scenarios, we derived 35 scenarios that are used as input data to calibrate the models that provide scenario extension until 2300 (see section 6). Here we focus on the 18 scenarios that can directly be used by SCMs and ESMs.

We report emissions from GHGs and air-pollutants mapped to sectors compatible with historic datasets (CEDS [1], [2] / GFED [3], [4]) as well as non-emission variables that are required by ESMs to enable them to be run in "activity driven" mode. "Activity driven" mode means that ESMs model the CDR activities endogenously using activity variables such as agricultural area of bioenergy crops, forest area or alkalinity levels added to the ocean instead of directly using the negative emissions from these activities as computed by the IAM. All variables are reported in the RESCUE project google drive folder¹, containing CEDS emissions and non-emission variables.

We extended the scenario analysis as compared with the planned extent. The reason is that the PIK team integrated the carbon dioxide removal (CDR) option of Ocean Alkalinity Enhancement (OAE) into the REMIND-MAGPIE framework. The broader CDR portfolio led to changes in the results that were substantial. This required more checks of the model implementation and the scenarios and to validate the results. The PIK team coordinated with the project partners to run the scenarios with and without Ocean Alkalinity Enhancement.

In order to report managed forest area – as requested by ESM teams – we now use a version of the land-use model MAGPIE, in which timber production is explicitly represented. Please be aware that this also led to a substantial change in future land-use change (LUC) CO₂ emissions in the scenarios.

Technical details on spatial, temporal and sectoral resolution of the output data can be found in the Appendix (section 8).

4.1 Scenario design

As already explained above, the scenarios were derived at different stages of the project. The Tier 1 scenarios cover the main overshoot vs. non-overshoot dynamics of 1.5°C and 2°C scenarios as well as the sensitivity regarding the Ocean Alkalinity Enhancement (OAE) CDR option. Tier 2 scenarios a) widen the sensitivity analysis by also analyzing the effect of disabling distinct CDR measures or land-based mitigation options and b) take feedback from stakeholder interaction workshops into consideration. As a consequence, already, the Default Tier 2 scenarios differ from the Tier 1 scenarios, particularly the most ambitious 1.5°C no/low OS scenario. Furthermore, upon suggestion by stakeholders, we added two sensitivity scenarios, in which developing countries have more time to ramp-up climate mitigation, shifting more of the burden to the richer countries.

¹ <https://drive.google.com/drive/folders/1chTtJlOaUmVFxBbyp3EbrvFVogp1Q-mq>

Table 4.1. Scenario Matrix. *The Tier 1 1.5°C no/low OS scenarios are not allowed to exceed the cumulative CO2 budget of 500 Gt CO2 from 2020 at any point in time. In contrast, the Tier 2 1.5°C no/low OS scenarios may temporarily exceed these 500 Gt CO2 by about 150 Gt CO2 or even by 225 Gt CO2 in the scenario without ecosystem protection and restoration (please refer to sections 3.2, 4.3 and 4.44 for details).

Scenario name	Cumulative carbon budget from 2020	Target formulation	Sensitivity options
2°C high OS	1150 Gt CO2	End of century budget; overshoot allowed (high OS)	● Default (Tier 1) ● No OAE (Tier 1)
2°C no/low OS	1150 Gt CO2	Peak budget; only minimal overshoot allowed (low/no OS)	● Default (Tier 1) ● No OAE (Tier 1)
1.5°C high OS	500 Gt CO2	End of century budget; overshoot allowed (high OS)	● Default (Tier 1,2) ● No OAE (Tier 1) ● No DAC / no EW (Tier 2) ● No A/R (Tier 2) ● No ecosystem protection and restoration (Tier 2) ● Carbon price convergence in 2070 (Tier 2)
1.5°C no/low OS	500 Gt CO2*	Peak budget; only small overshoot allowed (low/no OS)	● Default (Tier 1,2) ● No OAE (Tier 1) ● No DAC / no EW (Tier 2) ● No A/R (Tier 2) ● No ecosystem protection and restoration (Tier 2) ● Carbon price convergence in 2070 (Tier 2)

Table 4.1 gives an overview over the scenario specifications. The Default scenarios differ with respect to two different settings:

A) No or low overshoot (no/low OS) scenarios are, in case of the Tier 1 scenarios, not allowed to exceed a prescribed CO2 budget at any point in time within the 21st century (Tier 1 scenarios) or, in case of Tier 2 scenarios, may only exceed it by a small margin. Here climate policy starts immediately. By contrast, high overshoot scenarios (high OS) only need to match cumulative CO2 emissions in 2100, i.e., they have the flexibility to temporarily exceed the given budget by a large margin, but they need to return to it by the end of the century via CDR. These so-called end-of-century budget scenarios (EocBudg) reflect a world with delayed climate policy starting to raise ambitions from current policies only in 2035. To reflect these

narratives, the carbon price trajectories between these two types differ: carbon prices in no/low OS scenarios increase strongly until mid century and are constant afterwards (or even recede in case of the 1.5°C no/low Tier 1 scenarios, see section 3.2 for details), while carbon prices in high OS scenarios start at low levels and increase exponentially, such that they only reach their maximum by the end of the century, deferring climate change mitigation.

B) Scenarios differ with respect to the cumulative CO₂ emissions at the peak or in 2100. Scenarios with a budget of 500 Gt CO₂ are compatible with a 1.5°C target (1.5°C) and scenarios with 1150 Gt CO₂ with a well below 2°C target (2°C). Please refer to section 3.2 for details on the differences between implementation of the carbon budget in the Tier 1 and Tier 2 no/low OS 1.5°C scenarios.

Complementing these Default scenarios, we derived sensitivity scenarios in which we vary the assumptions on CDR (deactivating each OAE, EW and DACCS and A/R), land-use (deactivating CO₂ pricing on natural vegetation) and equity (postponing the convergence of carbon prices towards a globally uniform level to 2070, compared to 2050 in the Default scenarios).

The improved REMIND-MAGPIE model and the better interfacing with the IAM models is used in the ScenarioMIP process to provide better and more comprehensive scenario data on climate forcers to ESMs.

4.2 Results default Tier 1 scenarios

This section covers the main findings of the Tier 1 scenarios, which are the ones that will be used by the full-complexity level ESMs.

4.2.1 Overview

Figure 1 gives an overview over the scenarios, showing annual and cumulative emissions as well as the temperature response evaluated with the Simple Climate Model (SCM) MAGGIC610. We find that the CO₂ emission profiles differ largely between these scenarios. For the no/low OS 1.5°C target with OAE the point of net-zero CO₂ is already reached in 2041. While still strengthening climate policies immediately, the less ambitious no/low OS wb2°C scenario only reaches net-zero CO₂ emissions by 2100. In contrast, in the high OS scenarios the net-zero year shifts to 2062 and 2077 for the 1.5°C and wb2°C target, respectively. That the point of net-zero CO₂ only differs by 15 years between the two high OS scenarios - compared to the almost 60 years in case of the scenarios with immediate climate policy-ramp-up - implies that delaying the transition results in a situation that leaves only very little leeway for climate policy adjustments to get back on track from a wb2°C to a 1.5°C compatible pathway, even with a temperature overshoot.

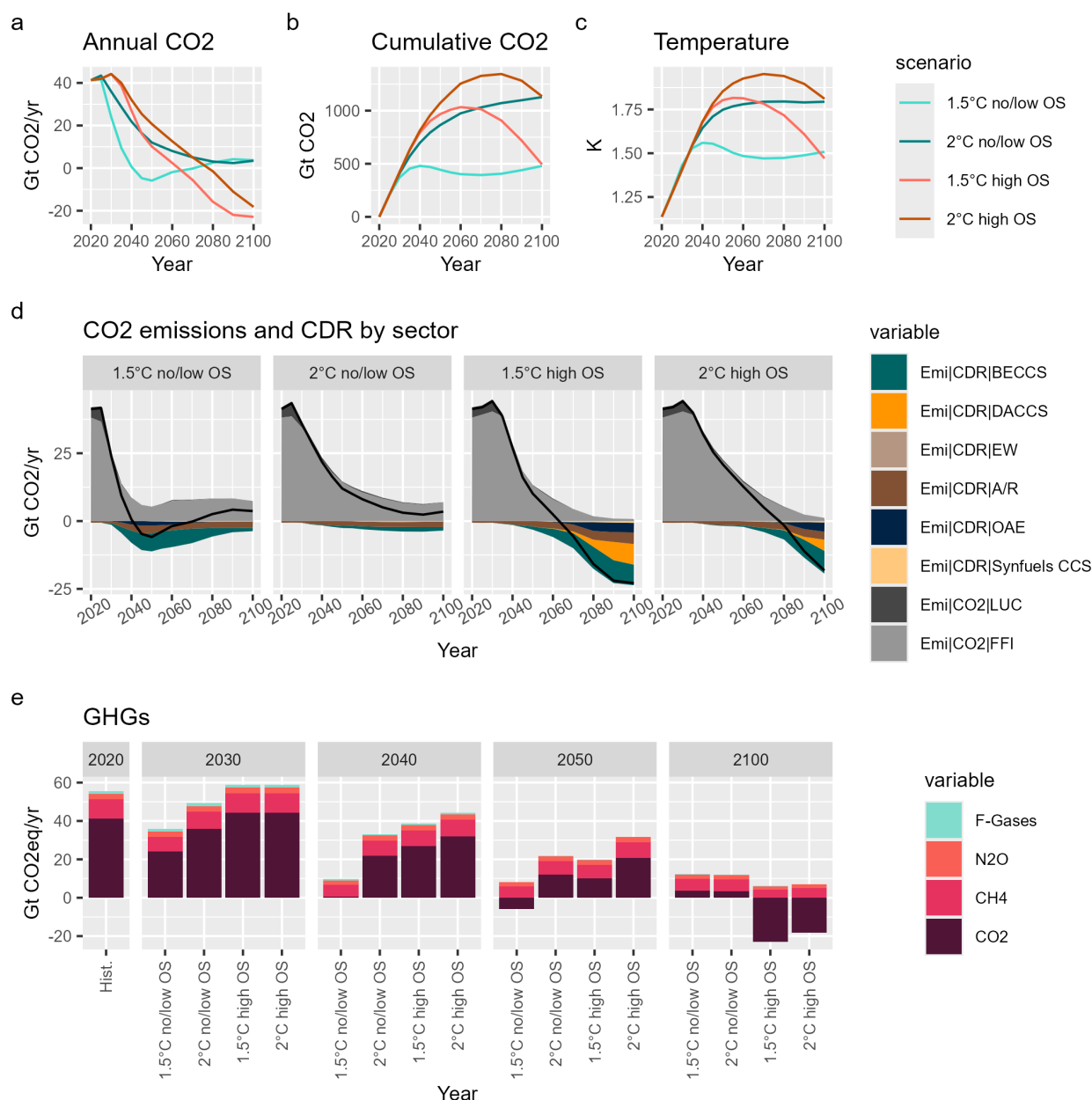


Figure 4.1. Overview of the Default Tier 1 scenarios showing a) annual CO2 emissions, b) cumulative CO2 emissions from 2020 on, c) annual mean temperature response, derived with MAGICC 6, d) CO2 emissions from land-use change (LUC) and Fossil Fuels and Industry (FFI) and as well as CDR by the different methods and e) the composition of GHGs by type.

Regarding the portfolio of CDR options (Figure 4.1b) we observe that BECCS and afforestation are being used in all scenarios, while DACCS and OAE become relevant at scale only in high OS scenarios and Industry CDR plays a minor role. EW was deactivated in the Tier 1 scenarios. As a consequence of the policy-delay the overall scale of CDR activities that is needed to still reach the 1.5°C target after high OS is massive with more than 25 Gt CO2/yr by 2100.

4.2.2 The carbon economy

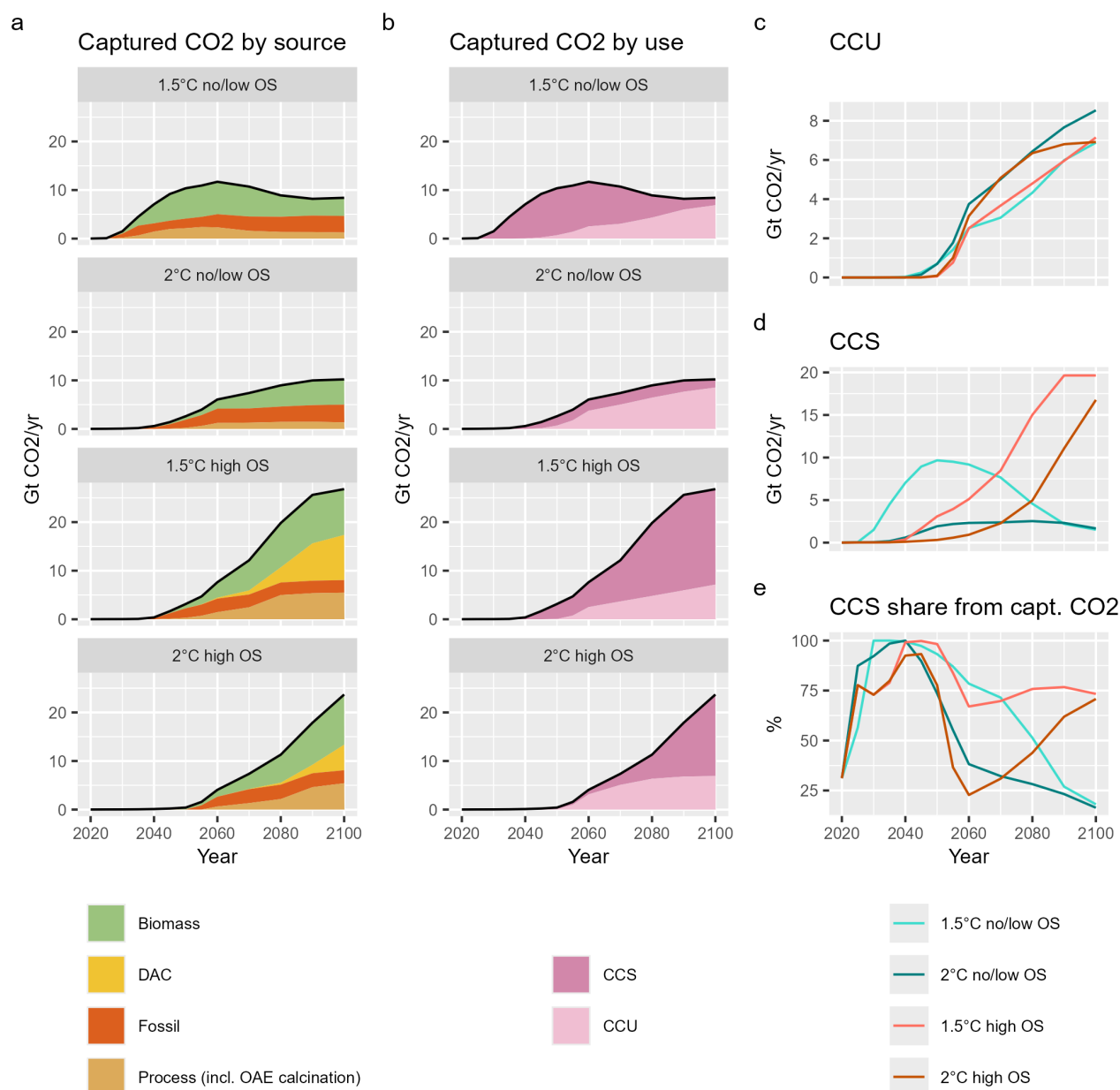


Figure 4.2. Captured, used and stored carbon in Default Tier 1 scenarios. a) Annually captured CO₂ by source. Please note that the process emissions also contain emissions that are captured in the calcination process from quicklime production for OAE, which becomes particularly prominent towards the end of the century in the high OS scenarios. b) Annually captured CO₂ by use. The “CCU” category denotes the amount of CO₂ that is captured, used within the economy to create e.g. synfuels and is eventually released again to the atmosphere, when the fuels are burned. CCS denotes the amount of CO₂ that is geologically stored underground. c), d) and show again the CCS and CCU values and e) shows the share of sequestered from total captured CO₂.

The tight carbon budget in the no OS 1.5°C scenario requires a very early and fast CDR ramp-up, reflected in high Carbon Capture and Storage (CCS) deployment. Already in 2040 7 Gt CO₂/yr are being stored geologically, which is substantially more than in all the other scenarios at that point in time (see Figure 4.2d). In such a strict 1.5°C scenario the maximum CCS growth rate is, with an annual increment of 600 Mt CO₂ in the period between 2030 and 2035, only slightly larger than the highest observed scale-up rates in

the OS scenarios. This has the interesting consequence that delaying emissions mitigation does not necessarily enable a slower phase-in of CDR, but only shifts years of strong CDR growth to the future.

It is important to emphasize that not all carbon captured is geologically stored (CCS), as the energy sector offers additional flexibility for carbon management (i.e., Carbon Capture and Utilization; CCU). Interestingly, we find that CCU only becomes relevant at scale in the second half of the century. Thus, for the case of the most ambitious 1.5°C no/low OS scenario, CCU does not contribute to reaching net-zero CO₂ emissions (see Figure 4.2c). And also, in case of the 1.5°C high OS, CCS is favored over CCU, indicated by the continuous high CCS share.

From the analysis we conclude that assumptions on both the target formulation (end-of century or peak carbon budget) and the target temperature (1.5°C or wb2°C) have a strong impact on a) total CDR deployment, b) timing of CDR deployment and timing of net-zero CO₂, c) the CDR portfolio and d) the fraction of geologically stored CO₂ from captured CO₂. Since only early mitigation in combination with a relaxed climate target (no OS wb2°C) would allow for slower CDR expansion rates, we argue that - additionally to strengthening policies that bring down positive emissions - near-term investments into CDR are important, as a large-scale and fast deployment may become inevitable regardless.

Future research shall extend previous work by Klein et al. (2014)¹² and provide a more detailed and integrated understanding of the value of carbon stocks and flows as well as the value of different energy carriers and feedstocks. This improved understanding is useful for assessing the robustness of carbon management and removal measures and, therefore, is also crucial for the interaction between IAMs and ESMs.

4.2.3 The energy system

All scenarios - high and no/low OS for both a 1.5°C and 2°C target - show a continuous growth in renewable energy sources reaching similar levels by the end of the century (see Figure 4.3). However, the transition happens at different velocities: While in the 1.5°C no/low OS scenario 40% of primary (190 EJ/yr) originates from solar PV or wind turbines already by 2040, it is only 21% (118 EJ/yr) in the 1.5°C high OS scenario. Accordingly, fossil energy is phased out substantially faster. Coal use needs to be reduced by 67% between 2020 and 2030 and almost reaches zero by 2040 in the 1.5°C no/low OS scenario, while 77 EJ/yr (46% of the 2020 value) remain in the 1.5° high OS scenario in that year.

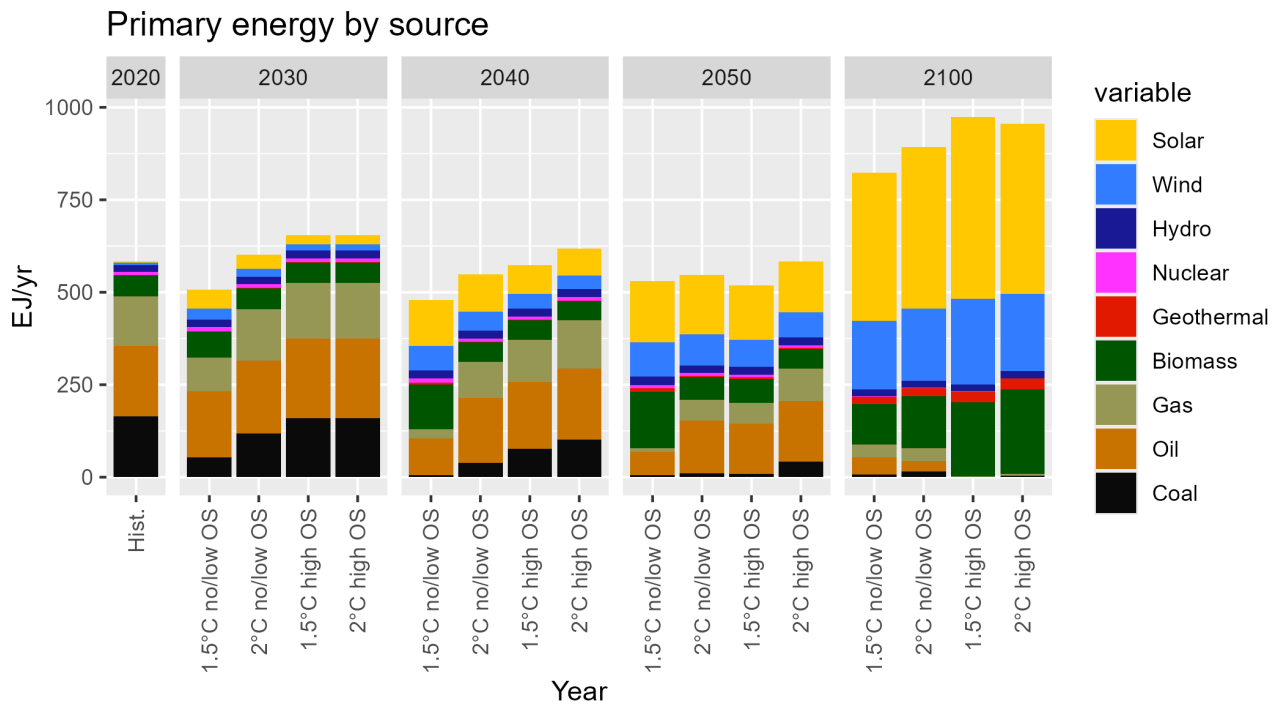


Figure 4.3. Primary energy production by source.

This fast transition away from fossil energy carriers in case of the limited overshoot goes along with a faster electrification, particularly reducing the consumption of liquid, gaseous and solid fuels (see Figure 4.4). In case of a high overshoot, this changes towards the end of the century. Here, despite the total final energy demand being overall higher, the consumption of carbonaceous fuels in the high overshoot case is, in 2100, 22% lower than in the scenario with no/low overshoot case.

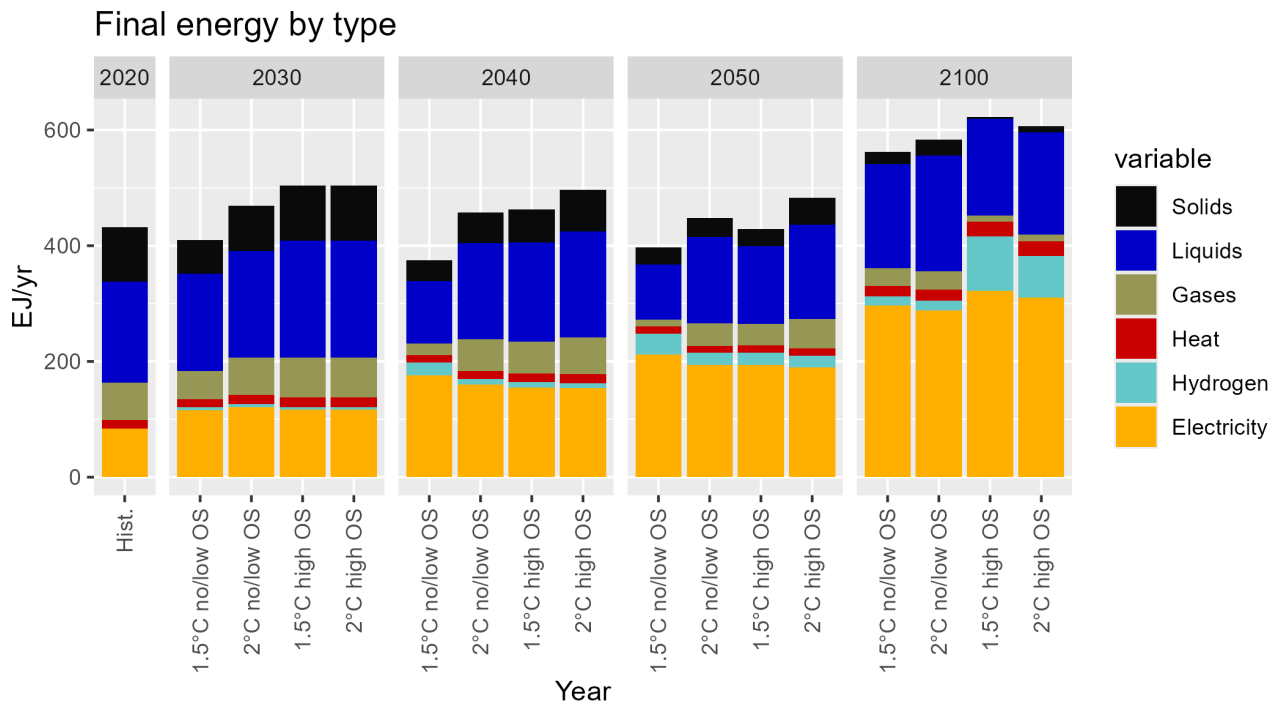


Figure 4.4. Final energy by type.

