Project: **1241**

Project title: **Carbon Dioxide Removal**

Principal investigator: **Julia Pongratz**

Report period: **2023-11-01 to 2024-10-31**

CDRSynTra project

DKRZ tools and resources have been crucial, since all our progress is based on the MPI-ESM simulations that we have performed on Levante. All post-processing, and data analysis has also been performed with DKRZ resources. Overall :

(1) Simulations performed: We have complemented our MPI-ESM simulations with 40 fully-coupled concentration-driven simulations featuring large-scale Afforestation/Reforestation. Combined, this simulations will help isolate the biogeophysical effects of large-scale tree planting. We have also complemented our initial set of MPI-ESM simulations featuring Ocean Alkalinity Enhancement, with 15 fully-coupled emission-driven simulations, featuring different patterns of alkalinity application over the sea surface, and forest wood harvesting. We have also performed 5 fully-coupled MPI-ESM simulations for model development and investigation purposes.

(2) First-author publications (detailed list attached): One paper published in Nature Communications led by Dr. Yiannis Moustakis, as described in past reports. One paper in preparation led by Dr. Yiannis Moustakis, focusing on how the Earth system responds to scaling up and/or combining land- and ocean-based Carbon Dioxide Removal methods.

(3) Master theses: Leon Brubacher has completed his master thesis titled "Investigating climate change mitigation following large scale afforestation/reforestation under a temperature overshoot scenario". For the analysis the student used DKRZ resources, and analyzed 20 of the simulations that we have performed with DKRZ resources (DKRZ user b382535) .Katharina Raberg has already started her master thesis studying in more detail how large-scale afforestation/reforestation affects hydroclimatic variability across different emissions trajectories, and to what extent emerging feedbacks affect these changes. This work will feature a large-scale data analysis of 120 of the simulations that we have performed with DRKZ resources. For the analysis the student is using DRKZ resources (DKRZ user b382908).

(4) Utilization in teaching: Work undertaken with DKRZ resources has also provided useful material for the Master's Vorlesung "Boden-Pflanze-Atmosphäre Kontinuum".

(5) Other: Apart from undertaking the computational effort required for revising our first published paper (point 2.a. above), during the allocation period we have also performed all the analysis that has led to the preparation of our new paper (point 2.b. above). In particular, this has included analyzing 21 MPI-ESM simulations that have been performed with DKRZ resources during this and past allocation periods, featuring the deployment, scaling-up and/or combination of Afforestation/Reforestation (AR) and Ocean Alkalinity Enhancement (OAE). This has been accompanied by simulations carried out by the FOCI Earth System Model (not with DKRZ resources). Our results suggest that global Carbon fluxes between the land, atmosphere, and ocean, respond linearly to scaling up and/or combining CDR methods (Fig. 1). This has important implications for monitoring, reporting and verifying CDR, and for designing future CDR portfolios.

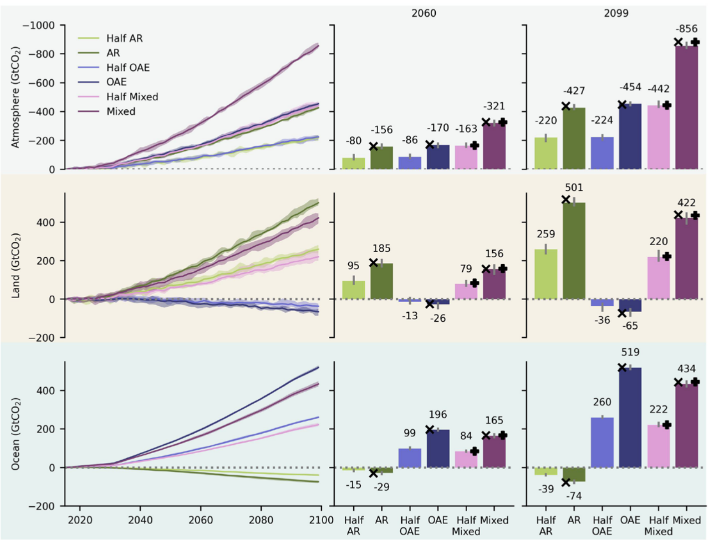

Figure 1: Global Carbon fluxes: The left column panels show the timeseries of intermodel average change in (top) atmosphere, (middle) land, and (bottom) ocean Carbon for all the different scenarios compared to the reference (no CDR applied)($GtCO_2$). The Mixed scenarios include both AR and OAE. Scenarios denoted with "half" suggest that half of the corresponding CDR method/portfolio is employed. The shading around the mean shows the minimum-maximum range across both models and all ensemble members. To aid interpretation, in the middle and right column panels the barplots show snapshots for 2060 and 2099. The bar height corresponds to the intermodel average, and the gray vertical lines show the minimum-maximum range across both models and all ensemble members. The "x" and "+"

marks indicate expectations from scaling up and combining CDR application respectively, based on linear expectations.

STEPSEC project

All our model simulations and data analysis have been performed by utilizing DKRZ tools and resources (Jupyterhub and Levante SLURM jobs and storage). In particular the performed simulations and analyses include:

(1) **Work for publication 'How to measure the efficiency of terrestrial carbon dioxide removal methods'**: Our implementation of a 2nd generation bioenergy crop PFT representing Miscanthus in JSBACH3.2 was finalized with an improved plant-physiological parameter set (Nützel 2024) and was published in Egerer et al. 2024, which, besides simulations described in past reports, includes a validation against observational data.

