Report

Project: **bm1241** Project title: Carbon Dioxide Removal Principal investigator: **Julia Pongratz** Allocation period: **2024-11-01 to 2025-10-31**

CDRSynTra project

During the allocation period significant progress was made, concluding the 1st phase of the CDRSynTra project. In particular, we have focused on extensively analyzing the simulations that were produced over the previous years. This has led to several papers that are currently in preparation, focusing on:

- How the large-scale deployment of afforestation/reforestation (A/R) affects climatic extremes. This analysis has been made possible since we have created a large simulation ensemble, enabling a robust quantification of uncertainty in climatic extremes. This work is led by the PhD student Katharina Raberg, supervised by Dr. Moustakis and Prof. Pongratz, who also finalized her Master thesis on this topic. Results so far have shown that heat extremes can be locally amplified at sites of A/R, but this is alleviated, when the overall planetary cooling due to A/R is considered. Precipitation extremes are less impacted by A/R without any clear signal of more or less intense extremes, despite an overall increase in average rainfall emerging over sites of A/R.
- How the large-scale deployment of A/R works under different emissions scenarios. This work led by Dr. Moustakis utilizes our simulation setup featuring different emissions scenarios (SSP5-8.5, 3-7.0, 5-3.4os, 1-2.6) and different configurations (emission- and concentration-driven), to disentangle the biogeophysical and biogeochemical effects of A/R. We're particularly interested in the interplay between carbon sequestration and temperature mitigation and how that changes across different background climates. This work has so far shown that:
    - There is no significant biogeophysically-induced warming at the global level by the large-scale application of A/R. Biogeophysically-induced regional warming is at least compensated for by the biogeochemically-induced overall planetary cooling.
    - The overall efficiency of global cooling (per unit of carbon removed) increases for the lower emissions scenarios.
    - The overall efficiency in removing carbon (expressed as atmospheric carbon reduction per land carbon uptake) increases with higher emissions scenarios.
- How the ocean biogeochemistry is affected by the application of marine and terrestrial CDR. This analysis led by Dr. Hao-wei Wey builds upon our simulations of Ocean Alkalinity Enhancement (OAE) and A/R. This work has shown that the mitigation signal in pH emerges quickly before 2030, while the signal for sea surface temperature and subsurface O2 emerges later, near 2070, making pH a robust indicator for monitoring, reporting, and verifying CDR.

Utilization in teaching: Work undertaken with DKRZ resources has also provided useful material for the Master's Vorlesung "Boden-Pflanze-Atmosphäre Kontinuum", at LMU's Department of Geography, and for the Masters' course "Catchment Hydrology", at the Department of Civil and Environmental Engineering, at Imperial College London.

STEPSEC project

(1) Standalone simulations in 10km resolution for Germany based on land use forcing by CRAFTY-DE (published in the STEPSEC final report to BMFTR)

Simulations to quantify the national CDR potential through A/R and bioenergy with carbon capture and storage (BECCS) in Germany on 10 km resolution were run with JSBACH3.2. 1500 years of spin-up were run, followed by three shorter historical simulations to cover the period from 1900 to 2019. Thereafter, six future experiments combining national SSP-CDR scenarios with different background climates (SSP126, SSP585) were run. While analysis of parts of the simulation output is still ongoing, most of the data has been moved to the long-term archive.

(2) Standalone simulations for stylized sensitivity study (Nützel et al. in prep.)

45 additional future stylized global standalone simulations, where a fixed amount of agricultural land in every grid cell is replaced by CDR and is kept constant afterwards, were run with JSBACH3.2. The additional simulations add to the already existing 54 stylized simulations to compare future temporal dynamics of carbon storage efficiency of A/R and BECCS and were conducted to better understand the contributions of different boundary conditions and the processes in the model. The additional simulations include simulations to separate the effect of changing atmospheric CO2 concentrations on plant productivity for the A/R, BECCS and reference experiment with constant land use and simulations where A/R and BECCS are applied in combination to assess synergistic effects. All were simulated under different background climates and climate model forcings. All data output was post-processed and compressed reducing output file size by a factor of ~10. Output of three other models was uploaded to Levante, which were also post-processed and compressed to reduce storage. Currently, analysis of the data for a a publication led by Tobias Nützel is ongoing.