It is important to note that 17% of the total final energy demand is related to CDR, and particularly three quarters of total hydrogen production (71 EJ/yr) only fuels CDR processes (see Figure 4.5).

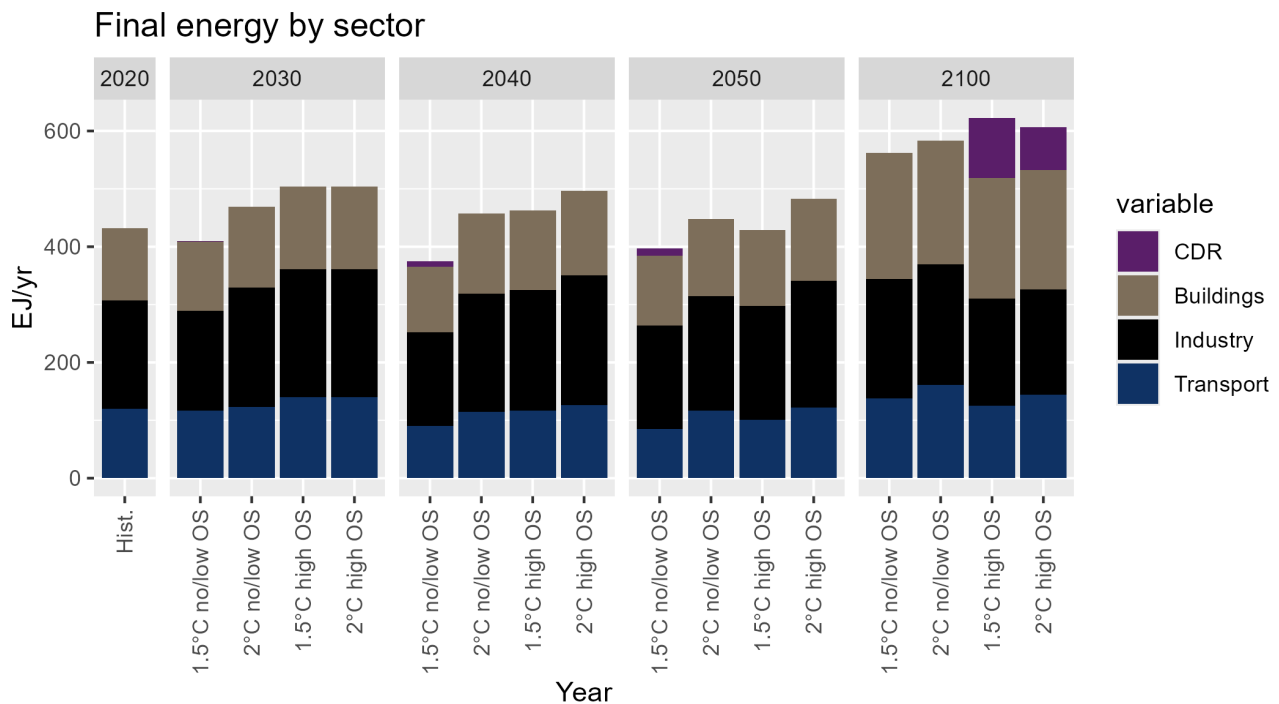


Figure 4.5. Final energy by sector.

4.2.4 The land system

The high early mitigation pressure in the 1.5°C no/low OS scenario is also translated to the Agriculture, Forestry and Other Land-Use (AFOLU) sector. We find that biomass use increases to more than 120 EJ/yr globally already by 2040, requiring substantial and fast crop yield increases (see Figure 4.6).

In contrast, the delay in mitigation leads to more bioenergy (200 EJ/yr) by the end of the century in the 1.5°C high OS scenario. To that end, 330 Mha of land needs to be dedicated to bioenergy until 2100, which is 100 Mha more than what is needed for the 1.5°C no/low OS scenario at its peak demand in 2050. To provide such large quantities of land without losing carbon-rich ecosystems - particularly forests - crop yields need to increase even more until 2100. Another driver for the yield increases is the large increase in forest area. We observe that more than 500 Mha of land is net converted into forest area, mostly induced by a carbon price on land that incentivizes planting new forests for their carbon value.

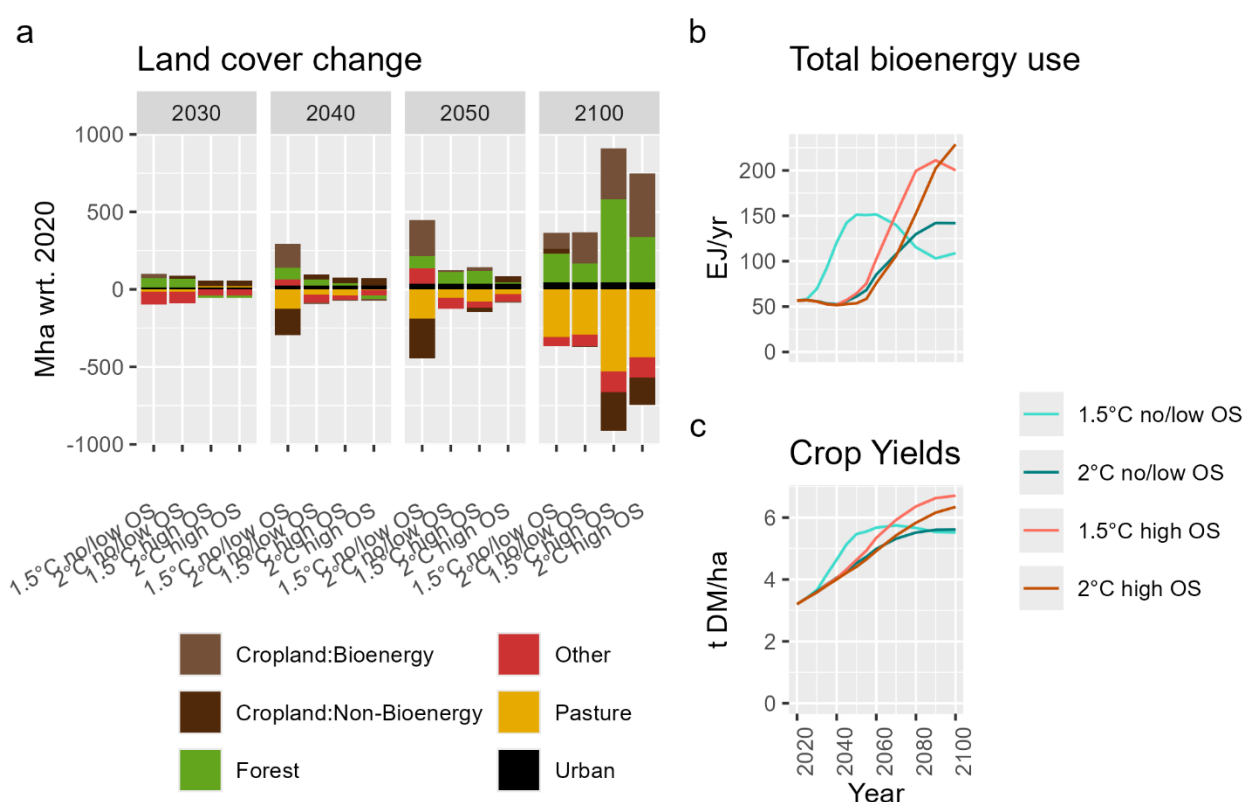


Figure 4.6. Land system overview of Tier 1 scenarios. a) Land cover change by land type with respect to the 2020 values. b) Total bioenergy use, including traditionally used biomass as well as biomass used for 1st generation biofuels and modern 2nd generation biofuels based on lignocellulosic biomass. c) Globally averaged crop yields of food crops.

4.3 Comparison between Tier 1 and Tier 2 scenarios

While the Tier 1 scenario also featured less ambitious climate targets, the Tier 2 scenarios only comprise the strict PA-compatible runs that limit warming to 1.5°C or return to that level by 2100. Therefore, we here only show the comparison between the 1.5°C no/low OS and 1.5°C high OS scenarios.

4.3.1 Differences due to the alternative design criteria of the 1.5°C no/low OS scenario

As explained in section 3.2, the Tier 2 scenarios do not only complement the Tier 1 scenarios by adding sensitivity scenarios - they were also designed to align them more with the wording of the Paris Agreement. Since not both conditions - exactly meeting the same carbon budget of 500 Gt CO₂ in 2100 and not surpassing the same budget before - can be met at the same time, the Tier 2 1.5°C no/low OS scenario now also exceeds this budget, though to a much smaller extent than the 1.5°C high OS scenario. As can be seen in Figure 4.7a, showing cumulative anthropogenic CO₂ emissions for both Tier 1 and Tier 2 scenarios, the Tier 2 1.5°C no/low OS scenario now exceeds the budget of 500 Gt CO₂ from 2020 by about 150 Gt CO₂ before returning to 500 Gt CO₂ by 2100 and thereby - again - matching the budget of the 1.5°C high OS scenario at that point in time. By contrast, the cumulative emissions of the 1.5°C high OS scenario are almost equal to those of the respective Tier 1 scenario.

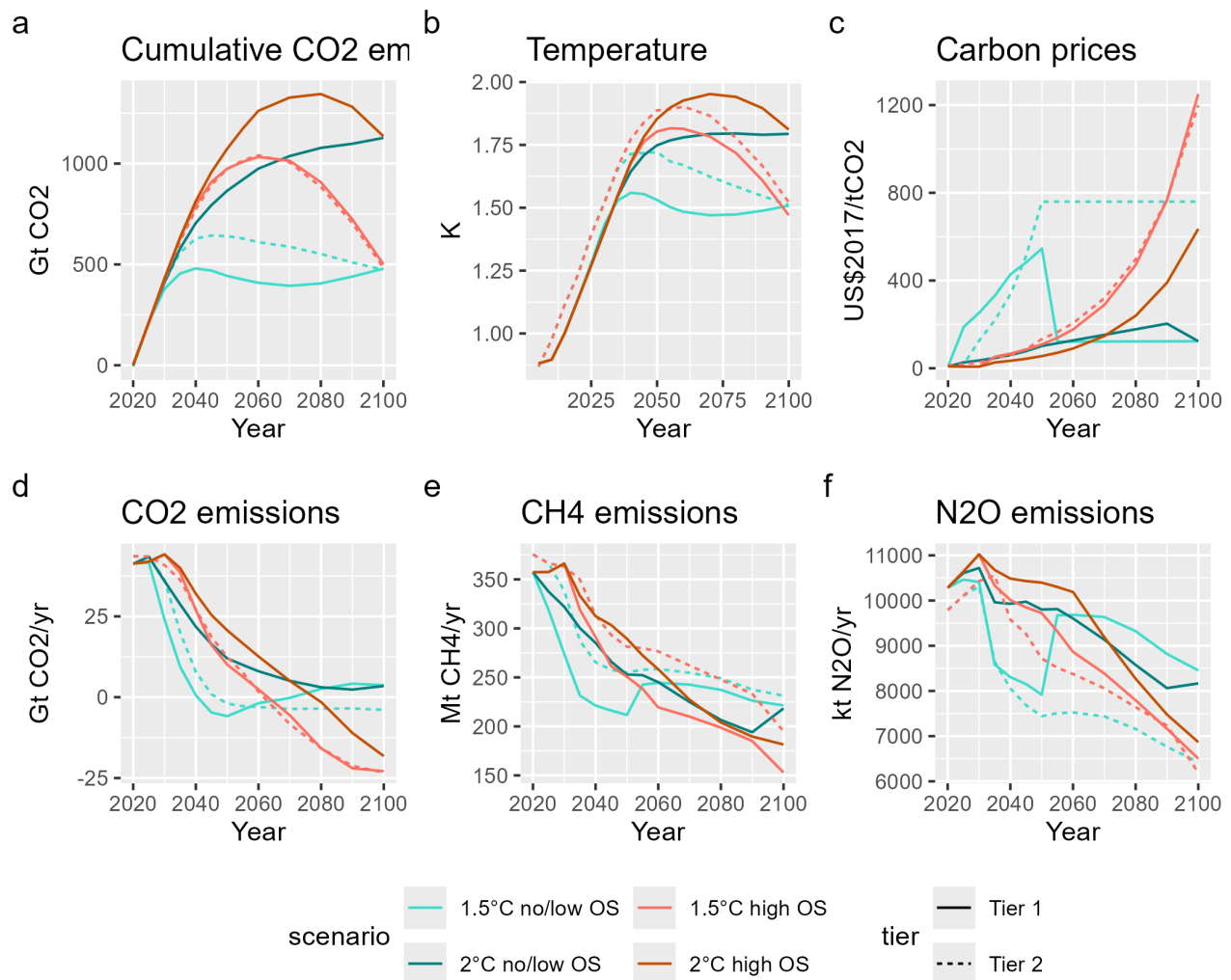


Figure 4.7. Overview of comparison between all Tier 1 and Tier 2 scenarios showing a) cumulative anthropogenic CO₂ emissions from 2020, b) increase in global surface mean temperature above pre-industrial levels, c) globally averaged CO₂ prices, d) annual CO₂ emissions, e) annual CH₄ emissions and f) annual N₂O emissions. Please note that Tier 2 scenarios only comprise scenarios that reach 500 Gt CO₂ of cumulative CO₂ emissions by 2100, aligning with the 1.5°C target, while Tier 1 scenarios additionally comprise runs only achieving a “a well-below 2°C-compatible budget of 1150 Gt CO₂.”

As a consequence of the higher levels of CO₂ emissions the temperature in the Tier 2 1.5°C no/low OS scenario is now higher than in the respective Tier 1 scenario (see Figure 4.7b). It must be noted, though,

that the temperatures are not directly comparable, since the Tier 2 scenarios use an updated version of the MAGICC model (version 7 instead of version 6), which was applied to derive the temperature response leading to generally higher temperatures in the new scenarios. However, the scenario still returns to 1.5°C by the end of the century with a 50% probability.

One of the peculiarities of the Tier 1 1.5°C no/low OS scenario is the small “dip” in cumulative emissions in the second half of the century, as explained in section 3.2. Since the corresponding GHG price levels drop quite substantially to achieve this (see Figure 4.7c), non-CO₂ GHGs also increase after reaching the peak (see Figure 4.7e,f). In the Tier 2 scenarios, GHG prices are kept constant after the peak, so CH₄ and N₂O keep declining after the peak, which is more plausible from a policy perspective. Tables 4.2 and 4.3 give an overview about key conditions/properties (design criteria) and results (model outcome), respectively, in which the Tier 1 and the Tier 2 1.5°C no/low OS scenarios differ.

Table 4.2. Comparison of properties (design criteria) of the Tier 1 and Tier 2 scenarios.

Condition	Tier 1 1.5°C no/low OS	Tier 2 1.5°C no/low OS
The 2050 and the 2100 CO ₂ budget are constrained at the same time	Yes	No
Net CO ₂ emissions keep declining after the peak	No	Yes
Temperature keeps declining until 2100	No	Yes
GHG prices do not fall below pre-peak levels	No	Yes

Table 4.3. Comparison of key scenario results (model outcome) of the Tier 1 and Tier 2 scenarios. *Temperature response was only evaluated with the reduced complexity ESM MAGICC. The temperature response in the full complexity ESM runs may lead to a different result.

Result	Tier 1 1.5°C no/low OS	Tier 2 1.5°C no/low OS
Temperature does not exceed 1.6°C* (only “minimal” overshoot)	Yes	No
Difference in peak temperature to the 1.5°C high OS scenario is at least 0.25K*	Yes	No
Year of net-zero CO ₂ emissions	2040	2045

4.3.2 Differences due to changed assumptions on CDR

There are three main changes regarding the implementation of CDR in REMIND-MAGPIE between the default Tier 1 and Tier 2 scenarios: Final Energy (FE) consumption for CDR was limited to 10% of each region's total FE demand, Enhanced Weathering (EW) was added as a CDR option and CDR via long-lived materials was added.

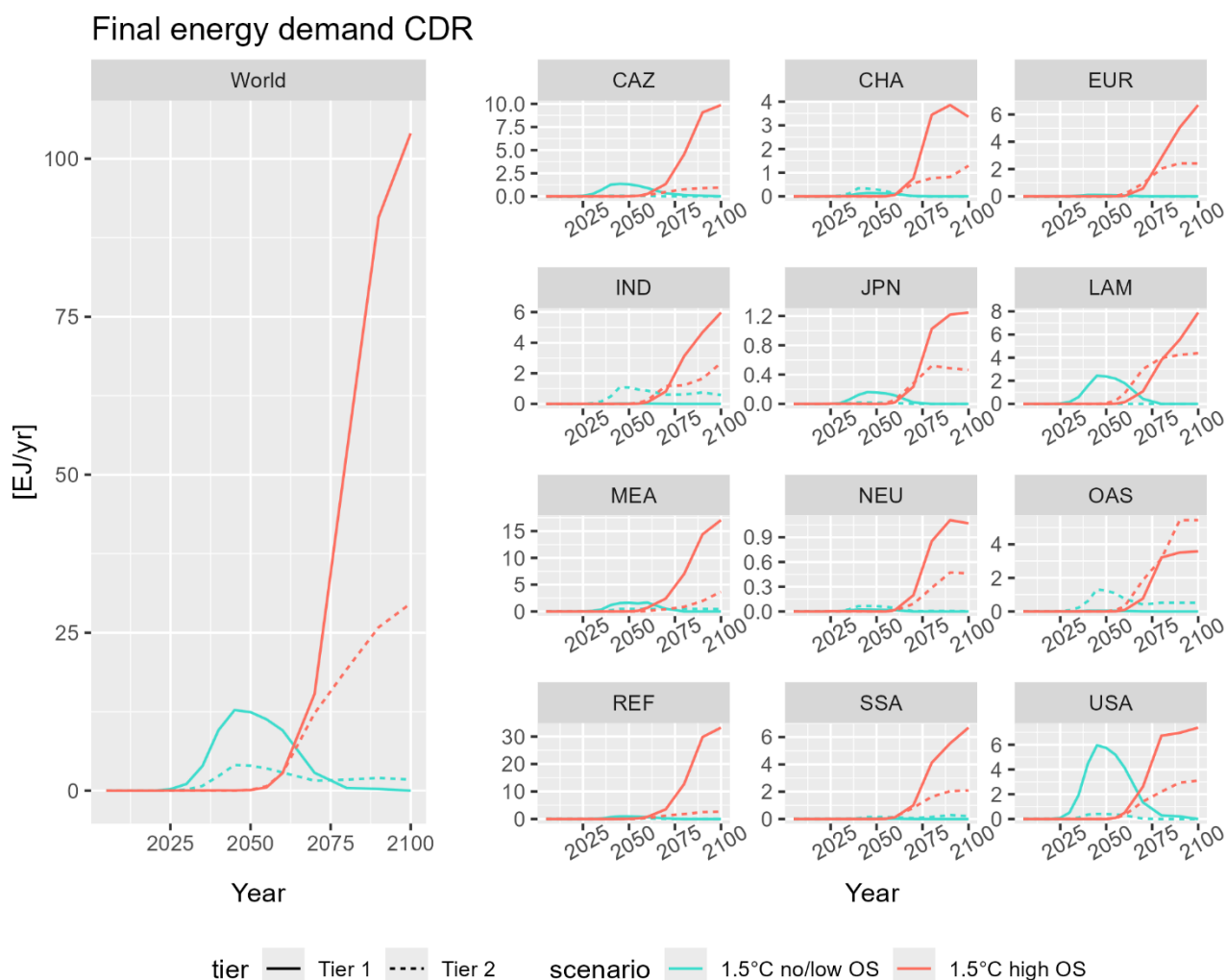


Figure 4.8. Comparison of the final energy demand for CDR activities in each region between Tier 1 and Tier 2 scenarios. The main driver for the reduced final energy demand in the 1.5°C high OS Tier 2 scenario compared to the respective Tier 1 scenario, is the assumption that regions can only use at maximum 10% of their total final energy demand for CDR. For a mapping between REMIND-MAGPIE native regions and countries, please refer to Table A.1 in the Appendix.

As can be seen in Figure 4.8, in the Tier 1 1.5°C high OS scenario a large fraction of FE is used for CDR activities mostly concentrated in only a few regions, such as in REF (Reforming economies, particularly Russia) and in CAZ (Canada, Australia and New Zealand) with 33 EJ/yr and 10 EJ/yr in 2100, respectively. The 10% constraint strongly reduces the amount of FE for CDR activities in these (and in other) regions, such that the total amount of FE for CDR is reduced from 104 EJ/yr to 30 EJ/yr in 2100.

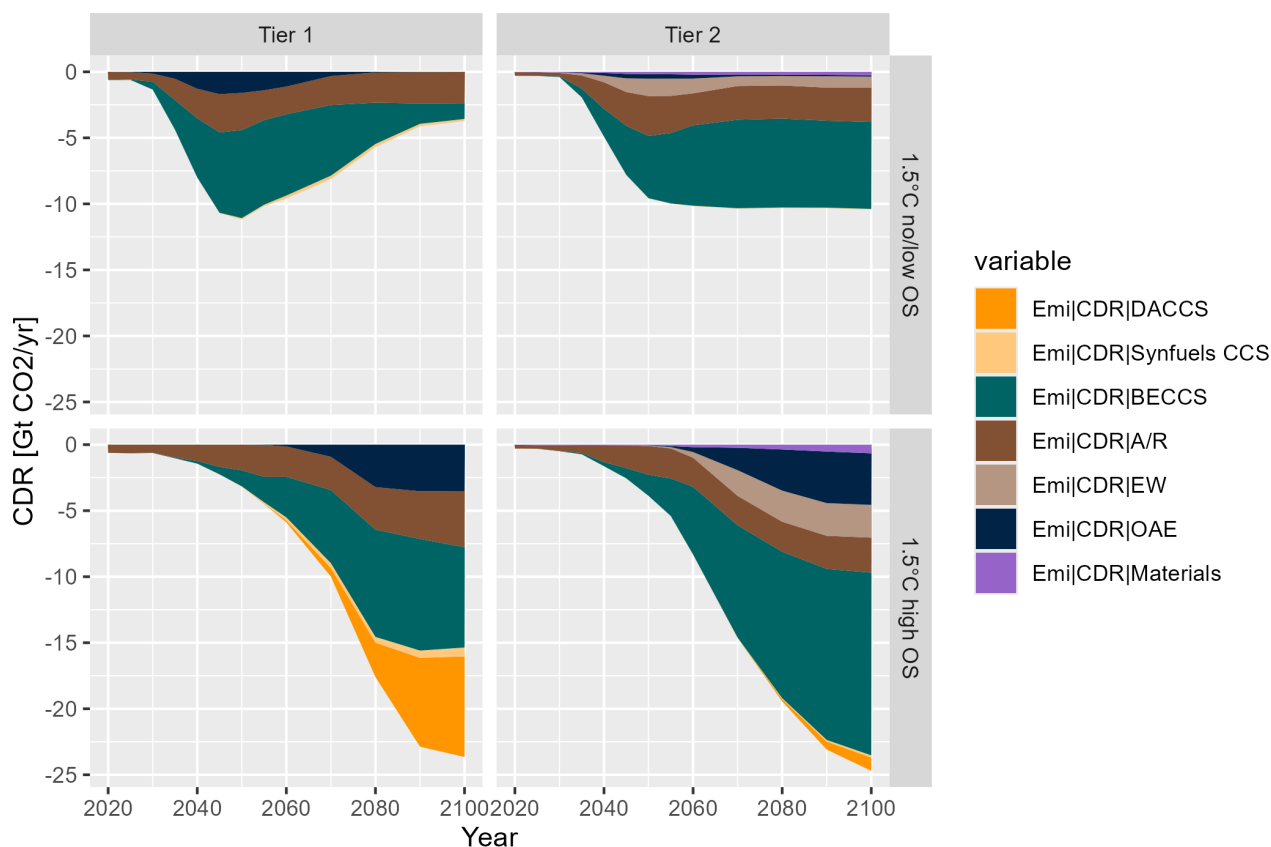


Figure 4.9. Comparison of global CDR deployment by CDR type between the 1.5°C Tier 1 and Tier 2 scenarios.