(2) **Work for study 'Forestation in CMIP6: Wide model spread in tree cover and land carbon uptake':** Data were analyzed using DKRZ resources. The results will be published by the end of 2024.

(3) **Standalone simulations in T255 resolution for Central Europe as input for our project partners for the model CRAFTY-DE:** The carbon sequestration potential of different plant functional types (PFT) was calculated for the Central European domain as an input for the German agent based model CRAFTY-DE (Fig. 2). The simulations were performed for different configurations: disturbances on/off, different background climate and CO_2 (SSP119, SSP126, SSP370). Test runs will be performed by the end of 2024 with land-use input from CRAFTY-DE on 5km resolution.

(4) **Standalone simulations for idealized sensitivity study (Nützel et al. in prep.)** : To compare future temporal dynamics of carbon storage efficiency of AR and bioenergy with carbon capture and storage (BECCS), 54 future idealized global standalone simulations were run with JSBACH3.2, where a fixed amount of agricultural land in every grid cell is replaced by CDR (Forest or BECCS based on our 2nd generation bioenergy plant implementation published in Egerer et al. 2024) and is kept constant afterwards. The idealized setup includes variations of the start year of CDR (2015, 2030, 2050, 2070), background climate (SSP1-2.6, SSP3-7.0) and climate model forcings (3 from ISIMIP3b) (Fig. 3). Additionally, through synergies with bm1255 (ESM2025), a similar set of idealized standalone simulations can be used to quantify the impact of accounting for disturbances (fire, wind throw). Three spin-ups and historical runs using the three different ISIMIP3b climate model forcings were run as a basis for the future experiments. For all of these simulations CMOR-like post-processing and compression was optimized reducing output file size by a factor of ~10. To enable a robust inter-model comparison these simulations were also performed by three other state-of-the-art dynamic global vegetation models (JULES, LPJmL, LPJ-GUESS) and results are already (JULES) or will be (LPJmL, LPJ-GUESS) uploaded to Levante for the analysis lead by Tobias Nützel by the end of this year. Additionally, a complementary set of sensitivity simulations (combined AR & BECCS, parameter sensitivity, CO_2-/climate-effect separately) will be run by the end of this year.

(5) **Machine learning modeling and analysis for the work 'Socio-economic determinants of global tree-planting efforts' :** To robustly quantify the impact of socio-economic factors on global tree planting at country level, we developed and run over 200 random forest regression models using current available tree planting statistics, observation, and multi-source socio-economic datasets. Non-linear dynamics of each socio-economic factor (poverty, governance, tenure security...) were identified for tree planting (Bao et al. in prep.). DKRZ computing resources were used for the extensive model testing, hyper-parameter optimization, post-analyses and plotting. Till the end of this year, final model testing, validation, and post-analyses will be conducted for the current work, using the granted computing resources of 2024.

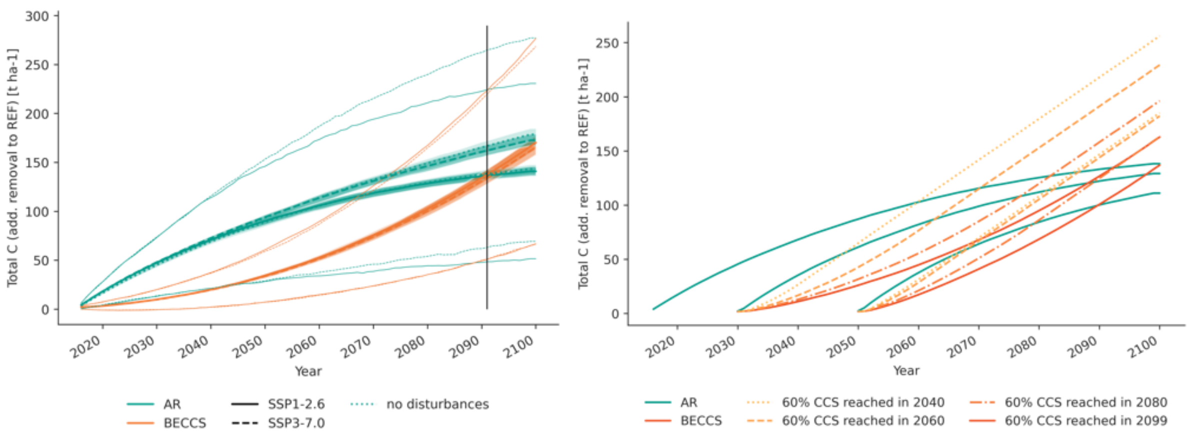

Figure 2: Comparison of temporal dynamics of total C storage (global mean; additionally removed C compared to the reference) between AR and BECCS in JSBACH3.2 standalone. Left: Temporal dynamics depending on background climate and CO_2 (SSP1-2.6, SSP3-7.0) and impact of excluding disturbances for AR (dotted lines). The filled areas represent the uncertainty induced by three different climate model forcings. The thinner lines represent the global lower / upper quartiles, respectively. The vertical black line visualizes the point in time when BECCS gets more efficient than AR in the model. Right: Temporal dynamics depending on various start years of CDR application and assumptions on scale-up of CCS infrastructure (based on SSP1-2.6 climate and CO_2 in JSBACH).