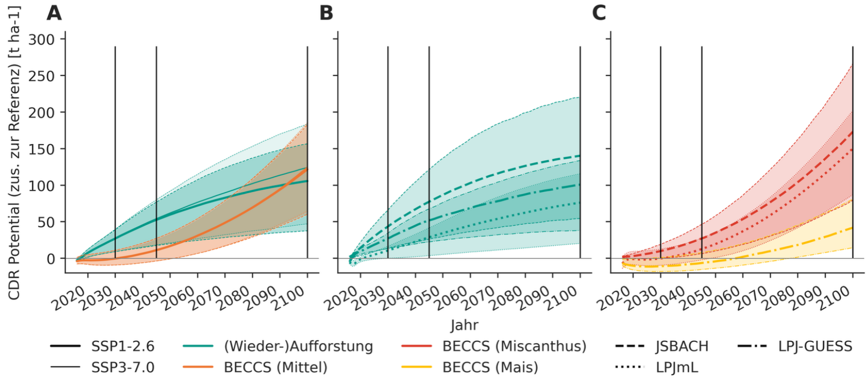

***Fig.1: Temporal dynamics of simulated CDR potentials of A/R and BECCS:** shown compared to the reference experiment with* constant *present-day land use. Colored areas and thin lines indicate spatial heterogeneity of the results. The vertical black lines mark representative years for short-, medium- and long-term climate targets. A)* Mean across *simulations of the three DGVMs for A/R and BECCS under SSP126 and SSP370 climate (3 simulations per DGVM / experiment based on different climate model forcings). B) A/R simulations of the three DGVMs under SSP126 climate. C) BECCS simulations of the three DGVMs under SSP126 climate (see B). The different bioenergy crops used in the DGVMs are plotted with different colors.*

(3) Modeling of socioeconomic constraints and projecting future A/R potential (Bao et al. in prep.)

We have developed over 100 machine learning models through thousands of iterations of testing, training and validation, using multi-source high-resolution planted forest and socioeconomic datasets. These can effectively capture the global relations between A/R efforts and their socioeconomic constraints. Non-linear relations of socioeconomic constraints (poverty, governance, tenure security...) and A/R efforts were identified at the country level (Fig. 2). The trained models were subsequently employed to project realistic A/R areas for each country under different future SSPs. Till the end of this year, the remaining modelling and post-analyses of current work will be conducted, using the granted computing resources of 2025.

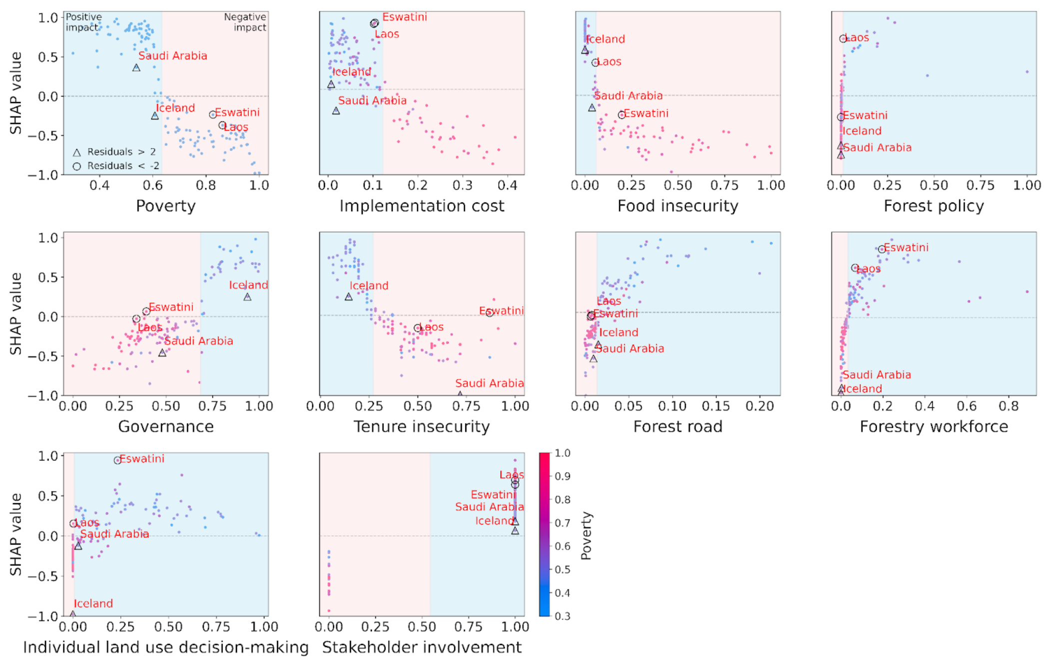

***Fig. 2:* Scatter plots of SHAP values against standardised explanatory variables for the model ensemble group of response variables:** The SHAP values are averaged across all well-performing random forest models ($R^2 \geq 0.5$) within the ensemble group. SHAP > 0 means that the explanatory variable positively affects the response variable (blue areas), while SHAP < 0 indicates a negative impact (pink areas). Poverty, as the top ranked explanatory variable, is used to color-code other explanatory variables to reveal potential correlations. Countries with standardised residuals > 2 are marked with triangles, while those with standardised residuals < 2 are marked with circles, to indicate outliers.