This has strong consequences for the CDR deployment (see Figure 4.9). In particular the large quantities of CO₂ removed from the atmosphere via DACCS in the 1.5°C high OS Tier 1 scenario (7.6 Gt CO₂/yr in 2100) cannot be reproduced in the respective Tier 2 scenario with only 1 Gt CO₂/yr in 2100. Instead, we observe that BECCS is taking up a much larger share of negative emissions, almost doubling the total amount of CDR from 7.6 Gt CO₂/yr to 13.8 Gt CO₂/yr in 2100. The reason here is that BECCS does not require energy, as it uses the energy from the feedstock and generates secondary energy carriers on top, so it is not constrained by FE supply, but rather increases it. EW (described below) and OAE, however, require energy inputs, so they compete with DACCS for the limited amount of final energy. And since both OAE and EW appear to be slightly less energy intensive, they mostly prevail over DACCS. Thus, also the availability of EW (which was not present in the Tier 1 scenarios) leads to a reduction of CDR via DACCS in the Tier 2 scenarios. Furthermore, the CCS injection rate is limited and in the 1.5°C high OS scenario this becomes binding such that DACCS, BECCS and OAE compete for the same limited annual CO₂ storage volume. Obviously, these large quantities of BECCS raise sustainability concerns. If biomass cultivation for BECCS was limited, to e.g. 100 EJ/yr, the amount of CDR by 2100 and thus the achievable temperature drawdown after the peak would be substantially smaller, so we observe strong trade-offs between the three objectives 1) limiting energy demand for CDR, 2) limiting biomass production to comply with sustainability criteria and 3) enable a substantial and relatively quick drawdown of global mean temperature - a reduction of around 0.25-0.30°C in less than 50 years - after the peak.

As touched upon already above, the Tier 2 scenarios have EW available as a CDR option. When available, it contributes significantly to CDR, both in low/no OS and high OS 1.5°C scenarios with 1.3 Gt CO₂/yr removed in 2050 in the 1.5° no/low OS scenario and 2.5 Gt CO₂/yr in 2100 in the 1.5°C high OS scenario.

Also, carbon stored in long-lived materials contributes to CDR, though to a much smaller extent with 0.3 and 0.7 Gt CO₂/yr removed from the atmosphere in 2100 in the 1.5°C no/low and high OS scenario, respectively.

4.3.3 Consequences for comparability

All the changes described above have to be considered, when analyzing the sensitivity scenarios (next section). The sensitivity of having OAE available was performed within the Tier 1 scenarios, while the other sensitivity scenarios with alternative assumptions on CDR deployment, land-based mitigation policies and equity were evaluated with the Tier 2 scenarios. In particular, due to the strongly reduced DACCS deployment in Tier 2, the differences between scenarios allowing or not allowing for that CDR option will be very small (see section 4.4.2).

In general, the above described changes between the assumptions in the Tier 1 and Tier 2 scenarios make it difficult to link the results from the high complexity ESMs that are driven by emissions from the Tier 1 scenarios with the more nuanced pathways of the Tier 2 scenarios. E.g., when analyzing the impacts of BECCS on ecosystems in an ESM, this can only be directly linked to the Tier 1 scenarios, because, despite that fact that the Tier 2 scenarios follow very similar CO₂ emissions pathways, the total amounts of biomass crop area differs strongly between these two scenarios.

With the Tier 1 scenarios being a bit more extreme (particularly the no/low OS scenario featuring super fast and stringent mitigation action) the results from the reversibility experiments in the ESMs can be seen as an upper bound, to what might be observed in the Tier 2 scenarios, since here the OS will be smaller.

4.4 Sensitivities of CDR and land-use assumptions

In the following we present the results of the scenarios, in which we changed assumptions regarding the CDR portfolio, land-use policies or equity considerations to assess the robustness of the findings.

4.4.1 No OAE (Tier 1)

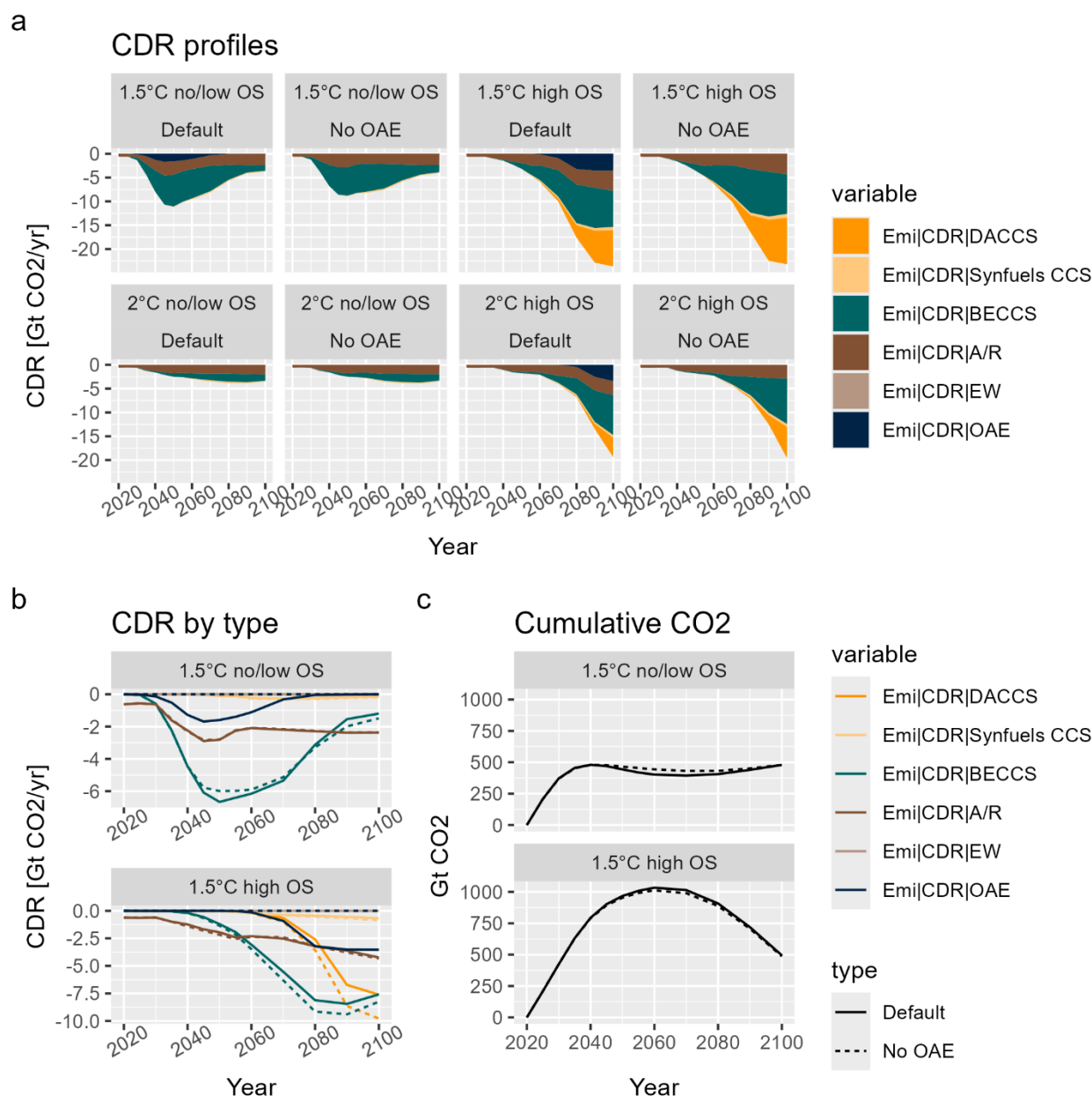


Figure 4.10. Overview figure showing the difference between scenarios with and without OAE being available as CDR technology. a) shows the composition (for 1.5°C and 2°C scenarios) and b) lineplots of the CDR technologies (for 1.5°C scenarios) and c) cumulative anthropogenic CO₂ emissions since 2020 (for 1.5°C scenarios). Please note that the CDR quantities of the OAE technology are net values, including positive emissions from limestone calcination. The gross CO₂ uptake from the ocean is larger.

We find that the impact of the availability of OAE on the deployment of other CDR activities depends on the pathway type. While it does not show up in a 2°C no OS scenario, it is being deployed in the 1.5°C no/low OS to some extent. However, while the availability of OAE increases the total CDR volume in the peak year 2040 by 1.2 Gt CO₂/yr, it does not reduce the deployment of other CDR technologies. This is different in the high OS scenarios. Particularly in the 1.5°C high OS scenario OAE acts as a substitute for BECCS and particularly DACCS, reducing the amount of CDR from these technologies in 2100 by 0.7 Gt CO₂/yr and 2.2 Gt CO₂/yr, respectively, while increasing the total CDR volume only by 0.5 Gt CO₂/yr (see Figure 4.10). The

reason that it here rather acts as a substitute for BECCS and DACCS is that all these technologies compete for the limited annual CCS capacities (we assume a global injection cap of ca. 20 Gt CO₂/yr), which becomes binding only in the high OS scenarios. Overall, the impact of OAE availability on peak CO₂ emissions is rather small. If OAE is not available, the peak of cumulative emissions in 2060 is only 21 Gt CO₂ smaller than in the case with OAE.

It is important to note that OAE was limited in our scenarios to not exceed a total volume of 5 Gt CO₂ that is taken up by the ocean per year for precautionary principles. Given that this technology also produces some positive emissions from the limestone calcination process, the net effect is even smaller and only 3.5 Gt CO₂/yr are effectively removed from the atmosphere in 2100 in the 1.5°C high OS scenario. If the technology was not restricted, it is likely that the share amongst the CDR technologies in the 1.5°C high OS scenario would be larger. Also, parameters such as the carbon uptake rate of the ocean per unit of alkalinity or the distribution costs are still very uncertain and more optimistic assumptions may lead to higher levels of OAE (see Kowalczyk et al. (2024) for details on the assumptions regarding OAE in REMIND11).

4.4.2 No DACCS / EW (Tier 2)

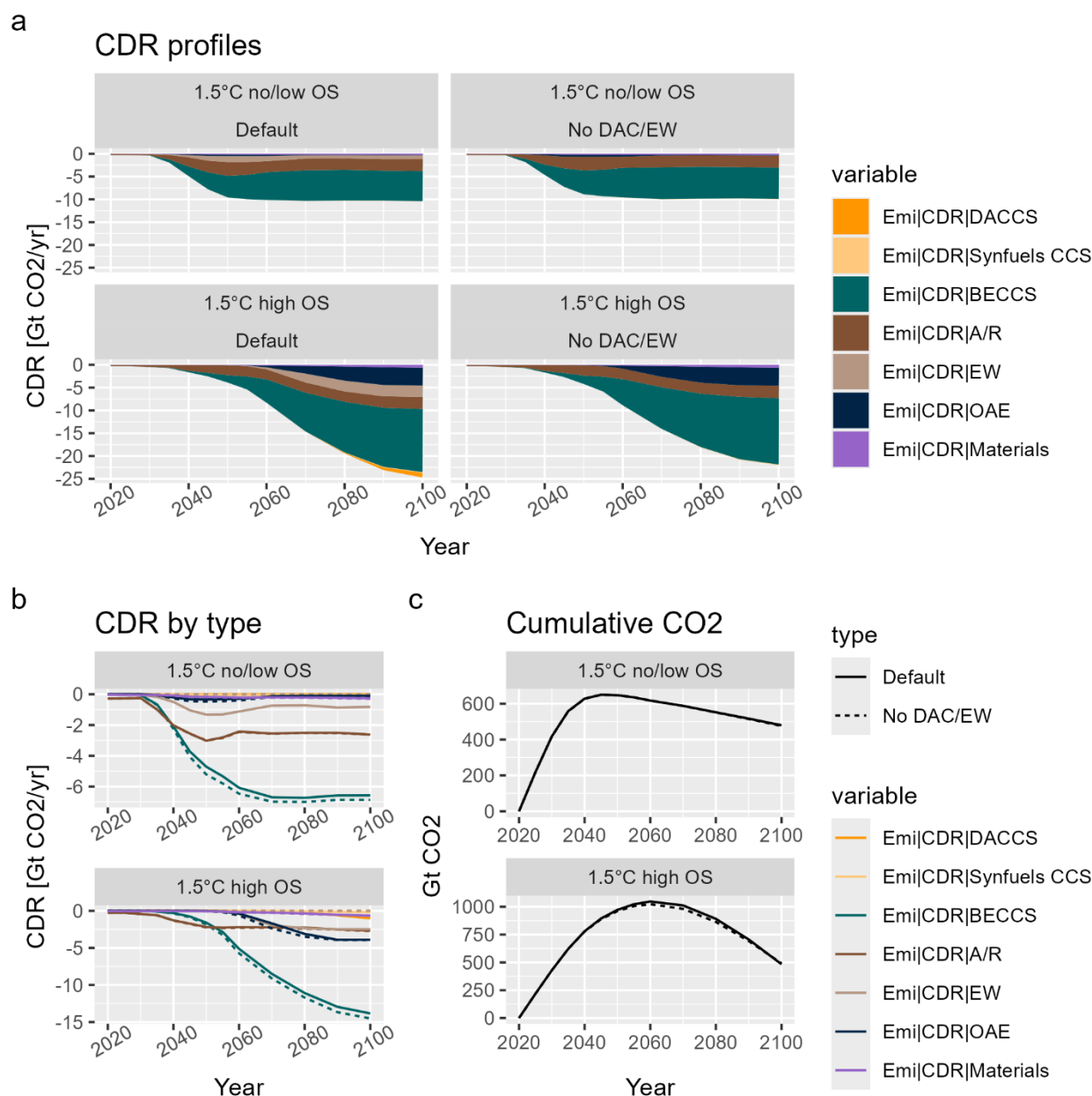


Figure 4.11. Overview figure showing the difference between Tier 2 scenarios with and without DACCS and EW being available as CDR technologies. a) shows the composition and b) line plots of the CDR technologies and c) cumulative anthropogenic CO₂ emissions since 2020. Please note that the Tier 2 scenarios have substantially less CDR from DACCS than the Tier 1 scenarios. For details, please refer to section 4.3.2.

For the 1.5°C no/low OS we find that the availability of DACCS has no impact for reaching net-zero CO₂ emissions in 2045, as it does not show up at all (see section 4.3.2, above, for an explanation). EW on the other hand removes 1 Gt CO₂/yr in that year (see Figure 4.11). Here observe that the availability both substitutes other CDR technologies, particularly BECCS - EW availability reduces CDR via BECCS by 340 Mt CO₂/yr in 2045 - and increases the total CDR quantities, allowing for 540 Mt CO₂/yr more residual emissions in 2045.

To return to 1.5°C after a high overshoot, the availability of EW and DACCS increases CDR volumes in 2100 by 2.7 Gt CO₂/yr (12%). At the same time, these technologies also substitute the other CDR options to a relatively small extent, particularly reducing the amount of CDR via BECCS by 0.7 Gt CO₂/yr in 2100, i.e., by 5%. Also, the impact on total cumulative CO₂ emissions in the peak year 2060 is, with an increase of 25 Gt CO₂/yr under availability of DACCS and EW, only limited.

4.4.3 No A/R (Tier 2)

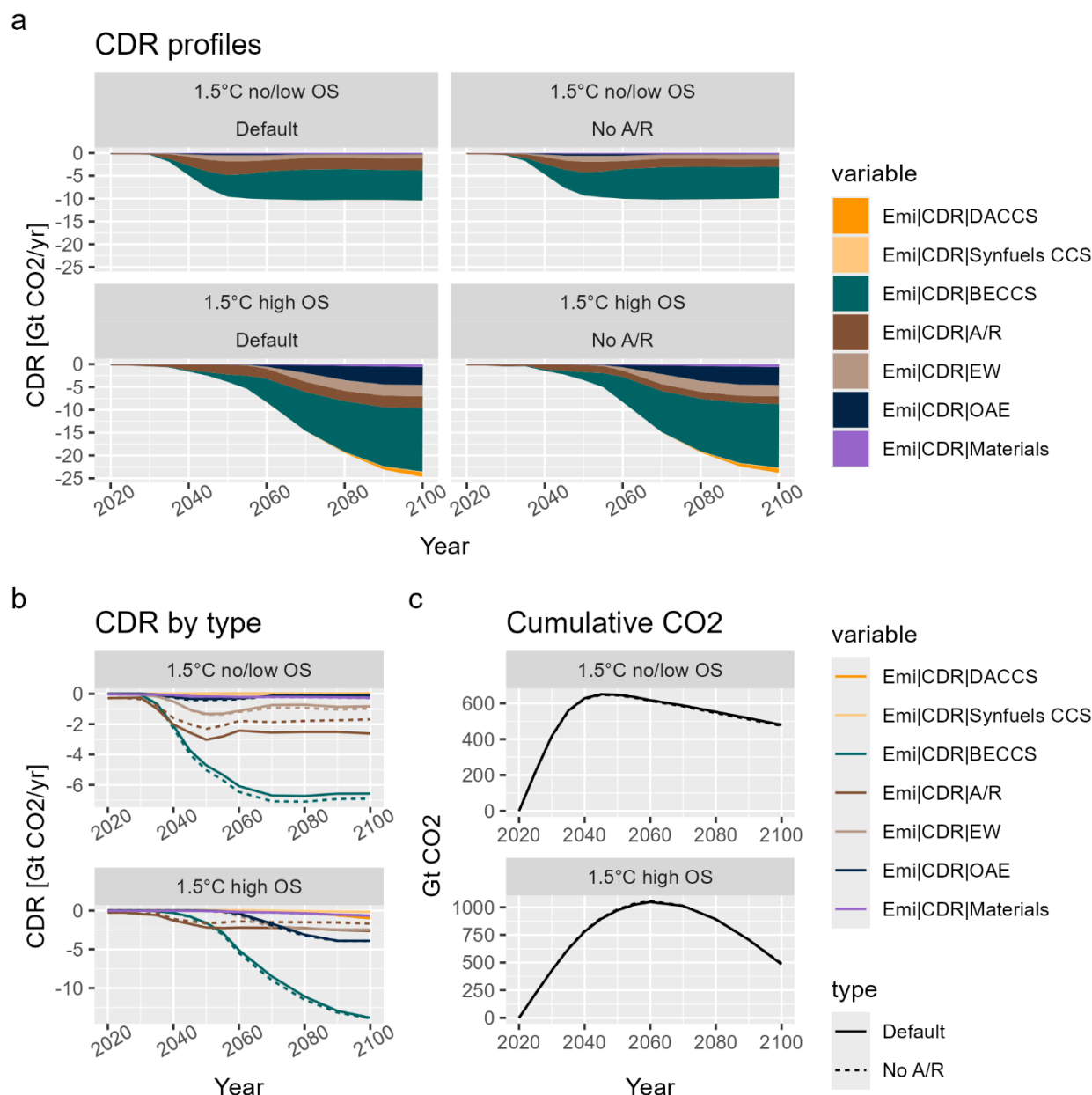


Figure 4.12. Overview figure showing the difference between Tier 2 scenarios with and without targeted A/R being available for CDR. a) shows the composition and b) lineplots of the CDR technologies and c) cumulative anthropogenic CO₂ emissions since 2020. Please note that A/R shown here - as defined within the RESCUE project - also contains regrowth of forest on abandoned

cropland additionally to targeted (policy-induced) A/R. Since the fraction of this “non-intentional” A/R is quite large, deactivating policy-induced A/R only reduces the amount of CO₂ removed via A/R to some extent.

Policy-driven afforestation and reforestation (A/R) in MAgPIE entails two parts: 1) targeted area quantity targets from already implemented (NPI) and planned (NDC) policies and 2) price-driven A/R incentivized by remunerating the carbon uptake on land with the CO₂ price. In the sensitivity scenarios without A/R, both types are deactivated. An important assumption is that we still allow for “unintentional” regrowth of natural vegetation on formerly managed land, for instance on abandoned cropland. We here define A/R as the net CO₂ uptake on all kinds of managed land, i.e. the net effect of gross positive land-use change emissions (i.e. from deforestation and other conversion of carbon-rich ecosystems) and negative emissions from A/R. Thus, also the unintentional part is accounted for in the A/R. Since this part makes up a large share of total A/R, the overall effect of deactivating the policy-driven A/R activities is limited: in both scenarios, the no/low and the high OS 1.5°C scenario, the total CDR from A/R is less than 1 Gt CO₂/yr throughout the whole century (see figure 4.12). Accordingly, the effect on the deployment of other CDR options is quite small.

4.4.4 No ecosystem protection (Tier 2)

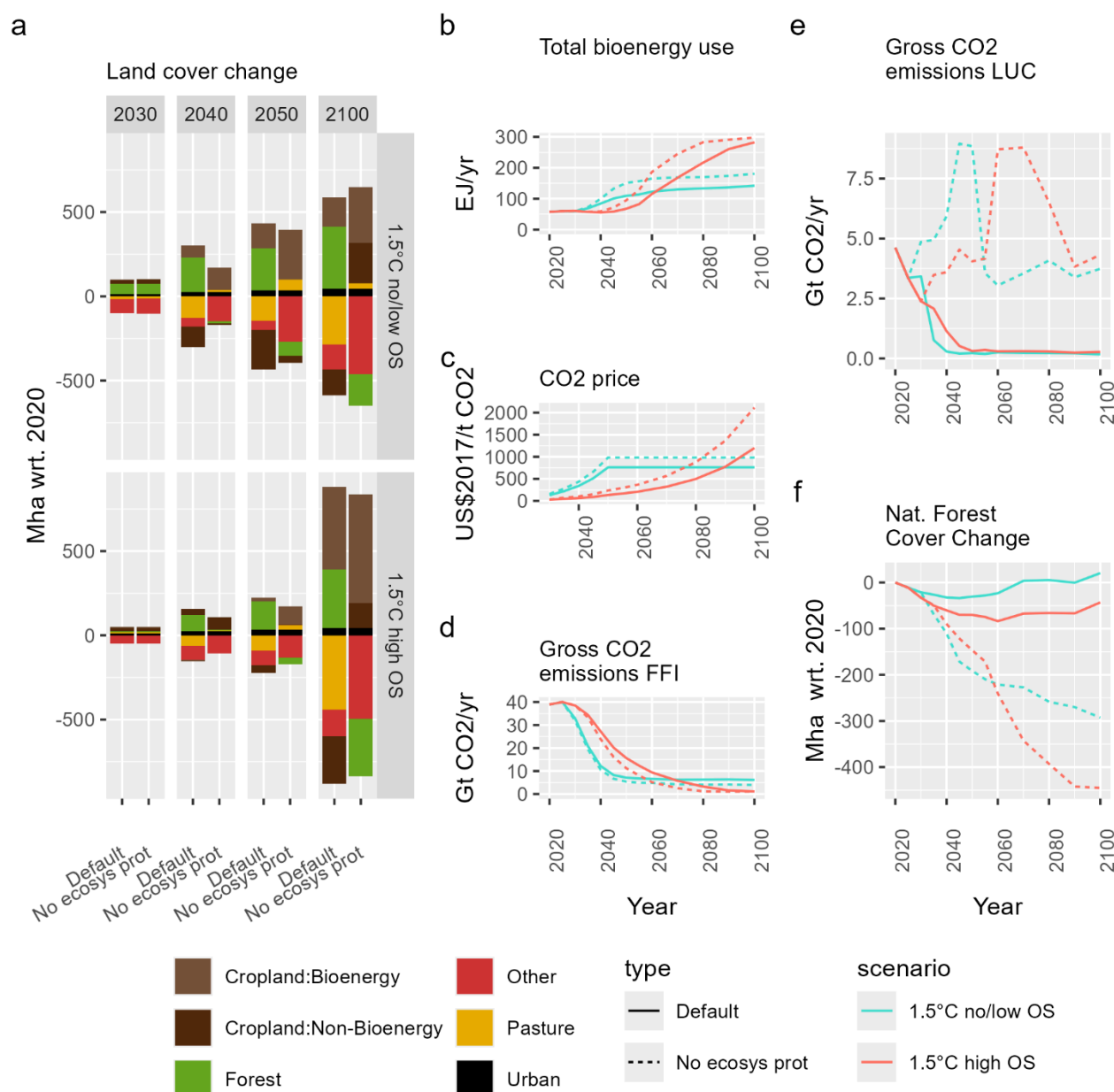


Figure 4.13. a) Land cover change, b) bioenergy use, c) CO2 price, d) gross CO2 emissions from Fossil Fuels and Industry (FFI), e) gross positive land-use change (LUC) emissions and f) forest cover change in natural forests in the 1.5°C no/low and high OS scenarios with and without ecosystem protection. Ecosystem protection is implemented via a CO2 price on land that effectively protects carbon-rich ecosystems by making it economically unattainable to convert e.g. a forest into a different land type. By deactivating this CO2 price on land also the price driven re- and afforestation (see section above) is deactivated to avoid nonsensical results in which forests are cut down (no protection) just to grow new forests afterwards (driven by a CO2 price). Please note that the targeted area quantities from NPi and NDC policies (see above, section 4.4.3) were kept activated in the scenarios, since these are not linked to ecosystem protection.

In line with Merfort et al. (2023)[5], we observe that the lack of ecosystem protection and restoration has a strong effect on land cover change and the overall system dynamics in general. As can be seen in Figure 4.13a, in both scenarios, the no/low and high OS 1.5°C scenario without ecosystem protection, large quantities of forest and non-forest natural lands are converted into cropland. The respective LUC CO2

emissions are huge (Figure 4.13e), which increases the CO₂ price that is necessary to still reach the climate target. The higher CO₂ price in turn increases the bioenergy demand (see Figure 4.13b), which in turn leads to even more land conversion. While this effect is well-understood, we show for the first time that the LUC emissions have a very different time dynamic in the low/no OS and the high OS scenarios, with LUC emissions peaking around 2045-2050 and 2060-2070, respectively. The total loss of natural forest compared to a world with functioning ecosystem protection (Figure 4.13f) is even higher in the high OS scenario (400 Mha by 2100) than in the no/low OS scenario (300 Mha by 2100).

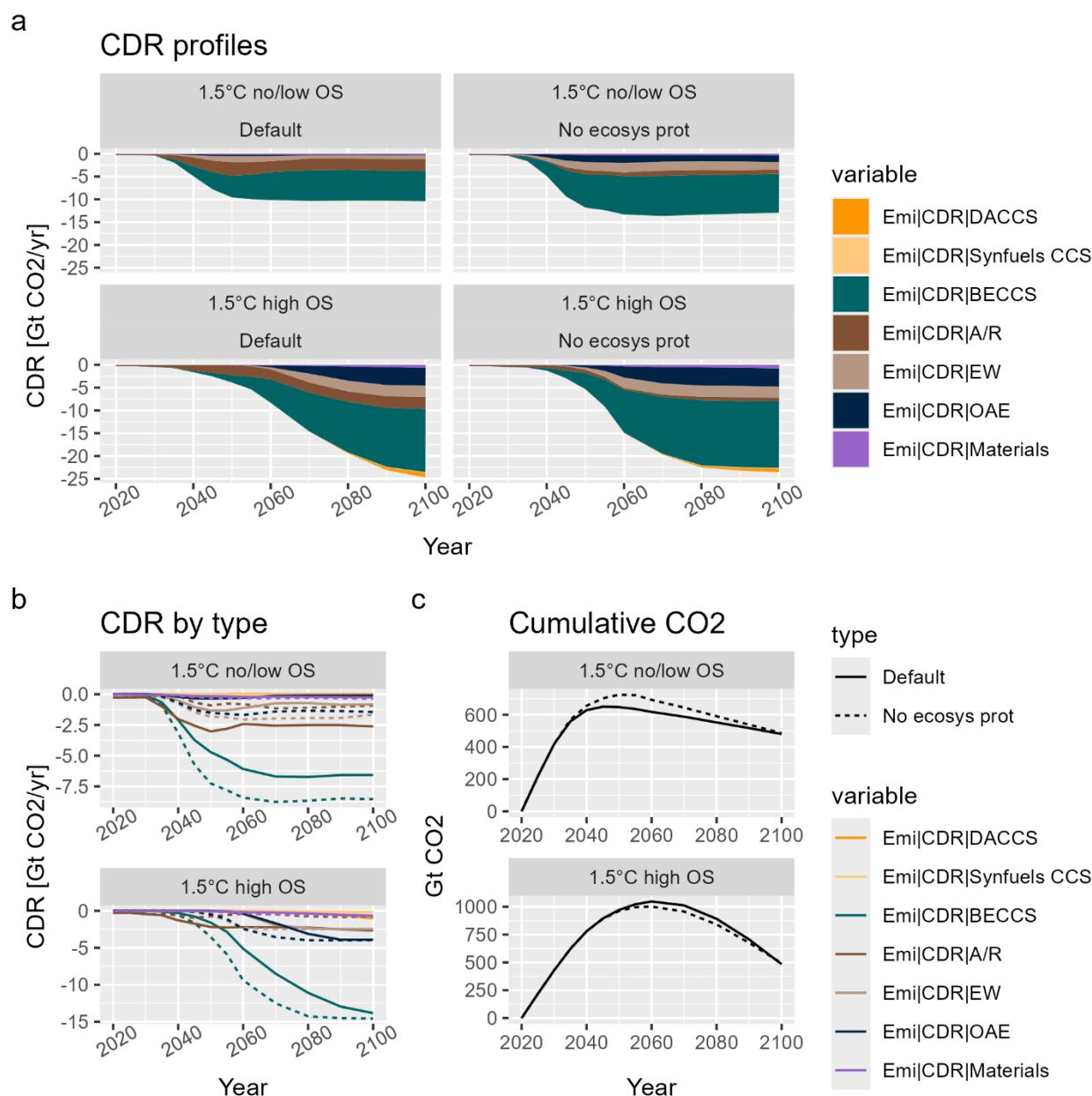


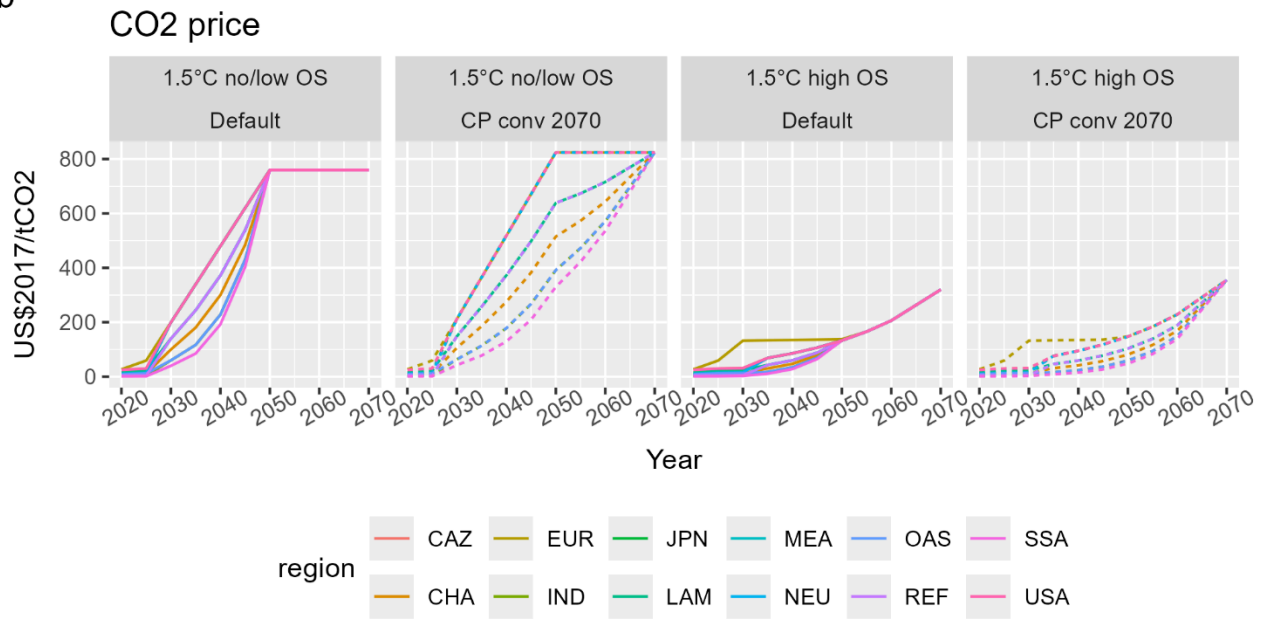
Figure 4.14. Overview figure showing the difference between Tier 2 scenarios with and without ecosystem protection via a CO₂ price on land being implemented. a) shows the composition and b) lineplots of the CDR technologies and c) cumulative anthropogenic CO₂ emissions since 2020.

Regarding the CDR deployment we observe a strong increase in BECCS if ecosystem protection is missing. In the 1.5°C no/low OS scenario CDR via BECCS increases from 4.7 to 7.3 Gt CO₂/yr and in the 1.5°C high OS scenario from 1.6 to 3.5 Gt CO₂/yr by 2050 (see Figure 4.14). But also the deployment of other CDR technologies, particularly OAE and EW, increases. Due to the limits on final energy supply for CDR (see section 4.3.2) this effect is limited in the high OS scenario towards the end of the century, when the constraints become binding. Interestingly, the combination of limits on energy use in CDR technologies, constraining annual CCS injection rates and the strongly reduced net carbon uptake on land (CDR from A/R, which is not affected by either of the constraints), leads to the fact that in 2100 total CDR quantities are lower in the 1.5°C high OS scenario without ecosystem protection (23.5 Gt CO₂/yr) compared to its equivalent with ecosystem protection (24.7 Gt CO₂/yr). As a consequence, cumulative net CO₂ emissions need to be smaller before reaching the end of the century. In other words, mitigation has to happen earlier and gross CO₂ emissions from fossil fuels and industry need to decline substantially faster (FFI, see Figure 4.13d). This effectively reduces the magnitude of the overshoot (Figure 4.14c). This is different in the 1.5°C no/low OS scenario. Here the additional LUC emissions cannot be compensated quickly enough, such that in a world without ecosystem protection cumulative CO₂ emissions are about 75 Gt CO₂ larger at the peak than in a world with land protection (see Figure 4.14c), even though carbon prices are almost 30% higher (see Figure 4.13c).

4.4.5 Carbon price convergence in 2070 (Tier 2)

By default, we assume that CO₂ prices converge to a globally uniform level by 2050. Before 2050 prices are regionally differentiated with lower prices in low-income regions (see Figure 4.15). In sensitivity scenarios, we postpone the year of carbon price convergence to 2070 (also Figure 4.15). To still reach the same climate target (with no/low OS or high OS), CO₂ prices in developed regions need to be higher than in the scenario with convergence year 2050 and also the long term (post-2070) globally uniform price level is higher. As a consequence, we observe that developing regions such as Sub-Saharan Africa (SSA) reduce their emissions at a slightly slower pace, particularly in the high OS scenario around mid-century (see Figure 4.16). On a global level that increases net CO₂ emissions until around 2070 compared to the scenario with CO₂ price convergence in 2050. To compensate for the higher emissions around mid-century, the level of net-negative emissions after the peak needs to increase. We therefore see a small increase in overall CDR quantities in both scenarios (no/low OS and high OS 1.5°C) in comparison to a CO₂ price convergence in 2050. Also, the level of the OS is higher with 9 and 45 Gt CO₂ that are emitted more until the peak in the no/low and high OS 1.5°C scenario, respectively (see Figure 4.17c).

b



b

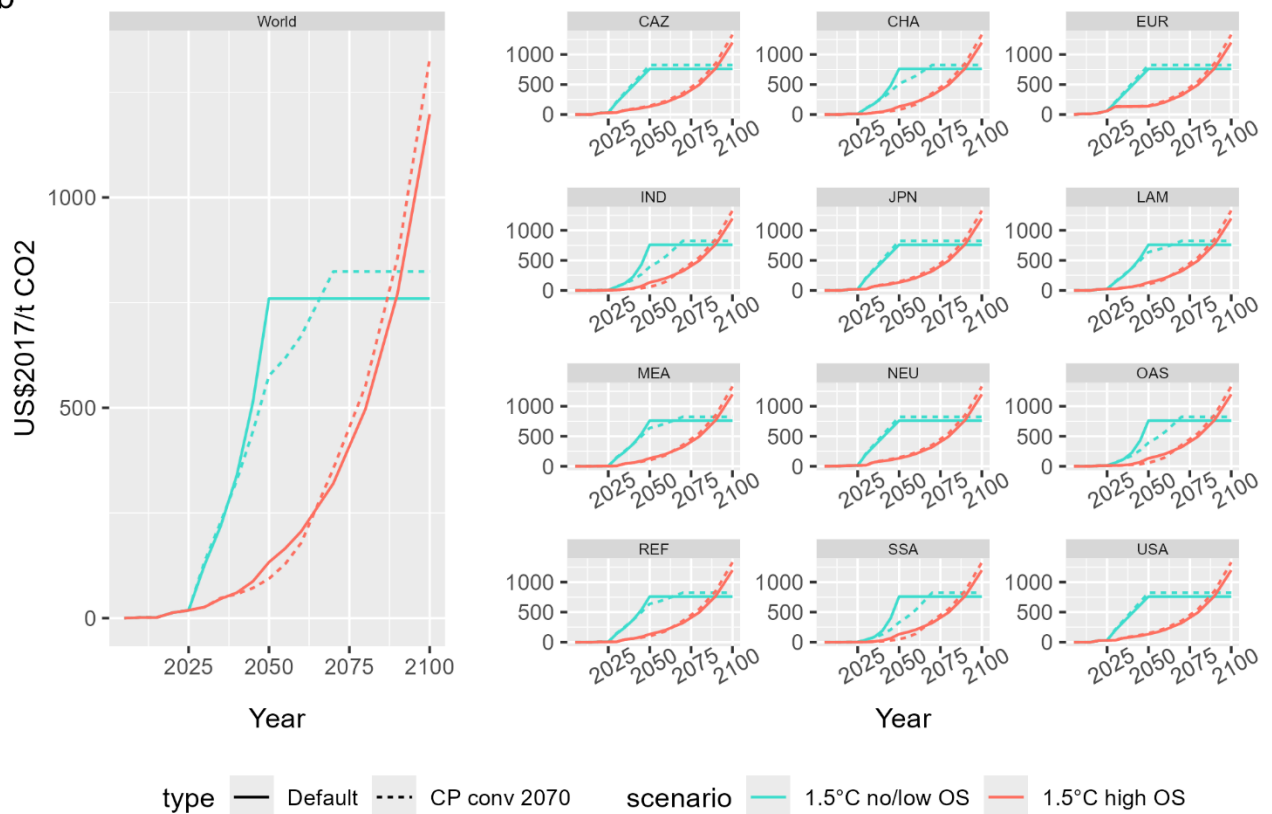


Figure 4.15. Regional and global weighted average CO2 prices in Tier 2 1.5°C no/low and high OS scenarios with default assumptions (carbon price convergence 2050) and higher equity assumptions (carbon price convergence 2070). a) shows CO2 prices by region until 2070 with each facet showing a different region to allow for a direct comparison between CO2 prices across regions. b) shows CO2 prices by scenario until 2100 with each facet showing a region or the global average to allow for a direct

comparison between CO₂ prices across scenarios. For a mapping between REMIND-MAGPIE native regions and countries, please refer to Table A.1 in the Appendix.

Overall, the effect of a prolonged period of differentiated CO₂ prices is rather small, though, and this has different reasons for the no/low and the high OS scenario. In the case of the 1.5°C no/low OS scenario, carbon prices need to be very high in early years already to reach a 1.5°C target with an OS that is as small as possible. And regarding the starting point of carbon prices in 2030, we assume that least developed countries (in the SSA region) start with a CO₂ price that is the level of 20% of the CO₂ price in developed countries (see Table 4.4). But even these 20% lead to considerable CO₂ prices in a 1.5°C

no/low OS scenario (40 \$/tCO₂ in 2030). If the time horizon for price convergence is prolonged to 2070, that does not change the prices in 2030 - in contrast, since the CO₂ prices in developed regions are slightly higher, they are also slightly higher in developed regions (42 \$/tCO₂ in SSA in 2030). Also in 2035, prices are still very similar (CO₂ prices in SSA decrease from 85 to 78 \$/tCO₂ with the prolonged price convergence). Only in the following years, this prolonged convergence period starts to become virtually effective with a price reduction from 192 to 129 \$/tCO₂ in 2040 in SSA. Since CO₂ prices in 2030 and 2035 are almost identical that means that the most crucial near-term mitigation in 2030 and 2030 is almost identical in developing regions between the 2050 and 2070 CO₂ price convergence scenarios (see emissions reductions in Figure 4.15). Thus, the way these prolonged equity pathways are constructed does not decrease the near-term burden for developed regions in the no/low OS 1.5°C scenario. Future research should go a step further and assess the impact of other enhanced equity considerations, e.g., by increasing the initial spread of carbon prices (for instance, reducing the 20% price level in SSA in 2030 to 10%) instead of or additional to the prolonged convergence period. We expect that the effect - that more equitable mitigation policies increase the overshoot magnitude - would be intensified, i.e., we expect that the cumulative emissions at the peak would be even higher then and that the higher near-term emissions would need to be compensated by more CDR in the long run.

Table 4.4. Assumptions on carbon price differentiation in the 1.5° no/low OS scenario. For a mapping between REMIND-MAGPIE native regions and countries, please refer to Table A.1 in the Appendix.

Region	CAZ, EUR, JPN, NEU, USA	LAM, MEA, REF	CHA	IND, OAS	SSA
CO ₂ price 2030 relative to developed countries	1	0.7	0.5	0.3	0.2

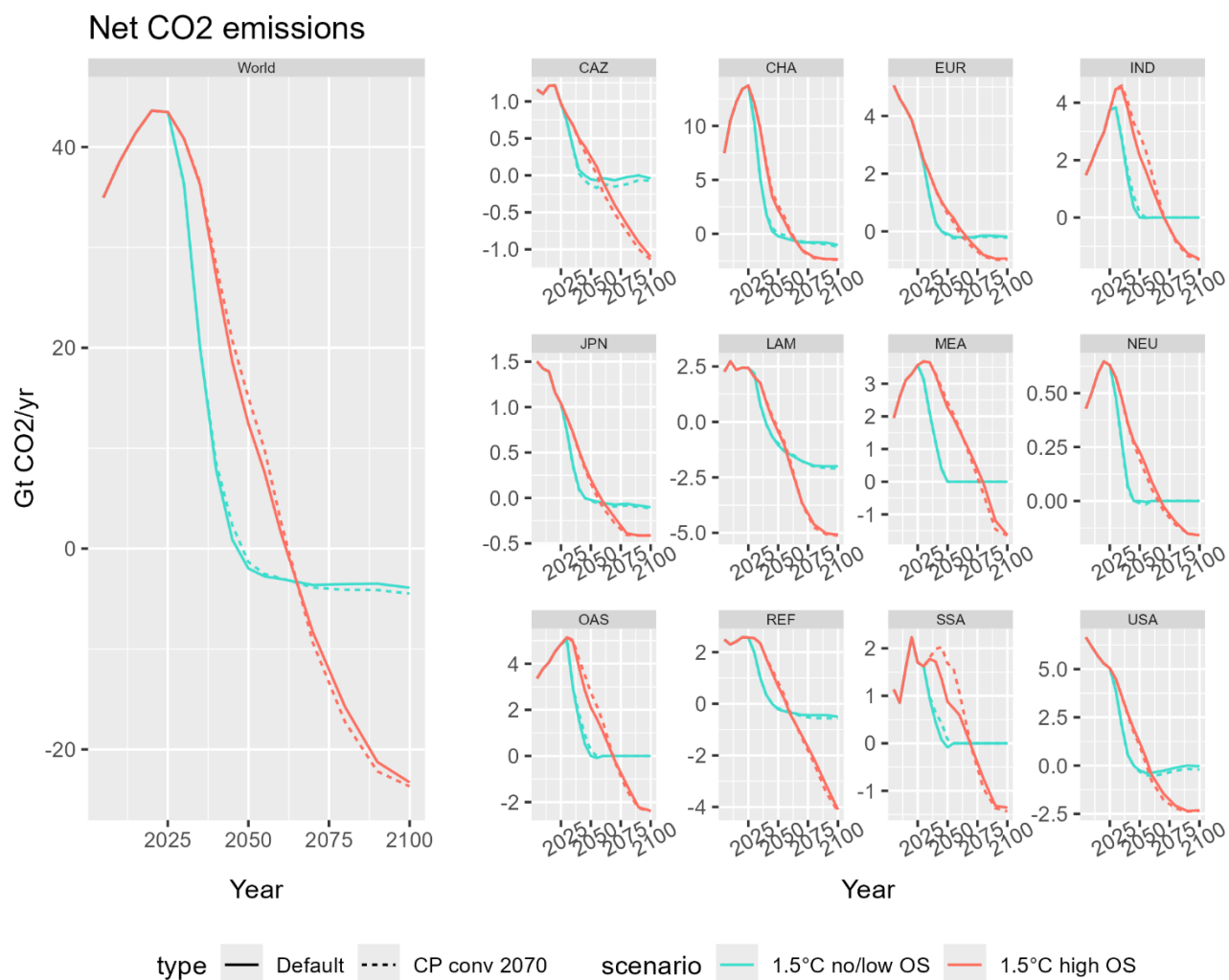


Figure 4.16. Annual net CO₂ emissions by region for Tier 2 Tier 2 1.5°C no/low and high OS scenarios with default assumptions (carbon price convergence 2050) and higher equity assumptions (carbon price convergence 2070). For a mapping between REMIND-MAGPIE native regions and countries, please refer to Table A.1 in the Appendix.

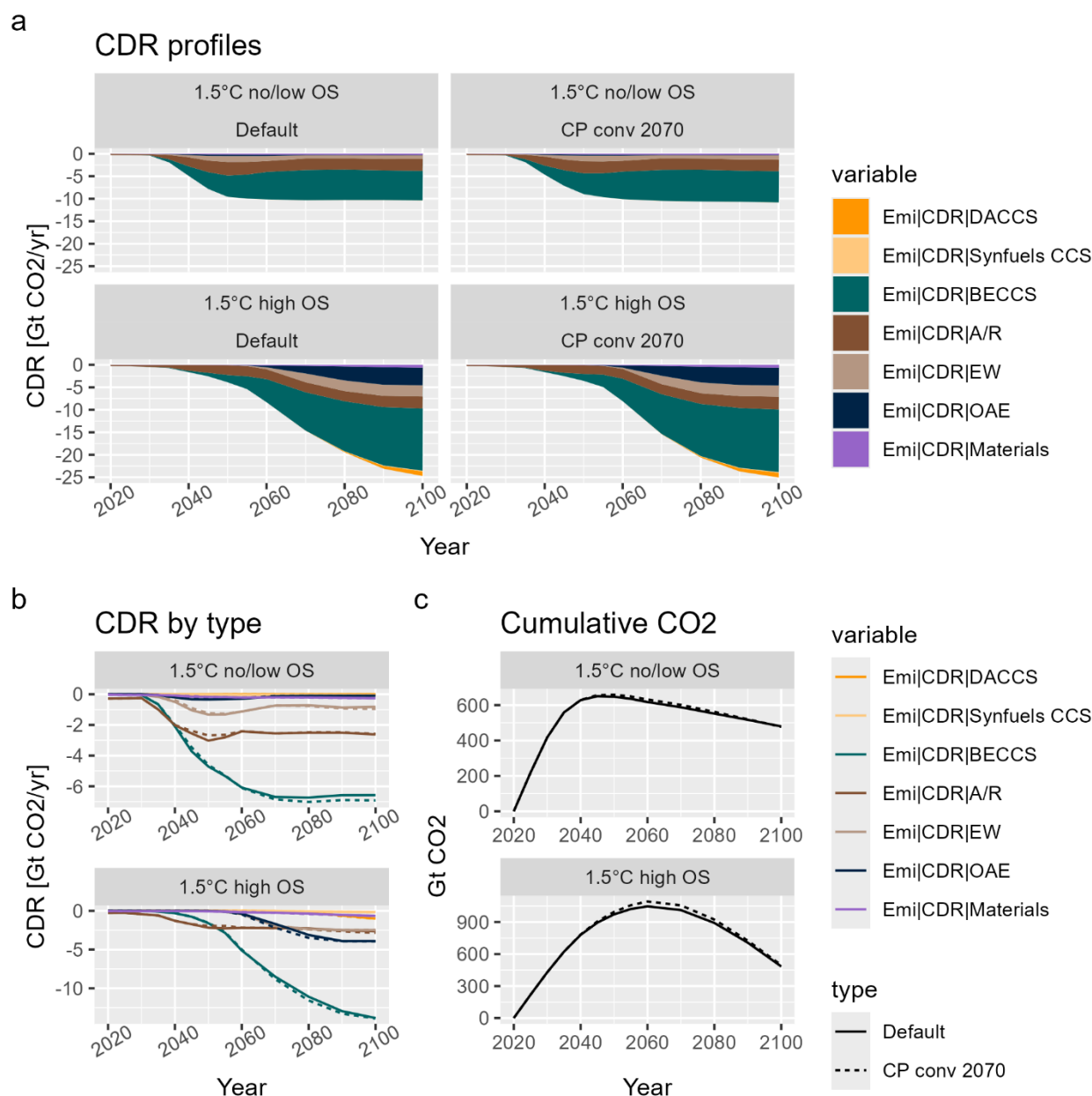


Figure 4.17. Overview figure showing the difference between Tier 2 scenarios with default assumptions (carbon price convergence 2050) and higher equity assumptions (carbon price convergence 2070). a) shows the composition and b) lineplots of the CDR technologies and c) cumulative anthropogenic CO₂ emissions since 2020.

4.4.6 Summary sensitivities

Regarding the individual contributions of individual CDR technologies we find that each of them can reduce the reliance on BECCS to some extent, but BECCS remains the most prominent CDR option, both in no/low and high OS scenarios. Future research should also analyze scenarios, in which BECCS is constrained, to assess how that influences the deployment of other CDR technologies and the relation between residual positive emissions and CDR. We expect that the missing CDR from BECCS will be partially compensated by other CDR technologies. However, due to the constraint on final energy for CDR, this will

only be possible to some extent, so we expect that the total amount of CDR will be reduced, which would effectively limit the amount of potential overshoot, forcing stronger near-term mitigation also in a “high OS” world.

Regarding the impact of ecosystem protection, we affirm the results by Merfort et al. (2023) [5], showing a huge increase of bioenergy and LUC emissions in case of missing land-use regulatory policies that prevent loss of carbon-rich ecosystems. We complement the findings by showing that the risk is even higher in an overshoot pathway, with potentially even more bioenergy and respective LUC emissions.

More equitable climate change mitigation policies with prolonged CO₂ price differentiation between regions were found to increase the level of the overshoot. Policies that also affect the very near-term (2030-2035) CO₂ price differentiation were not analyzed but present important avenues for future research, as we expect stronger effects on the magnitude of the overshoot in that case.

5 Harmonization and gridding of emission and land-use scenarios

5.1 Overview

Once the interfaces and the variables that are transferred between the models are clarified and the scenarios are computed (see section 4) harmonization and gridding are important steps in the workflow to bridge the IAMs with ESM by generating the climate forcings that are used as input to the ESMs. In RESCUE this is addressed in WP1.3.

Harmonization means that climate forcing scenario data (mainly: emissions and land-use) starts from the historical climate forcing data used in the ESM, with a realistic, smooth transition between history and the future. This means that gaps between the two are closed for a specific base year (or harmonization year), by applying necessary and plausible adjustments to the scenario data, transitioning (partially or fully, depending on the case) towards the original scenario data over the modelled time period.

Differences between historic and scenario data can be due to various reasons.

1. Differences in variable definitions in models and historic data sets. This is a very common reason and is related to the general topic of system boundaries. E.g., it is well-known that hydroelectric reservoirs emit CH₄, but in many IAMs this is not explicitly modeled. Similarly, emissions from peat-land conversion are not explicitly represented in ESMs, although changes in peat-land are endogenous in some IAMs, e.g. REMIND-MagPIE.
2. Historic data uncertainty. In some cases, different data sources for historic emissions vary quite a lot, because underlying activity data and emission factors differ. See for example Figure 1 in Minx et al. (2021)[6]. This is important for the interaction of IAMs and ESMs. While IAMs are usually calibrated to EDGAR data for many emission variables, because it is policy relevant. Differently, inputs to ESMs for the historical period use CEDS for anthropogenic emissions, for instance because it has a longer time series back in time. Since these two data sets show differences also the IAMs and the ESMs will show differences. In the future a synthesis of the data bases might be useful.
3. Differences in update schedules of historic data and models are not synchronized.
 - a. Revisions of historic data are pending, while model data is already updated. This happens if revisions of a historic data-set are more time consuming than up-dating assumptions in a model. It must be noted here that historical data sources rely on emission factors and activity data, as do models. This can also happen for instance when an experiment wants to reuse ESM historical runs to avoid computationally costly reruns when updates are small (similar to point 4).
 - b. Update of model data is pending, while historic data is already revised. This is the common case one would expect. However, final revisions and approvals of a complete data-set can take time.
4. A model is based on an older dataset and is supposed to use data from a model that is updated to revised historic data. This is the case that we have to deal with in the RESCUE scenarios. The ESMs rely on the CMIP6 data, while REMIND-MagPIE has been updated and was closer to the revised, yet provisional data.

This list of reasons for differences between historic data and scenarios is more a coordination and resources problem than a scientific problem. The harmonization needs could be substantially reduced by improved coordination between research communities about update schedules for data-sets and model versions. Still, it is also the case that (a) there is real, considerable uncertainty in historical emissions estimates, and (b) there are various scientific reasons for why some historical datasets fit better to some models than to others.

Gridding translates regionally aggregated data into geospatial explicit data. IAMs generally compute scenarios at the level of aggregate units such as national states. ESMs need inputs that are geospatially explicitly resolved. Since the IAM data is supposed to be used by different models with different grids, the data is gridded to a very fine level of granularity of 0.25° for land-use and 0.5° for emissions data. This means that ESMs mostly need to aggregate these fine grid cells, rather than to shift the regional information to make the IAM data fit with a specific ESM.

In the following, we report on the harmonization for the scenarios presented in section 4 based on data that merged CMIP6 historical data with provisional updates, which we call CMIP6+.

The tools developed are available on open source platforms and are currently used in the context of the ScenarioMIP/CMIP7 process that is crucial for the WG1 contribution to the IPCC's Seventh Assessment Report. The tools are also used to integrate IAMs with the Impact Modelling Community that contributes to the IPCC's WG2. The update of the tools to the CMIP7 data is part of the RESCUE project.

5.2 Harmonization, downscaling, and gridding of emissions

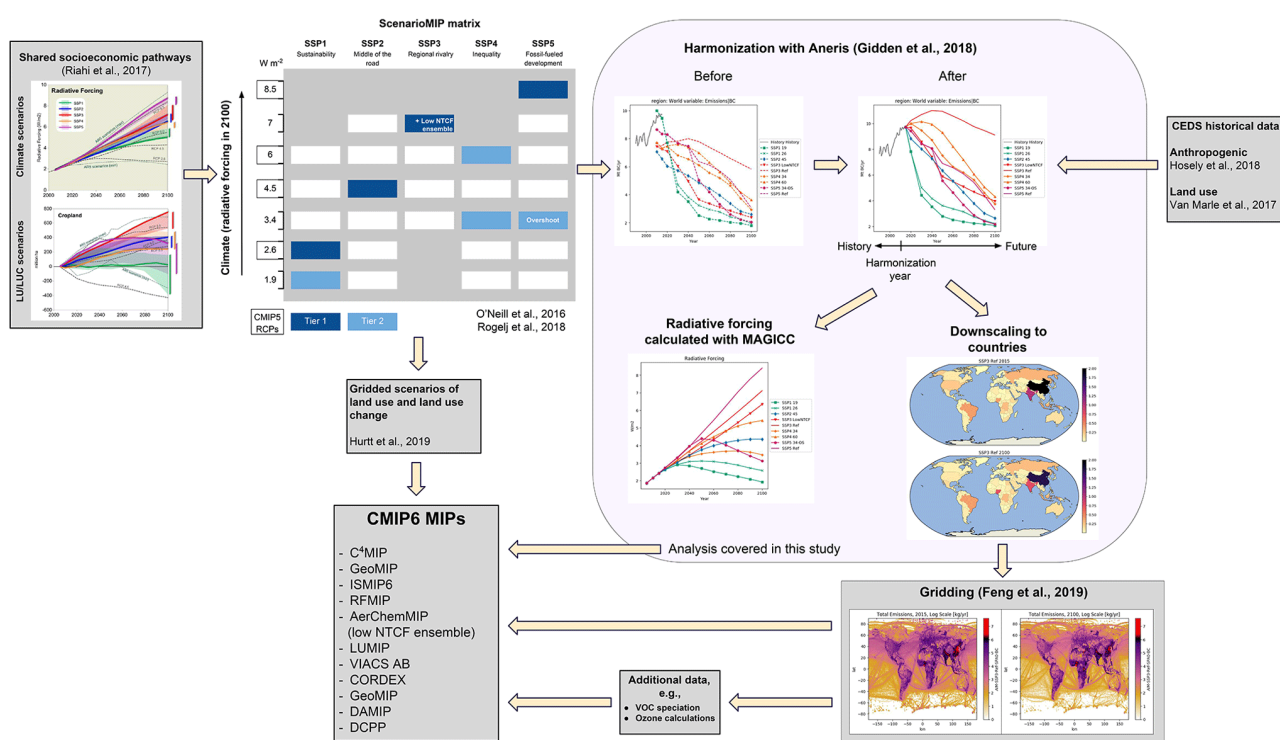


Figure 5.1: Schematic description of the harmonization and downscaling approach from Gidden et al. (2019)[7]

The emissions and aerosol data that was mapped to the CEDS and GFED sectors as explained above needs to be adjusted for use in ESMs in a two-step approach: First, the emissions are harmonized to historical

emissions without changing the given the regional and sectoral resolution and second, the emissions in each sector are downscaled from the regional model-native resolution to a geo-spatial grid. For both steps the Concordia[8] tool was developed and applied. The procedure follows the same approach that was described in detail by Gidden et al. (2019)[7] (see overview Figure 5.1) and Feng et al. (2020)[9].

5.2.1 Harmonization of emissions

The harmonization uses the Aneris[10] tool and provides a smooth transition between a base year in the historic data sets (CEDS, GFED and other sources, see Table A.6 in the Appendix). At same time, the approach ensures that consistency with the original scenario results is retained to the best extent possible. To avoid rerunning the simulation of historical periods within the ESMs, we use exactly the same data that was used in CMIP6 up until, and including, 2015. To reflect what emissions have been emitted around the world since then, we made use of multiple updated historical datasets to extend the historical period to 2020. To maintain consistency with CMIP6, we extended the post-2015 period by adding the changes from the provisional updates of the CEDS database. This has been done for all countries, sectors and emission species. Given that the differences between CMIP6 (CEDS2017) and the new release (CEDS2021) are quite large for some country-sector-species combinations, an algorithm was developed to extend the CEDS17 data. It aims at bringing the 2020 as close as possible to the value of the CEDS21 release, while not exceeding typical differences and growth rates observed historically in order to avoid large jumps that may cause unintended consequences in the ESMs. Figure 5.2 illustrates the data extension for the example of CH₄ emissions from the energy sector in China). Please note the substantial differences in historical data between the two data releases.

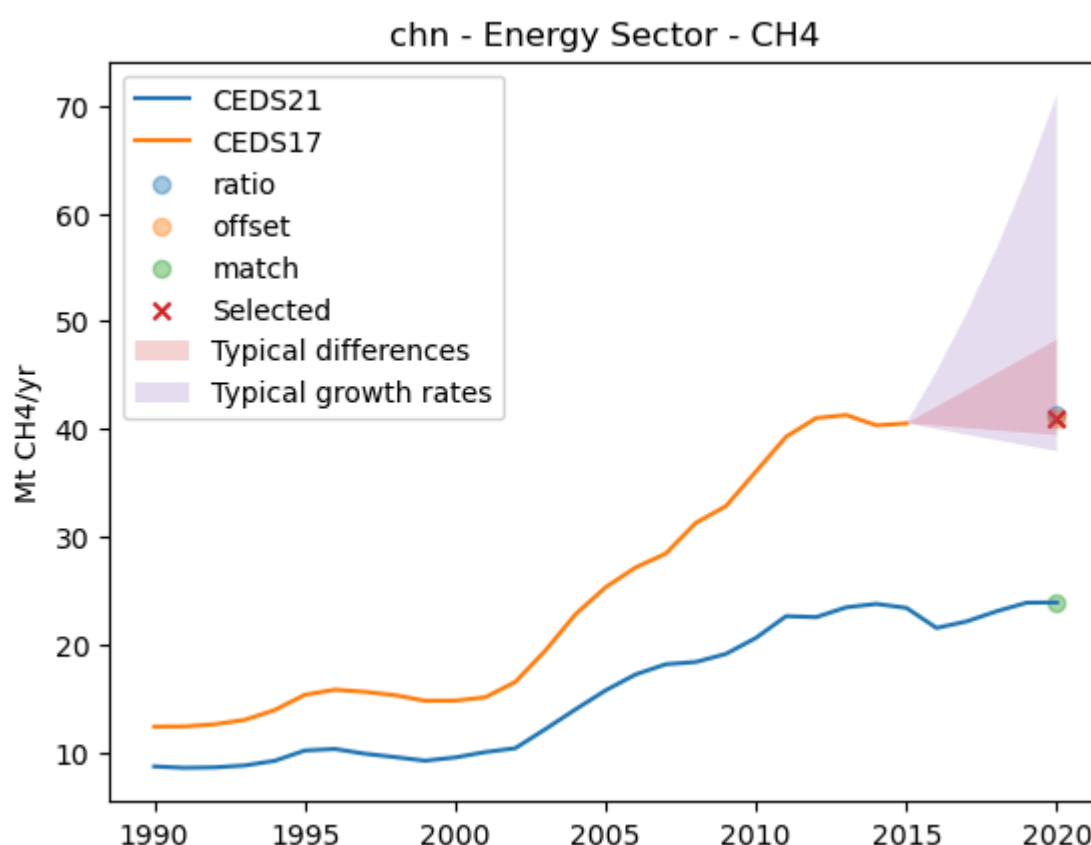


Figure 5.2: Extension of CMIP6 data. Illustrative example of CH₄ from the Energy Sector in China.

2020 then constitutes the base-year for harmonization between historical and scenario data. For each combination of region (12 REMIND-MAGPIE regions, see Table A.1, Appendix), pollutant species (see Appendix, section 8.2) and sector (see Appendix, section 8.2, particularly Tables A.2 and A.3), future emissions are adjusted to achieve a smooth (non-disjoint) transition to the original scenario values produced by the IAM, such that the level in 2020 matches the respective value in the historic dataset. To maximize the consistency with the original model runs (in terms of emissions trends and absolute emissions values), there are different harmonization methods that can be applied. Ratio and offset methods maintain relative or absolute differences between historic and scenario data, respectively, while convergence methods let harmonized scenario data converge to the original model data in a given year. For special cases override methods can be applied (see Gidden et al. [10] for details). Exemplarily, Figure 5.3 shows the harmonization of BC emissions from the Energy sector. The full set of harmonized data can be found here:

<http://rescue-task1.3.s3-website.eu-north-1.amazonaws.com/harmonization/>

Energy Sector|Modelled

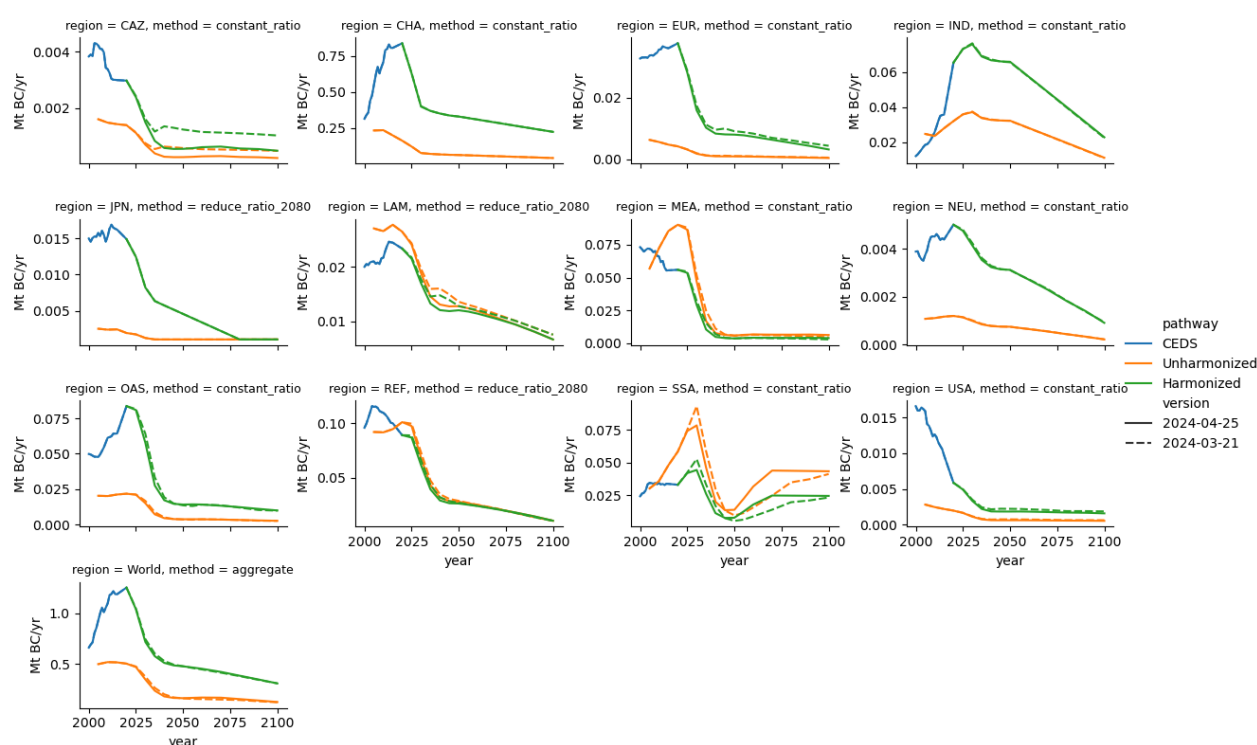


Figure 5.3: Regional Black Carbon (BC) emissions timeseries for the energy (supply) sector as an example for the harmonization process. While the original scenario data (orange; ‘Unharmonized’) does not perfectly match the historical emissions data (blue; ‘CEDS’), the harmonized trajectory (green; ‘Harmonized’) connects continuously to it. Note, the huge differences between historic data and unharmonized model data is due to the difference in China. In more recent updates of CEDS, historic values have been revised downwards moving the historic values closer to the scenario data.

5.2.2 Downscaling and gridding of emissions

The downscaling follows a two-step approach: First, the data at the model-native regional resolution (see Table A.1 in the Appendix) is disaggregated to country-level. Second, the country level data is downscaled to grid cell level (0.5°x0.5° resolution). The country-level downscaling differentiates between emissions

from the Agriculture, Forestry and Other Land-Use (AFOLU) sector and those from fuel combustion and industrial processes. AFOLU emissions are distributed to countries following a linear approach, in which the fraction of regional emissions in each country stays constant over time. By contrast, emissions from fuel combustion and industrial processes follow a dynamic approach. Here, population and GDP trajectories from the SSPs are used such that the countries' emissions intensity (emissions per GDP) converges over time (for more details refer to Gidden et al. (2019)[7]). The gridding of the country level emissions follows the same approach as described in Feng et al. (2020)[9], using spatial proxy data. Generally, these spatial proxies replicate the spatial pattern of historical emissions. For future emissions these proxy grids use the data from the last available year in the historic data set and are kept constant over time. For example, if in a specific country large parts are attributable to a coal-fired power plant in a specific location, that future emissions from the energy sector will also largely happen in that same region. Similarly, it implies that for industrial emissions, we do not assume changes in the location of emissions from cement and steel production. These proxies are generally only applied within countries, after the country-level downscaling has already taken place.

The specifics of the present IAM scenarios required some changes to the downscaling procedure compared to CMIP6 that are mainly related to CDR activities. In order for the ESMs to be run in “activity driven” mode, net CO₂ emissions need to be split into gross positive emissions and negative emissions. That way, ESMs can omit emissions in their input from sectors that they model endogenously. In the Energy sector bioenergy conversion processes (converting lignocellulosic biomass to secondary energy carriers such as electricity or liquid fuels) and in the Industry sector burning carbon-neutral fuels (biofuels or synfuels) can be combined with CCS. So far, the amount of CO₂ that was thereby effectively removed from the atmosphere was subtracted from the gross emissions in these two sectors, respectively, resulting in a net emissions flux to the atmosphere (or from the atmosphere in case of net-negative emissions). Similarly, in the Aggregate - Agriculture and LUC sector net fluxes to or from the atmosphere are now split into gross positive emissions from LUC and into negative emissions from re- and afforestation (A/R) as well as negative emissions from regrowth in managed forests. For gross positive emissions, we use the same sectoral proxy approach as in Feng et al.[9]. For BECCS, we used the static lignocellulosic biomass potential that served as the gridding proxy for all negative emissions in CMIP6. As an example, Figure 5.4 shows carbon removal via BECCS downscaled to 0.5°x0.5° grid cells. CDR from A/R and regrowth is gridded, applying the area of managed forests from the 1.5°C no/low OS scenario without OAE as a proxy. Enhanced Weathering (EW) is not present in the Tier 1 scenarios, but is already implemented in Concordia and uses the agricultural land area from the same scenario as a proxy. Since both the gridded (negative) CDR emissions from A/R as well as EW use scenario data, they are both dynamic and evolve over time. DACCS is gridded using a spatial gridding proxy that is the cell-wise product of renewable energy potentials and CO₂ storage potentials to reflect both the energy-intensive capture process and the availability of geological storage of CO₂. Industry CCS uses the same land mask as DACCS together with a mask of industrial CO₂ emissions. CO₂ uptake by the ocean via OAE is mapped to all oceans limited to the Exclusive Economic Zones (EEZs) of the respective countries of the regions where OAE takes place in the underlying scenarios. Additionally we exclude the polar regions (not above 67.5 degree latitudinal) due to presumed too low OAE efficiency levels, as well as very small overseas territories.

CO2 anthropogenic emissions

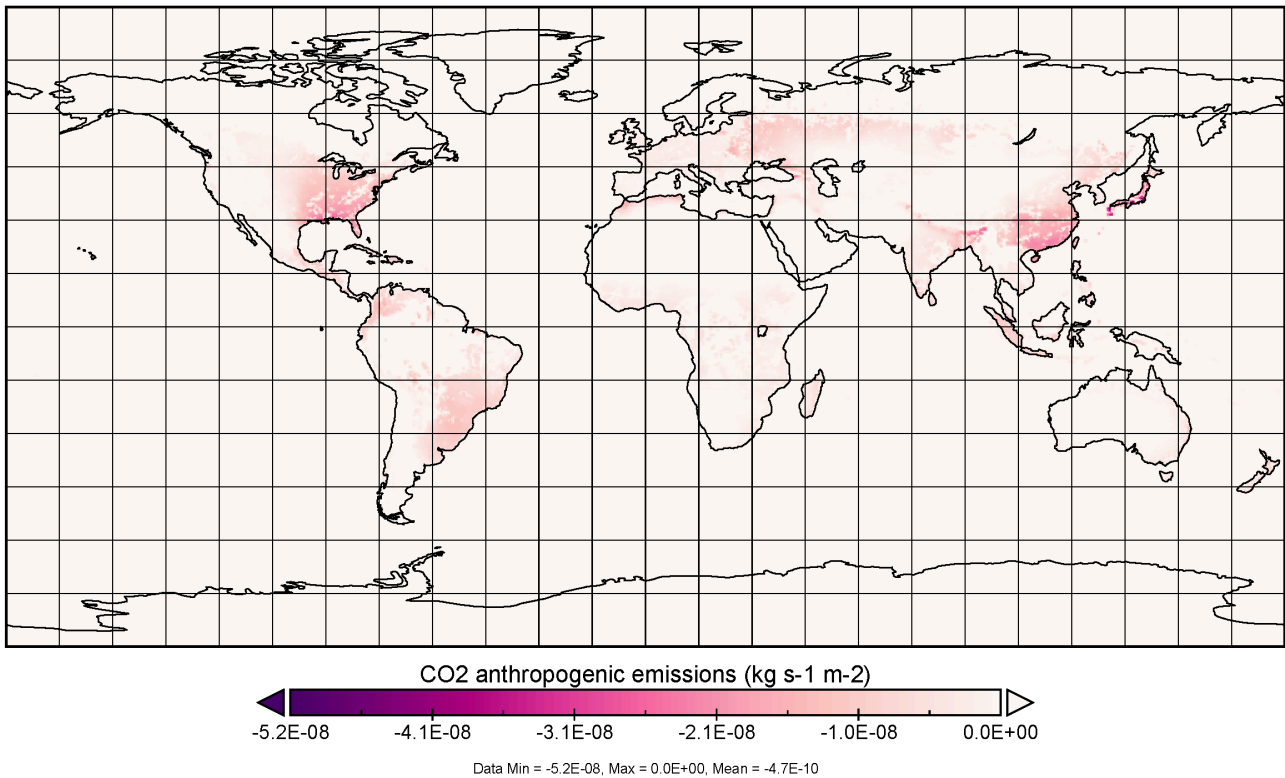


Figure 5.4. Example of carbon dioxide removed from the atmosphere via BECCS for the 1.5°C high OS scenario. This figure shows the snapshot of a single month (December) in the year 2100. It is therefore not representative for the overall BECCS deployment and rather serves as an illustrative example.

5.3 Harmonization, downscaling and gridding of land use

Harmonization and downscaling of land-use data is done via `mrdownscale`², an open source tool which was developed within the Horizon Europe RESCUE and OptimESM projects³ (see section 3.1 that discusses the link between RESCUE and OptimESM), that is now also used for other projects, e.g. ScenarioMIP. This tool emphasizes a clear separation of steps (see following subsections), checking consistency after each processing step. Further, the harmonization or downscaling method can easily be exchanged or adapted to the specific needs of a project.

Land-use data generated by the REMIND-MAGPIE model (“input”) is harmonized and downscaled using the LUH2v2h⁴ historical land-use dataset as a high-resolution target, operating on a 2015 to 2050 time horizon.

5.3.1 Category mapping

² <https://github.com/pik-piam/mrdownscale>

³ Horizon Europe project grant no. 101081193

⁴ <https://luh.umd.edu/data.shtml>

As a first step input variables are mapped to target variables, using disaggregation weights derived from a reference dataset with fine-grained variables (based on LUH2v2h consistent LandInG data[11]).

5.3.2 Aggregate target to low resolution

Harmonization requires two datasets at the same resolution, so we aggregate the target dataset to input data resolution. MAgPIE's native resolution is based on so-called clusters which are sets of $0.5^\circ \times 0.5^\circ$ cells with similar bio-geophysical properties given by a clustermap. To derive the mapping from MAgPIE clusters to LUH cells ($0.25^\circ \times 0.25^\circ$) we modify the clustermap by splitting each $0.5^\circ \times 0.5^\circ$ cell into four $0.25^\circ \times 0.25^\circ$ cells, then filling holes via nearest neighbor, and removing cells not present in LUH.

5.3.3 Temporal extrapolation aggregated LUH

The fade-over harmonization method requires both datasets to cover all timesteps from 2015 to 2050 (harmonization period), so cluster-resolution LUH data is extrapolated to 2050: A linear model is fitted for each variable and cluster using LUH data from 1995 to 2015. If a significant trend ($p < 0.05$) exists, the model predicts values until 2050; otherwise, the historical mean is used.

Extrapolated wood harvest is calculated by applying the historical wood harvest share of maximum possible wood harvest to extrapolated available wood land.

5.3.4 Harmonization

To harmonize, we crossfade from extrapolated LUH data to input data over the harmonization period 2015–2050. The value $v(t)$ for timestep t is calculated as:

$$v(t) = (1 - \text{norm}(t)) \times \text{LUH} + \text{norm}(t) \times \text{input}, \text{ where } \text{norm}(t) = (t - 2015) / (2050 - 2015).$$

Figure 5.5 shows for each year how many of the 200 clusters have a specific relative difference between cropland in input and harmonized data. Over time there are more and more clusters without any difference in cropland between input and harmonized data.

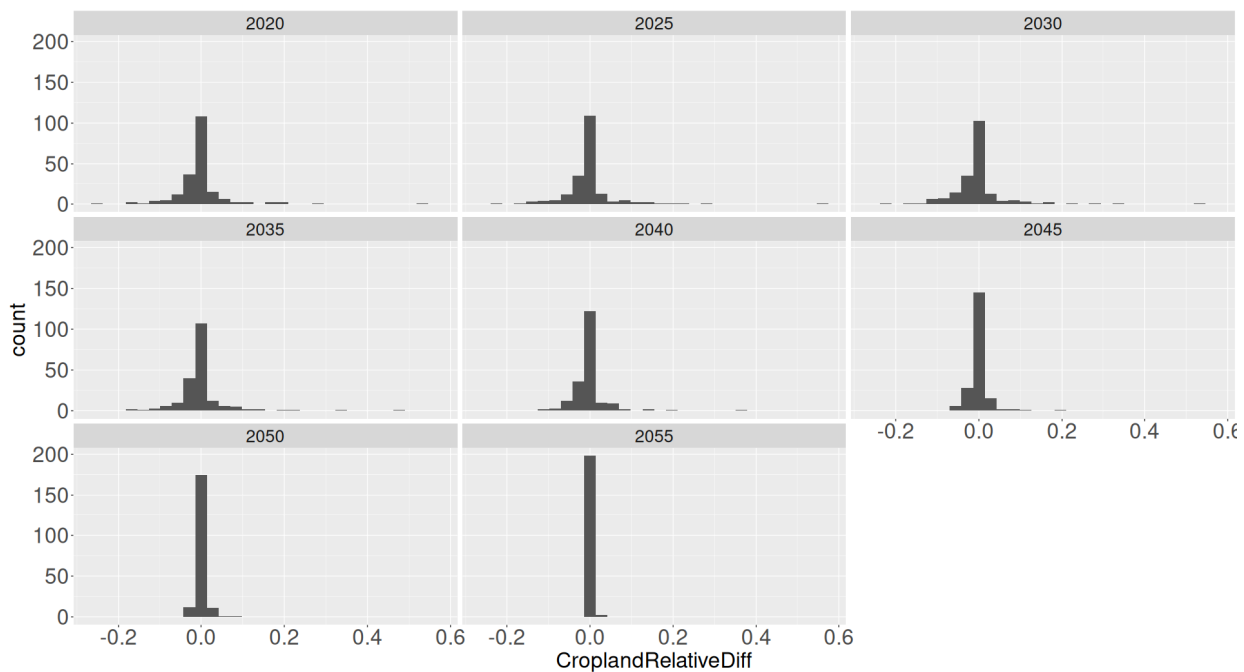


Figure 5.5. Illustration of deviation between original IAM land-use data (input) and harmonized data (output).

This process can cause primary land to expand even if neither LUH nor input shows expansion, if primary land in the input data is higher than in LUH. In such cases, primary land expansion is replaced with secondary land. Consequently, even after the harmonization period the harmonized dataset might differ from the input data.

The wood harvest area timeseries is adjusted for consistency with land. Changes in primary land determine primary wood harvest area, so wood harvest area from primary land is shifted to secondary land or vice versa. If secondary land harvest exceeds available land, it shifts between secondary types (e.g. forest to non-forest).

Instead of harmonizing wood harvest weight (bioh) directly, the weight per hectare is harmonized, then multiplied by harmonized wood harvest area to maintain consistency.

5.3.5 Downscaling

The harmonized low-resolution land data is downscaled to $0.25 \times 0.25^\circ$ using 2015 LUH data as reference. Then, land is scaled so that total land area in each grid cell is constant over time. For illustrative purposes, at the top low-resolution data, at the bottom gridded data:

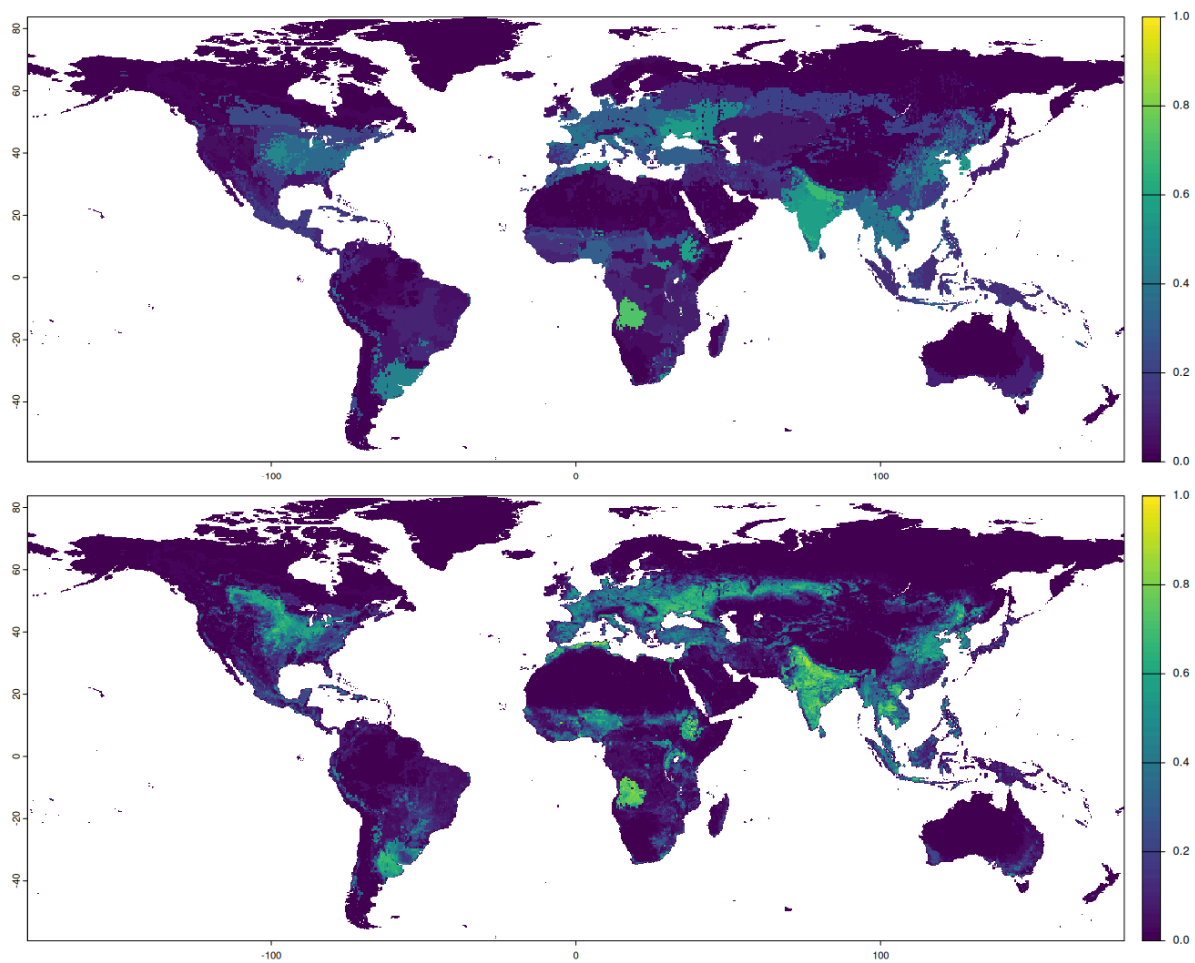


Figure 5.6. Share of cropland relative to total land area as illustration of the gridding process that downscales cluster level data to a 0.25°x0.25° grid - world.

The same plot, zoomed into India:

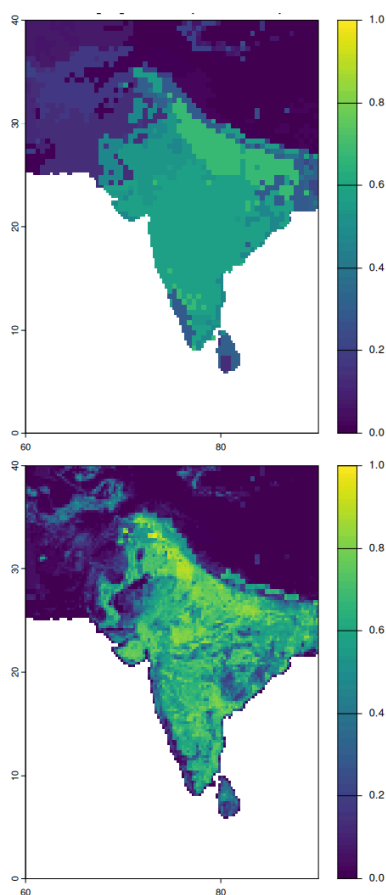


Figure 5.7. Share of cropland relative to total land area as illustration of the gridding process that downscales cluster level data to a 0.25°x0.25° grid - zoom India.

Fertilizer and wood harvest area are then disaggregated using the already downscaled land data for each respective timestep as weight. Wood harvest weight (bioh) is disaggregated using wood harvest area as weight. Wood harvest type shares (fulwd, rndwd) are disaggregated using LUH 2015 wood harvest type data as weight. Additionally, wood harvest type shares are calculated per country to fill cells without wood harvest.

5.3.6 Transitions

Land transitions are estimated based on a combination of land use states information and historical LUH2 transitions. The estimation is split into two steps. In the first step net transitions are estimated by extracting the differences in land use states of two consecutive time steps. Land expansions are proportionally projected onto land reductions in the same cell. In a second step net transitions are enriched by historical LUH2 transition information to reflect gross land transitions. This enrichment is achieved by extracting average land type internal transitions (where the amount of expansion equals the amount of reduction of a land category in one cell) in the historical period from 1995 to 2015. Adding them proportionally to the corresponding land type in the calculated net transitions data set creates the final estimate of future gross land use transitions.

5.4 Additional IAM-ESM interface variables

Additionally to the GHG and aerosol emissions and the land-use data the ESMs require information on the CDR activities from the IAMs to be enabled to be run in “activity driven” mode.

5.4.1 BECCS sequestration rate

Regarding BECCS, the ESMs only model the growth and harvest of bioenergy crops endogenously so they require information on the economic and technological details of the energy conversion and CCS process to determine how much of the carbon in the harvested biomass is ultimately removed from the atmosphere. It should be noted that the system boundaries of IAMs and ESMs overlap here. This required intensive exchanges between the research communities to clarify the different model assumptions. Harmonization of all assumptions in the different models remains challenging.

For that, we derive a variable that quantifies the globally averaged amount of CO₂ that is geologically stored per unit of biomass that is harvested and is given in kgCO₂/tDM (see Figure 5.8). This value reflects different processes that are explicitly modeled within REMIND-MAgPIE. It takes into account that a) biomass can be traded between regions and some biomass is lost during the trade process. Further, b) only a fraction of the biomass is used in combination with a carbon capture (CC) process. i.e. some biomass is converted to a secondary energy carrier without capturing excess carbon. There are c) different BECCS technologies with different CC rates, e.g. producing hydrogen from biomass allows for a higher capture rate than producing bioliquids. Ultimately, d) not the whole amount of CO₂ that was captured is also stored geologically - a fraction is being used to produce synthetic fuels, so, in burning these fuels, the carbon will eventually be released to the atmosphere.

All these processes are subject to the cost-optimization in REMIND-MAgPIE and differ between scenarios and over time. For instance, in the 1.5°C high OS scenarios (EocBudg500), the sequestration rate only reaches high levels towards the end of the century, when the mitigation pressure increases, while it already reaches its maximum around 2050 in the 1.5°C no/low OS scenarios (PkBudg500), due to the fact that a temperature overshoot is not allowed here and carbon prices are already very high in the near-term.

Since the harvested biomass is not necessarily consumed in the same region where it is produced, also not all of the CO₂ is sequestered in the biomass-producing region. We therefore derived a global average value instead of regionally differentiated sequestration rates.

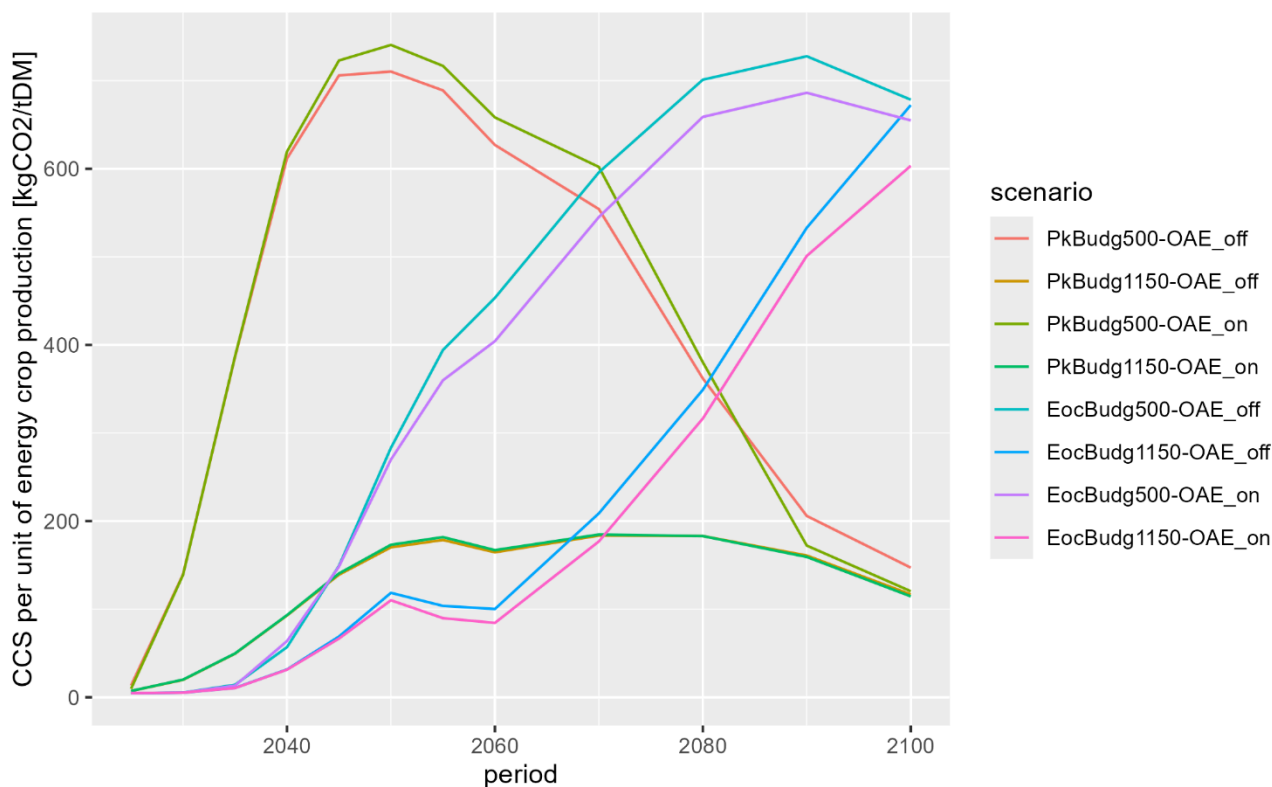


Figure 5.8. Globally averaged BECCS sequestration rate.

5.4.2 OAE alkalinity additions

To model the increased carbon uptake by the ocean induced by quicklime discharge, the ESMs require the geo-spatial information on the alkalinity additions⁵. We therefore do not only report the total CO₂ uptake by the ocean (as discussed in section 4.4.1), but also the levels of alkalinity, given in trillion mol total alkalinity added to the ocean per year (Tmol TA/yr). This variable is also downscaled to 0.5°x0.5° grid cell level using the same proxy (EEZs excluding polar regions) as was used for the respective CO₂ emissions (see exemplarily Figure 5.9). Please note that the levels of alkalinity additions for the different world regions are subject to economic optimization, but they are additionally limited to not exceed 5 Gt CO₂/yr on a global level.

⁵ This element was added to the work plan of T1.3.

Alkalinity Addition as part of OAE

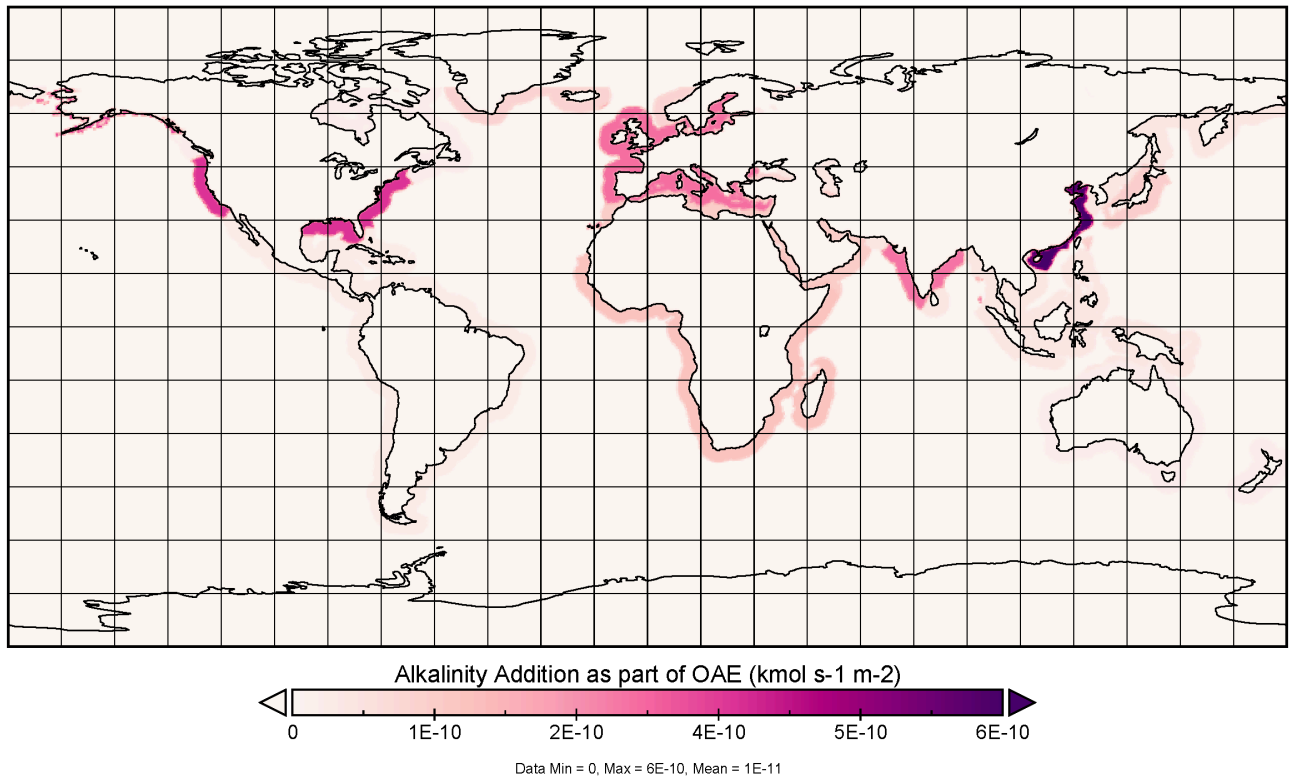


Figure 5.9. Total Alkalinity levels that are added to the ocean for the 1.5°C high OS scenario in December 2100.

6 Extension of emission scenarios until 2300

6.1 Introduction

IAMs used for generating future scenarios are usually designed to simulate till 2100. There is a need for longer scenarios to explore earth system feedbacks under overshoot scenarios with explicit representation of CDRs. Under this context, we developed a method to extend future scenarios of CO₂, CH₄, and N₂O emissions from different sectors and those of CDR technologies starting in 2100 through to 2300 by using output of REMIND-MAgPIE till 2100. In the following, we first summarize the methodological framework for extending emission scenarios until 2300. We then present a set of extended scenario outcomes.

6.2 Development of the IAM emulator for REMIND-MAgPIE

Our approach to emulating IAMs builds upon the framework established by Xiong et al. (2025)[12], which utilizes marginal abatement cost (MAC) curves to represent emissions derived with complex cost-effective IAMs as a response to varying carbon prices. We extend the Xiong framework by developing an IAM emulator (or emIAM) specifically tailored to REMIND-MAgPIE, incorporating model-specific insights gained through collaboration with the model developers, and explicitly accounting for sectoral details of GHG emissions and various CDR approaches. The steps for developing the IAM emulator for REMIND-MAgPIE are shown in Figure 6.1.

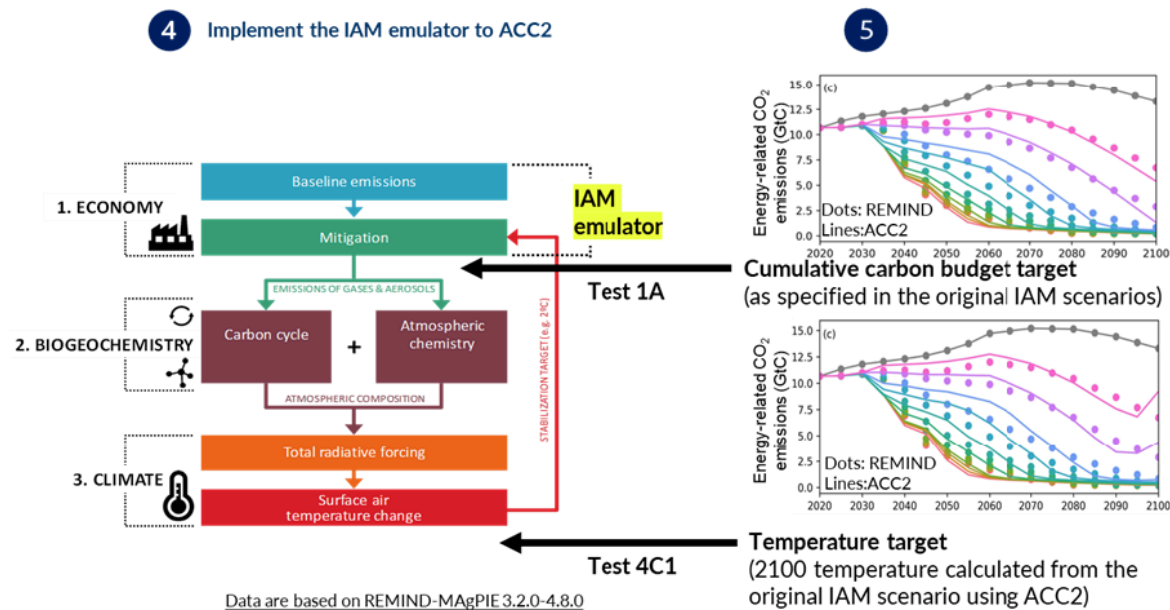
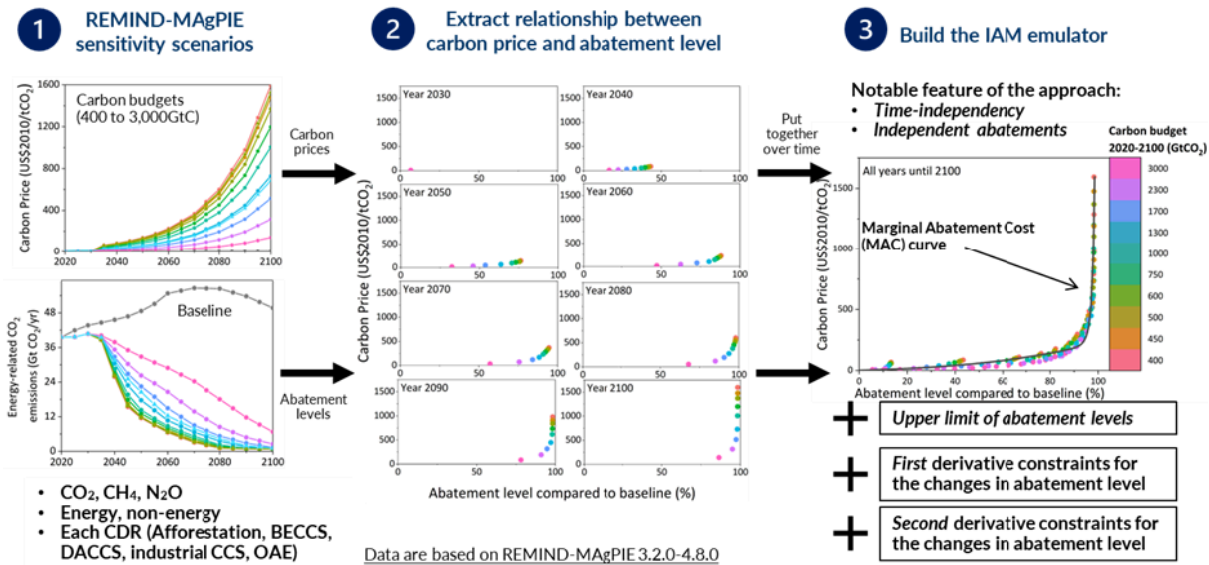


Figure 6.1. Schematic overview figure describing the development of the IAM emulator for REMIND-MAGPIE. The figure above shows the data for global energy-related CO₂ emissions for illustration. Data were obtained from a set of ten sensitivity scenarios simulated by REMIND-MAGPIE (versions 3.2.0-4.8.0). The chromatic colors indicate the respective carbon budgets for the period 2019 – 2100 in GtCO₂. The gray color indicates the baseline scenario.

6.2.1 Data used for developing the IAM emulator

For the purpose of developing the emulator, REMIND-MAGPIE has been simulated to provide ten sensitivity scenarios under a wide range of cumulative carbon budgets by the end-of-century (400, 450, 500, 600, 750,

1000, 1300, 1700, 2300, and 3000 GtCO₂ for the period of 2019-2100). These scenarios are driven by externally imposed carbon price pathways. No additional non-price constraints are implemented to enforce specific emission targets such as net-zero emissions by a certain year.

We utilized the scenarios before harmonization (i.e. unharmonized scenarios) to develop the IAM emulator because the IAM emulator aims to capture the fundamental, price-driven behavior of the IAM, isolated from the effects of scenario harmonization. From this set of unharmonized scenarios, we extracted the relationship between the imposed carbon price and the resulting emission abatement (expressed as a percentage reduction relative to the baseline for each GHG and sector) or the removal level (in GtCO₂ for each CDR technique).

6.2.2 The scope of the IAM emulator

Our emulator individually captures the emission reduction of each of the three major GHGs (CO₂, CH₄, and N₂O) originating from each sectors (energy-related and non-energy-related sectors), as well as the CO₂ removal through each of the five CDR methods (afforestation, BECCS, DACCS, industrial CCS, and OAE). The energy-related sector includes emissions from “Energy Sector”, “Industrial Sector”, “Transportation Sector”, “Aircraft”, “International Shipping”, “Residential Commercial Other”, and “Solvents Production and Application”. The non-energy-related sector includes emissions from “Aggregate - Agriculture and LUC” and “Waste”. Climate forcers other than the three major GHGs were not incorporated in our IAM emulator because their emissions generally do not respond to carbon price, rather driven primarily by other factors such as clean air policies. An exception is ammonia, but we did not develop an emulator for ammonia because it is not a very important gas for the simulations of earth system models.

6.2.3 Building the IAM emulator

We approximated the price-quantity relationship of REMIND-MAgPIE, using equation $\ln\left(\frac{f(x)}{f(0)}+1\right)=a\cdot x^b+c\cdot x^d$ for sectoral emission reductions and equation $f(x)=a\cdot x^b+c\cdot x^d$ for CDRs. $f(x)$ represents the carbon price level at x , while the variable x represents the abatement level relative to the assumed baseline level, expressed as a percentage for sectoral emissions or the absolute amount of CO₂ removed via CDR options. a , b , c and d are the parameters that are optimized for each gas, sector, and CDR option. These functions are termed as “MAC curves” in our study. It should, however, be noted that our MAC curves differ from more conventional MAC curves in the literature in two regards. First, our MAC curves are time-independent (Fig. 6.1), while MAC curves are often given for a certain year (e.g. 2030 and 2050). Second, our MAC curves are based on model output, while MAC curves are usually based on compilation of various datasets for potential mitigation measures with costs.

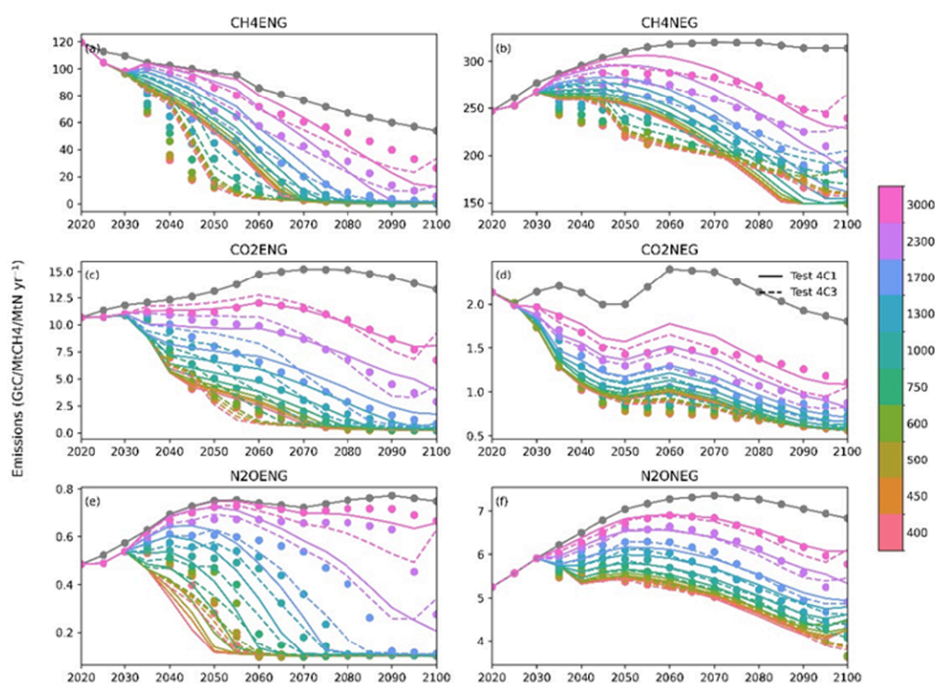
In addition, we further used the sensitivity scenarios to derive the maximum abatement or removal level of each gas, sector, and CDR option, which reflect the limit of, for example, CCS capacity and sectoral mitigation potential. We also calculated the maximum first and second derivatives of temporal changes in abatement levels for each gas, sector, and CDR option to capture the limits of the technological change rate and the socio-economic inertia. In sum, the set of MAC curves, abatement and removal limits, and the rate and inertia constraints for abatement and removal are the elements of the IAM emulator.

6.2.4 Verifying the IAM emulator

Before applying the IAM emulator for generating extended scenarios to 2300, we verified the performance of the emulator by evaluating the extent to which the original REMIND-MAgPIE outputs were reproduced

by varying the driver or the target of the scenario and cross-checking the endogenous variables. To this end, we used a set of experiments with different drivers or targets: i) carbon price pathway, ii) cumulative carbon budget target, and iii) temperature target. For the experiments using the temperature target, the IAM emulator was coupled with the reduced-complexity climate model ACC2 (Tanaka et al., 2021[13]). The coupled model, ACC2-emIAM, is a simple climate-economy model that can derive a cost-effective pathway to achieve a specified temperature target with lowest cost by optimization.

Despite the simplicity of our emulation approach, a substantial part of scenario features have been well reproduced by the emulator under various conditions. Figure 6.2 shows an example of such verifications using the 2100 temperature as the target. On the other hand, we also identified certain aspects of scenarios that cannot be well captured and reproduced by the emulator. Those include near-term mitigation, land-use CO₂ emissions, and afforestation. We also found that the coverage of uniform carbon price across gas, sector, and CDR option is an important element in the emulator that significantly affects the verification outcomes. Nevertheless, the scenarios have been adequately reproduced by the emulator, particularly in the second half of this century. This provides a strong foundation for using our emulator to extend scenarios beyond 2100 as discussed below.



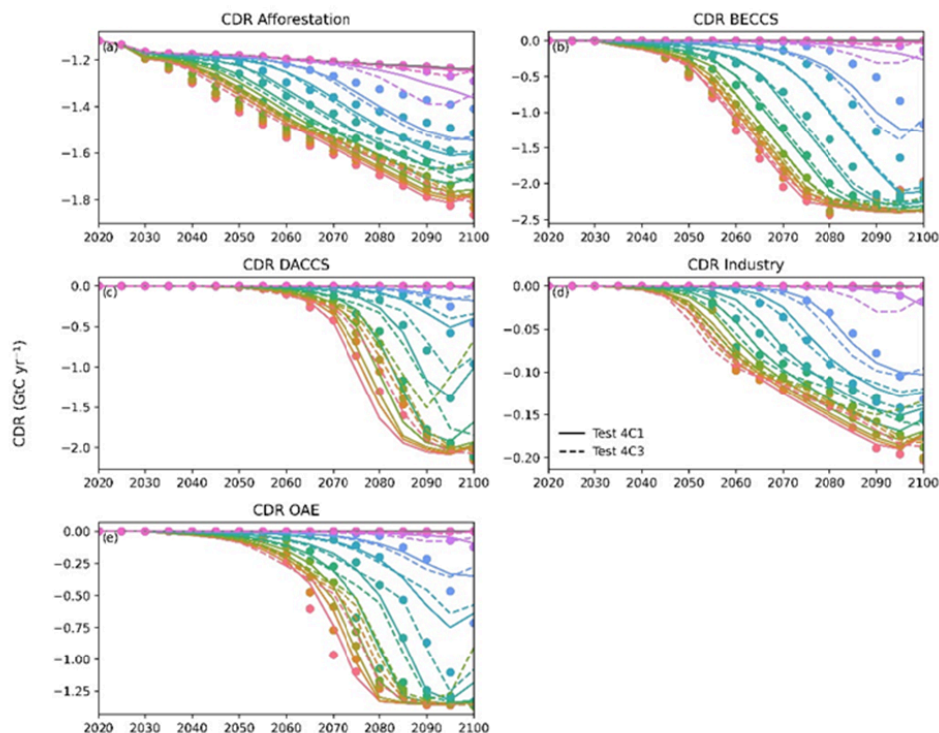


Figure 6.2. Comparison between the original scenarios calculated by REMIND-MagPIE and the reproduced scenarios by emIAM-ACC2 using identical 2100 temperature targets. Dots represent REMIND-MagPIE scenarios; lines represent emIAM-ACC2 scenarios. The chromatic colors indicate the respective carbon budgets for the period 2019 – 2100 in GtCO₂. The results are shown for each gas (CO₂, CH₄, and N₂O), each sector (energy-related sector and non-energy-related sector), and each CDR option (afforestation, BECCS, DACCS, industry CCS, and OAE). Two different methods are used for reproduced scenarios: i) a method partially applying uniform carbon price (solid lines; uniform carbon price for energy-related and non-energy-related emissions within each gas) and ii) another method fully applying uniform carbon price (dashed lines; uniform carbon price for all emissions and removals + GWP100 used for across different gases). The first method was used for extending scenarios till 2300 (see sections 6.3 and 6.4).

6.3 Design of the extended scenarios

6.3.1 Pre-2100 scenarios

We prescribed REMIND-MagPIE-based pre-2100 scenarios in ACC2-emIAM when deriving scenarios after 2100. Those scenarios include the four harmonized scenarios as follows: (i) cumulative carbon budget of 500 GtCO₂ using the end-of-century budget approach, (ii) cumulative carbon budget of 500 GtCO₂ using the peak-budget approach, (iii) cumulative carbon budget of 1150 GtCO₂ using the end-of-century budget approach, and (iv) cumulative carbon budget of 1150 GtCO₂ using the peak-budget approach. Note that all four scenarios include OAE. In addition, several other pre-2100 scenarios with larger cumulative carbon budgets were also prescribed to ACC2-emIAM (i.e., cumulative carbon budgets of 1700, 2300, and 3000 GtCO₂ using the end-of-century approach). The use of the wide range of pre-2100 scenarios enables the extension of scenarios with various overshoot profiles. While our emulator was derived from unharmonized scenarios, harmonized scenarios were prescribed to ACC2-emIAM because harmonized scenarios are those directly used by ESMs and reduced-complexity models.

6.3.2 Underlying assumptions in extended scenarios

We developed an extended baseline scenario until 2300 based on a set of simplifying assumptions due to limited literature on multi-century baseline projections and the inherent difficulty in projecting socio-economic factors over such long time scales (upper part of Table 6.1). Assumptions associated with the extended mitigation scenarios are detailed in the lower part of Table 6.1 for individual sectors and CDR options. To ensure that the extended scenarios are useful for ESM simulations (i.e., to understand the earth system response to zero emissions), we imposed a constraint of net-zero CO₂ emissions from the year when the specified temperature target is applied. We also assumed that energy-related and non-energy-related emissions would not increase after 2100 to prevent a “rebound” of emissions in extended scenarios.

Table 6.1. Assumptions in the extended baseline and mitigation scenarios for individual gases, sectors, and CDR options.

Scenario	Gas	Approach
Extended baseline scenario	Energy-related CO ₂	- Emissions under the SSP2 scenario based on economic extractability of available fossil fuel reserves are obtained - A scaling factor (from the ratio of 2100 emission level to REMIND-MagPIE outputs) is used to adjust emission pathways until 2300
	Non-energy-related CO ₂	Linear decline to 0 by 2150
	Energy-related CH ₄	Consistent trend in energy-related CO ₂
	Non-energy-related CH ₄	Keep at 2100 level
	Energy-related N ₂ O	Consistent trend in energy-related CO ₂
	Non- energy-related N ₂ O	Keep at 2100 level
	CDR Afforestation	Linear decline to 0 by 2150
	CDR BECCS	0
	CDR DACCS	0
	CDR Industry	0
	CDR OAE	0
Extended mitigation scenario	Energy-related CO ₂	- Determined by the emulator until 2175 - Linear decline to 0 by 2200
	Non-energy-related CO ₂	Determined by the emulator from 2100 onwards
	Energy-related CH ₄	- Determined by the emulator until 2175 - Linear decline to 0 by 2200
	Non-energy-related CH ₄	Determined by the emulator from 2100 onwards
	Energy-related N ₂ O	- Determined by the emulator until 2175 - Linear decline to 0 by 2200
	Non- Energy-related N ₂ O	Determined by the emulator from 2100 onwards
	CDR Afforestation	Linear decline to 0 by 2150
	CDR BECCS	Determined by the emulator from 2100 onwards
	CDR DACCS	Determined by the emulator from 2100 onwards
	CDR Industry	Determined by the emulator from 2100 onwards
	CDR OAE	Determined by the emulator from 2100 onwards

6.3.3 Cost-effective approach

Using ACC2-emIAM, we calculated cost-effective scenarios till 2300 for each gas, sector, and CDR option to achieve a specified temperature target (e.g., 1.5°C by 2150). Since scenarios before 2100 are the harmonized scenarios prescribed to ACC2-emIAM, the emulator was directly used only from 2100 onwards. The magnitude and duration of temperature overshoot are not exogenously given, rather determined by internal cost-effective calculations, considering the temperature target year and level, pre-2100 scenario, and other model assumptions.

6.4 Extended scenario outcomes

Figure 6.3 provides an overview of our extended scenarios up to 2300, with their profiles such as the temperature target level and year, the net-zero year, the carbon budget, and the overshoot height and

period summarized in Table 6.2. The scenario profiles were determined in consultation with potential scenario users (ESM and SCM users), as well as communication experts for EU climate policies. In RESCUE, given the development surrounding IPCC, the extended scenarios presented here will be simulated only by OSCAR (Deliverable 3.2). In the Horizon Europe RESCUE project, Cases A to D will be used for EMS simulations. The remaining ten scenarios, which cover higher temperature space, are potentially used in other studies (e.g., an ESM analysis of tipping elements). For the given temperature target level and year, as well as for the given net-zero year, ACC2-emIAM determines the overshoot level, overshoot duration, and cumulative carbon budget in a cost-effective manner. In Cases A to D, net-zero CO₂ emissions are required to be achieved by 2150, while in all other cases net-zero CO₂ emissions are reached at different years.

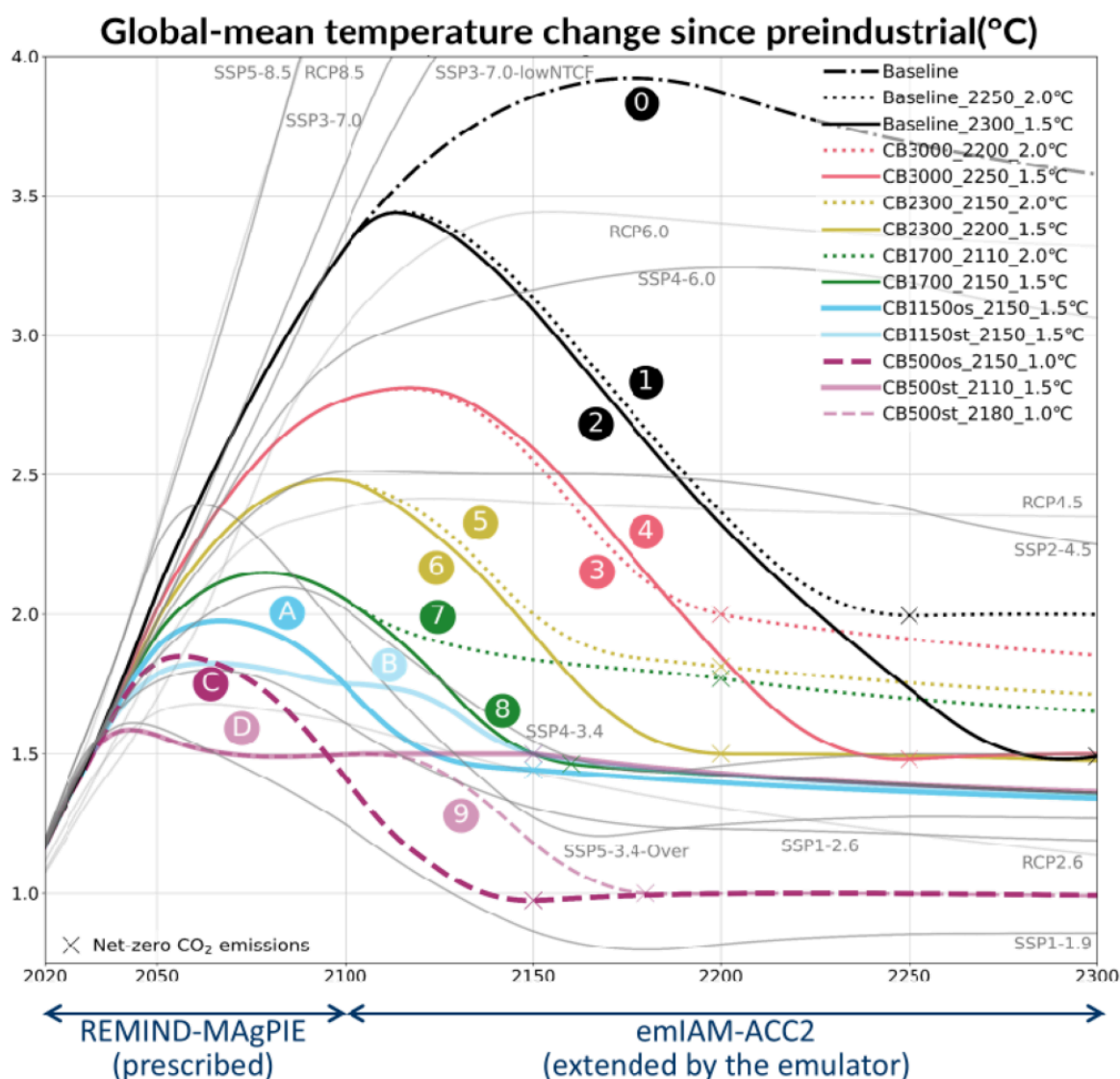


Figure 6.3. Overview of the extended scenarios. This figure shows the temperature pathways derived with ACC2-emIAM using a cost-effectiveness approach.

Table 6.2. Characteristics of the extended scenarios. See Figure 6.3 for scenario IDs.

ID	Pre-2100 scenario	Target level	Target year	Net zero	OS height	OS period	Carbon budget
0	Baseline	-	-		-	-	6,723
1	Baseline	2.0 °C	2250	2250	1.44 °C	197 yrs	2,819
2	Baseline	1.5 °C	2300	2300	1.94 °C	247 yrs	1,646
3	CB3000	2.0 °C	2200	2200	0.81 °C	150 yrs	2,797
4	CB3000	1.5 °C	2250	2250	1.31 °C	204 yrs	1,809
5	CB2300	2.0 °C	2150	2200	0.48 °C	99 yrs	1,992
6	CB2300	1.5 °C	2200	2200	0.98 °C	167 yrs	1,341
7	CB1700	2.0 °C	2110	2200	0.15 °C	52 yrs	1,823
8	CB1700	1.5 °C	2150	2160	0.65 °C	117 yrs	1,093
A	CB1150os	1.5 °C	2150	2150	0.48 °C	91 yrs	817
B	CB1150st	1.5 °C	2150	2150	0.32 °C	117 yrs	937
C	CB500os	1.0 °C	2150	2150	0.85 °C	117 yrs	-136
D	CB500st	1.5 °C	2110	2150	0.08 °C	36 yrs	660
9	CB500st	1.0 °C	2180	2180	0.58 °C	159 yrs	-151

Figure 6.4 shows the emission and the removal profile over time for each gas, sector, and CDR options for Case A (Figure 6.3). This scenario gives a temperature overshoot of approximately 0.48°C above the 1.5°C level, with a duration of 91 years before returning to the target level. A notable feature of the scenario is the very long-term individual CDR pathways generated by the emulator approach after 2100.

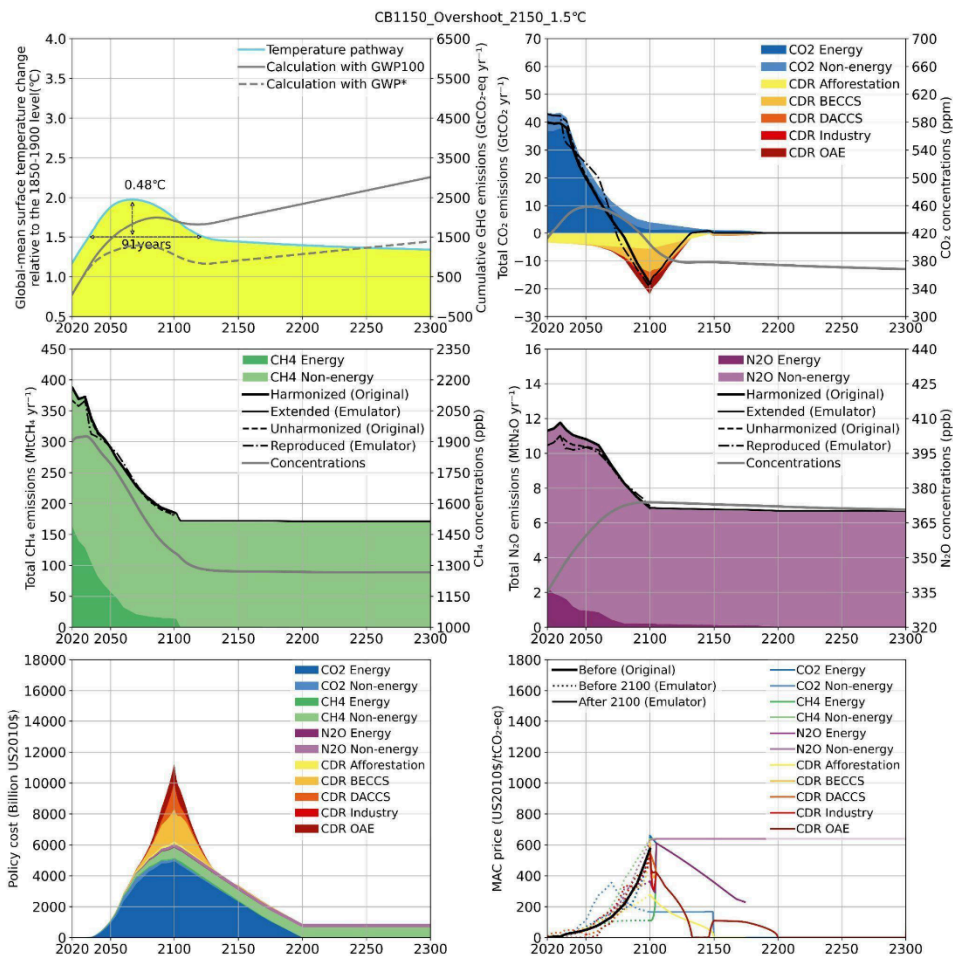


Figure 6.4. 1.5 °C scenario with overshoot till 2150 with peak warming of about 2 °C. This scenario corresponds to Case A in Figure 6.3.

For further information on the extended scenarios, figures for all extended scenarios, such as Figure 6.4, can be found in the google drive folder

<https://drive.google.com/drive/folders/1sUMczqtPN79PXmsEeH8PGyOjZocAfcBY?usp=sharing>

Data for the extended scenarios are contained in the file

“Tier1_Extension_2300_Harmonized.xlsx”, which can be accessed via the google drive link:

https://drive.google.com/drive/folders/1wJbQq0Ks_1blelQZukTyJJbZEXR1KJFj?usp=sharing

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8 Appendix

8.1 Spatial and temporal resolution of the REMIND-MAgPIE model output

All emission variables and most non-emission variables are spatially disaggregated to the 12 REMIND-MAgPIE regions CAZ, CHA, EUR, IND, JPN, LAM, MEA, NEU, OAS, REF, SSA, USA (see Table A.1). Additionally, all variables are also given as the global aggregate (“World”).

All variables are given for years until 2100 with 5-year time steps until 2060 and 10-year time steps afterwards.

Table A.1. Mapping of the 12 REMIND-MAgPIE regions to ISO country codes (reproduced from Baumstark et al. (2021)[14])

REMIND region	ISO code of countries belonging to this region
LAM	ABW, AIA, ARG, ATA, ATG, BES, BHS, BLM, BLZ, BMU, BOL, BRA, BRB, BVT, CHL, COL, CRI, CUB, CUW, CYM, DMA, DOM, ECU, FLK, GLP, GRD, GTM, GUF, GUY, HND, HTI, JAM, KNA, LCA, MAF, MEX, MSR, MTQ, NIC, PAN, PER, PRI, PRY, SGS, SLV, SUR, SXM, TCA, TTO, URY, VCT, VEN, VGB, and VIR
OAS	AFG, ASM, ATF, BGD, BRN, BTN, CCK, COK, CXR, FJI, FSM, GUM, IDN, IOT, KHM, KIR, KOR, LAO, LKA, MDV, MHL, MMR, MNG, MNP, MYS, NCL, NFK, NIU, NPL, NRU, PAK, PCN, PHL, PLW, PNG, PRK, PYF, SGP, SLB, THA, TKL, TLS, TON, TUV, UMI, VNM, VUT, WLF, and WSM
SSA	AGO, BDI, BEN, BFA, BWA, CAF, CIV, CMR, COD, COG, COM, CPV, DJI, ERI, ETH, GAB, GHA, GIN, GMB, GNB, GNQ, KEN, LBR, LSO, MDG, MLI, MOZ, MRT, MUS, MWI, MYT, NAM, NER, NGA, REU, RWA, SEN, SHN, SLE, SOM, SSD, STP, SWZ, SYC, TCD, TGO, TZA, UGA, ZAF, ZMB, and ZWE
EUR	ALA, AUT, BEL, BGR, CYP, CZE, DEU, DNK, ESP, EST, FIN, FRA, FRO, GBR, GGY, GIB, GRC, HRV, HUN, IMN, IRL, ITA, JEY, LTU, LUX, LVA, MLT, NLD, POL, PRT, ROU, SVK, SVN, and SWE
NEU	ALB, AND, BIH, CHE, GRL, ISL, LIE, MCO, MKD, MNE, NOR, SJM, SMR, SRB, TUR, and VAT
MEA	ARE, BHR, DZA, EGY, ESH, IRN, IRQ, ISR, JOR, KWT, LBN, LBY, MAR, OMN, PSE, QAT, SAU, SDN, SYR, TUN, and YEM
REF	ARM, AZE, BLR, GEO, KAZ, KGZ, MDA, RUS, TJK, TKM, UKR, and UZB
CAZ	AUS, CAN, HMD, NZL, and SPM
CHA	CHN, HKG, MAC, and TWN
IND	IND
JPN	JPN
USA	USA

8.2 Emissions in CEDS/GFED sectors

For the use in ESMs, emissions are harmonized to The Community Emissions Data System (CEDS) historic emissions data set (see section 5.2.1). Since these data do not cover emissions from fires, 9 aggregated CEDS/GFED sectors (Energy Sector, Industrial Sector, Residential Commercial Other, Aircraft, International Shipping, Transportation Sector, Solvents Production and Application, Waste, Agriculture) (see Table A.2) are complemented by 4 aggregated sectors from Global Fire Emissions Database (GFED) (Agricultural Waste Burning, Forest Burning, Grassland Burning) (see Table A.3). Also negative emissions from CDR are

not part of the historic dataset, which further extends the sectors for CO₂. The following emission species are reported in sectors that can be mapped to these sectors:

CO₂, CH₄, N₂O, BC, CO, NH₃, NO_x, OC, Sulfur, VOC, C₂F₆, CF₄, HFC, SF₆

For emissions from **C₂F₆, CF₄, HFC** and **SF₆** only totals are reported (CEDS+|9+ Sectors|Emissions|XXX|Total). For all other pollutants, values are disaggregated into the following sectors:

CEDS+|9+ Sectors|Emissions|XXX|Energy Sector
CEDS+|9+ Sectors|Emissions|XXX|Industrial Sector
CEDS+|9+ Sectors|Emissions|XXX|Residential Commercial Other
CEDS+|9+ Sectors|Emissions|XXX|Aircraft
CEDS+|9+ Sectors|Emissions|XXX|International Shipping
CEDS+|9+ Sectors|Emissions|XXX|Transportation Sector
CEDS+|9+ Sectors|Emissions|XXX|Solvents Production and Application
CEDS+|9+ Sectors|Emissions|XXX|Waste
CEDS+|9+ Sectors|Emissions|XXX|Agriculture
CEDS+|9+ Sectors|Emissions|XXX|Agricultural Waste Burning
CEDS+|9+ Sectors|Emissions|XXX|Forest Burning
CEDS+|9+ Sectors|Emissions|XXX|Grassland Burning
CEDS+|9+ Sectors|Emissions|XXX|Aggregate - Agriculture and LUC
CEDS+|9+ Sectors|Emissions|XXX|Total

For **CH₄, N₂O, BC, CO, NH₃, NO_x, OC, Sulfur** and **VOC** the sector “CEDS+|9+ Sectors|Emissions|XXX|Aggregate - Agriculture and LUC” aggregates the following four subsectors:

CEDS+|9+ Sectors|Emissions|XXX|Agriculture
CEDS+|9+ Sectors|Emissions|XXX|Agricultural Waste Burning
CEDS+|9+ Sectors|Emissions|XXX|Forest Burning
CEDS+|9+ Sectors|Emissions|XXX|Grassland Burning

For **CO₂**, these subsectors from Agriculture and Land-Use Change (LUC) are not reported individually, so only the aggregated variable is non-zero. This variable is reported twice: in its raw version – which is the one that reports the true land-use change emissions as reported by MAgPIE – and in a smoothed version, which was derived by applying a low-pass filter to reduce spikes. Please note that the “Smoothed” variable is only reported for use as training data for ACC2 (same is true for the “CDR Afforestation” variable, see below):

CEDS+|9+ Sectors|Emissions|CO₂|Deforestation and other LUC
CEDS+|9+ Sectors|Emissions|CO₂|Deforestation and other LUC|Smoothed

For **CO₂** additionally 6 CDR sectors are reported (see below a more detailed description, in particular on the OAE accounting):

CEDS+|9+ Sectors|Emissions|CO₂|CDR Afforestation
CEDS+|9+ Sectors|Emissions|CO₂|CDR Afforestation|Smoothed
CEDS+|9+ Sectors|Emissions|CO₂|CDR BECCS
CEDS+|9+ Sectors|Emissions|CO₂|CDR DACCS

CEDS+|9+ Sectors|Emissions|CO2|CDR Industry
 CEDS+|9+ Sectors|Emissions|CO2|CDR OAE Uptake Ocean
 CEDS+|9+ Sectors|Emissions|CO2|CDR EW

For CDR from afforestation we assume that all LUC CO₂ emissions that can be attributed to “human activity” are defined as CDR. They comprise regrowth in `Secondary Forest`, `Other Land` and `Timber Plantations`, as well as in forests that were intentionally planted to generate negative emissions, that is, via price-incentives (`CO<sub>2</sub>-price AR`), or via specific policy targets (`NPI\_NDC AR`). DACCS is Direct Air Carbon Capture and Sequestration, BECCS is Bioenergy with Carbon Capture and Sequestration. BECCS comprises direct CCS from processes converting biomass into secondary energy carriers and also industry BECCS, i.e., if industry processes that combust bioenergy (e.g., biofuels) capture a fraction of the released carbon via CCS. CDR Industry is related to synfuels produced with CO₂ from Direct Air Capture (DAC) that are used in the industry sector and there combined with CCS.

The Ocean Alkalinity Enhancement (OAE) CDR technology entails – during the process of quick lime (CaO) production – positive CO₂ process emissions (very similar to process emissions from cement production). Within the energy systems model REMIND, we prescribe that none of these emissions may be vented directly to the air, i.e., all must be captured. However, after capturing, this CO₂ can either be directly stored underground (CCS) or utilized to produce synthetic fuels (CCU). A part of these synthetic fuels is burned without a further CCS process, so that – depending on the scenario assumptions – a potentially substantial fraction of these process emissions will be vented as positive emissions eventually. The emissions related to OAE are explicitly reported in two separate variables, such that (negative) fluxes to the ocean and (positive) fluxes to the atmosphere are given individually. The net CDR from OAE is thus the sum of the following two variables:

CEDS+|9+ Sectors|Emissions|CO2|CDR OAE Uptake Ocean
 CEDS+|9+ Sectors|Emissions|CO2|OAE Calcination Emissions

Additionally, the Alkalinity fluxes to the ocean are reported in [Tmol TA/yr]:

RESCUE|OAE|Alkalinity Addition

Here we assume a constant efficiency value that determines the ratio between alkalinity added to the ocean and carbon fluxes from the atmosphere to the ocean of 0.57 molDIC/molTA. Please note that this variable needs to be downscaled to grid level, which is why this is included in “REMIND-MAgPIE-CEDS-RESCUE-Tier1-2024-10-11.csv”, which, apart from that variable, only contains emissions and air pollutants.

Please further note that Enhanced Weathering (EW) is turned off in the scenarios, so it is always zero.

Table A.2. CEDS sector aggregation.

CECD original sectors	Spatial resolution	9-sector aggregation
1A1a_Electricity-autoproducer	national	Energy Sector
1A1a_Electricity-public	national	Energy Sector
1A1a_Heat-production	national	Energy Sector
1A1bc_Other-transformation	national	Energy Sector
1A2a_Ind-Comb-Iron-steel	national	Industrial Sector

1A2b_Ind-Comb-Non-ferrous-metals	national	Industrial Sector
1A2c_Ind-Comb-Chemicals	national	Industrial Sector
1A2d_Ind-Comb-Pulp-paper	national	Industrial Sector
1A2e_Ind-Comb-Food-tobacco	national	Industrial Sector
1A2f_Ind-Comb-Non-metallic-minerals	national	Industrial Sector
1A2g_Ind-Comb-Construction	national	Industrial Sector
1A2g_Ind-Comb-machinery	national	Industrial Sector
1A2g_Ind-Comb-mining-quarrying	national	Industrial Sector
1A2g_Ind-Comb-other	national	Industrial Sector
1A2g_Ind-Comb-textile-leather	national	Industrial Sector
1A2g_Ind-Comb-transpequip	national	Industrial Sector
1A2g_Ind-Comb-wood-products	national	Industrial Sector
1A3ai_International-aviation	global	Aircraft
1A3aii_Domestic-aviation	global	Aircraft
1A3b_Road	national	Transportation Sector
1A3c_Rail	national	Transportation Sector
1A3di_International-shipping	global	International Shipping
1A3di_Oil_Tanker_Loading	national	International Shipping
1A3dii_Domestic-navigation	national	Transportation Sector
1A3eii_Other-transp	national	Transportation Sector
1A4a_Commercial-institutional	national	Residential Commercial Other
1A4b_Residential	national	Residential Commercial Other
1A4c_Agriculture-forestry-fishing	national	Residential Commercial Other
1A5_Other-unspecified	national	Industrial Sector
1B1_Fugitive-solid-fuels	national	Energy Sector
1B2_Fugitive-petr	national	Energy Sector
1B2b_Fugitive-NG-distr	national	Energy Sector
1B2b_Fugitive-NG-prod	national	Energy Sector
1B2d_Fugitive-other-energy	national	Energy Sector
2A1_Cement-production	national	Industrial Sector
2A2_Lime-production	national	Industrial Sector
2Ax_Other-minerals	national	Industrial Sector
2B_Chemical-industry	national	Industrial Sector
2B2_Chemicals-Nitric-acid	national	Industrial Sector
2B3_Chemicals-Adipic-acid	national	Industrial Sector
2C1_Iron-steel-alloy-prod	national	Industrial Sector
2C3_Aluminum-production	national	Industrial Sector
2C4_Non-Ferrous-other-metals	national	Industrial Sector
2D_Chemical-products-manufacture-processing	national	Solvents Production and Application

2D_Degreasing-Cleaning	national	Solvents Production and Application
2D_Other-product-use	national	Solvents Production and Application
2D_Paint-application	national	Solvents Production and Application
2H_Pulp-and-paper-food-beverage-wood	national	Industrial Sector
3B_Manure-management	national	Agriculture
3D_Rice-Cultivation	national	Agriculture
3D_Soil-emissions	national	Agriculture
3E_Enteric-fermentation	national	Agriculture
3I_Agriculture-other	national	Agriculture
5A_Solid-waste-disposal	national	Waste
5C_Waste-combustion	national	Waste
5D_Wastewater-handling	national	Waste
5E_Other-waste-handling	national	Waste
6A_Other-in-total	national	Industrial Sector
6B_Other-not-in-total	national	
7A_Fossil-fuel-fires	national	Energy Sector
7BC_Indirect-N2O-non-agricultural-N	national	Agriculture

Table A.3. GFED sector aggregation.

GFED original sector	Spatial resolution	4-sector aggregation
AGRI: Agricultural waste burning	0.25x0.25 degree	Agricultural Waste Burning
BORF: Boreal forest fires	0.25x0.25 degree	Forest Burning
DEFO: Tropical deforestation & degradation	0.25x0.25 degree	Forest Burning
PEAT: Peat fires	0.25x0.25 degree	Peat Burning
SAVA: Savanna, grassland, and shrubland fires	0.25x0.25 degree	Grassland Burning
TEMF: Temperate forest fires	0.25x0.25 degree	Forest Burning

8.3 Non-emissions variables

The following 28 variables are reported both on a regional level (12 regions, see above) and globally aggregated (“World”).

Table A.4. Non-emissions variables that are reported on a regional level.

Variable name	Description; Comments
RESCUE Price Carbon	Regionally differentiated carbon price that is applied to all GHG emissions in \$/tCO ₂ -eq
RESCUE Bioenergy Traditional	Traditionally used biomass, mostly used in developing regions for cooking and heating

RESCUE Landuse Intensity Indicator Tau	Indicator for agricultural yield increases; see Dietrich et al. (2012) ²² and Dietrich et al. (2014) ²³ for a detailed description
RESCUE Yield Bioenergy Crops	Averaged bioenergy crop yields
RESCUE Yield Food Crops	Averaged food crop yields
RESCUE Yield Forage	Average forage yields
RESCUE Yield Pasture	Average pasture yields
RESCUE Land Cover Change Cropland	Land cover change is calculated with respect to the base year 1995; Afforestation is divided into timber plantations (“Plantations”), afforestation from implemented or intended policies (“NPI/NDC”) or additional carbon price driven afforestation (“Afforestation”)
RESCUE Land Cover Change Other Land	
RESCUE Land Cover Change Pastures and Rangelands	
RESCUE Land Cover Change Urban Area	
RESCUE Land Cover Change Managed Forest Afforestation	
RESCUE Land Cover Change Managed Forest NPI/NDC	
RESCUE Land Cover Change Managed Forest Plantations	
RESCUE Land Cover Change Natural Forest Primary Forest	
RESCUE Land Cover Change Natural Forest Secondary Forest	
RESCUE Land Cover Other Land	Land cover reports cropland with a higher detail
RESCUE Land Cover Pastures and Rangelands	
RESCUE Land Cover Urban Area	
RESCUE Land Cover Cropland Fallow	
RESCUE Land Cover Cropland Tree Cover	
RESCUE Land Cover Cropland Food Crops	
RESCUE Land Cover Cropland Forage	
RESCUE Land Cover Cropland Bioenergy Grasses	
RESCUE Land Cover Cropland Bioenergy Trees	
RESCUE Land Cover Managed Forest Afforestation	
RESCUE Land Cover Managed Forest NPI/NDC	
RESCUE Land Cover Managed Forest Plantations	
RESCUE Land Cover Natural Forest Primary Forest	
RESCUE Land Cover Natural Forest Secondary Forest	

RESCUE OAE Alkalinity Addition	Annual regional alkalinity fluxes to the ocean, given in [Tmol TA/yr]. It is exactly the same variable as in the CEDS emissions file. It fits better to the “non-emission variables”, but as it needs to be gridded, it is part of the “CEDS” file as well (this is so far the only gridded non-emissions variable).
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The following 5 variables related to purpose grown modern energy crops are only reported on a global level. The reason is that due to international biomass trade, it is not clear how to attribute carbon that is captured and sequestered in one region to biomass that is cultivated in another.

Table A.5. Non-emissions variables that are reported on a global level.

Variable name	Description
RESCUE Bioenergy Production Energy Crops w/ CC	Primary energy production of modern grassy and woody energy crops is reported according to its use and is given in EJ/yr; “w/ CC” indicates the fraction of biomass that is used in a process with carbon capture (please note that not all of the carbon that is captured in such a process, also counts for CDR, since the captured carbon can also be used to produce synfuels); “w/o CC” represents the share of biomass that is used in a process without carbon capture; in case bioenergy is traded internationally (i.e., between regions), we assume that 5% of the biomass (on an energy content basis) is lost (“Trade Loss”)
RESCUE Bioenergy Production Energy Crops w/o CC	
RESCUE Bioenergy Production Energy Crops Trade Loss	
RESCUE Average CCS per PE Production Biomass from Energy Crops Per Energy	This variable indicates the amount of carbon that is, on a global average, sequestered per unit of primary energy biomass that is harvested and is given once on an energy content basis (kgCO ₂ /GJ) and once on a mass basis (kgCO ₂ /tDM; DM = dry matter). This takes into account that a) some biomass is lost during the trade process, b) a fraction of the biomass is not used in a process with CC, c) the average capture rate (kgCO ₂ /GJ) of all possible conversion processes is time dependent (e.g., producing H ₂ from biomass has a higher capture rate than producing bioliquids) and d) that not the whole CO ₂ , which was captured, is also sequestered (some is also being used to produce synfuels).
RESCUE Average CCS per PE Production Biomass from Energy Crops Per Dry Matter	

8.4 Sources for historical data

Table A.6. Sources for the historical emissions data for different species and sectors

Species	Sectors	Data source	Gridded variables
CO ₂ , CH ₄ , NH ₃ , SO ₂ , BC, OC, CO, NO _x , VOC	Aircraft	CEDS[1], [2]	_em_AIR_anthro
	Agriculture		_em_anthro
	Energy		
	Industrial		
	International Shipping		
	Residential, Commercial, Other		
	Solvents Production and Application		
	Transportation		
	Waste		

CO2	Deforestation and other LUC	GCB	_em_anthro
	CDR Afforestation	Le Quéré, C. (2016)[15] & Friedlingstein (2023)[16]	
CH4, NH3, SO2, BC, OC, CO, NOx, VOC	Agricultural Waste Burning	GFED[3], [4]	_em_openburning
	Forest Burning		
	Grassland Burning		
	Peat Burning		
N2O	Total	Gütschow et al. (2016)[17] v2.0 & v.2.3.1	
HFC		Velders et al. (2015)[18] & Velders et al. (2022)[19]	
C2F6, CF4		Carpenter et al. (2014)[20] & Say et al. (2021)[21]	
SF6		Carpenter et al. (2014)[20] & Simmonds et al. (2020)[22]	