Report: Assessing the carbon sink potential, climatic limits and impacts of artificial photosynthesis (Project 1319)

Project title: Assessing the carbon sink potential, climatic limits and impacts of artificial photosynthesis (*CITRONE*)

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Project overview

The IPCC considers large-scale use of negative emission technologies (NETs) necessary for limiting global warming. However, their Earth system feedbacks and impacts are not well constrained from model simulations. Therefore, in the project *CITRONE*, we developed, validated, and evaluated an extension to the Max Planck Institute Earth System Model version 1.2-LR [MPI-ESM, 1] representing a land-based NET approach to artificial photosynthesis [NETPEC project, 2, 3]. Following up on the project's first results (see report on the first project), we aim to conduct and analyse a model ensemble that spans the technologically uncertain parameters and scenarios of the NETPEC approach. A subset of ensemble members will extend to 2300 [4] to capture long-term impacts of the NETPEC approach. Further, we work towards expanding our model with a conceptual set of interactive land use decision rules. These rules will drive the NET land cover in response to the technology's impact on climate and carbon cycle. This expansion is supposed to sample parts of the yet unresolved negative emission scenario uncertainty which arises from potential side effects by NETs.

Report on the first project phase

CITRONE I was aiming at model development, evaluation and scientific progress on "the interactions between [the NETPEC technology], the land surface, the large-scale global circulation, and the carbon cycle" [5]. Initially, the project was not able to fully exploit the allocated computational resources, because of several reasons. The application for funding of the PhD student aiming to work on the model validation and evaluation (Moritz Adam) took several months in Fall 2022 and early 2023 (project drafting, stipend applications, interview preparation). Prior to this, his Master thesis was finalized on the *CITRONE* project allocation. Additionally, analyses were hampered by the required time for porting MPI-ESM and the implemented NET extension from HLRE-3 to HLRE-4 (collaboration with Thomas Kleinen, MPI-M).

Nonetheless, the expanded model [Fig. 1a] was validated successfully regarding energy and mass conservation, functioning and well-calibrated CDR representation, and interactive spatiotemporal NET deployment [Fig. 1b]. Scientific analyses so far span localized and distributed setups of NETPEC devices and scenarios of high and low overall use. Evaluation for highly efficient land use NET parameters show little impact on future surface climate, and spatially heterogeneous impacts of land use transitions. Currently, the hypothesis is being tested if less ambitious technology parameters cause higher Earth system impacts in turn. The manuscript on this evaluation is planned to be submitted for review in Fall 2023. Because of the delayed start of the responsible PhD student's project, the initially planned simulation ensemble for robustness testing remains to be completed as part of the next phase of *CITRONE*. Still, the ability to run the expanded MPI-ESM1.2-LR model on DKRZ's HLRE-4 has already enabled us to start addressing the novel research field of spatial explicit NET modeling and impacts [6-9].

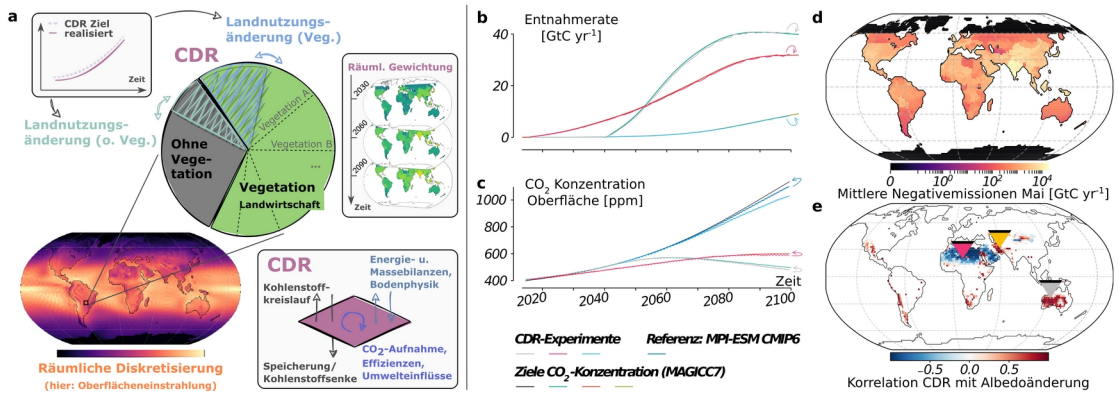

Figure 1: ***Extension of the JSBACH land surface model (a).*** *A spatio-temporal target drives the NET model, prescribing a spatial weighting and a global carbon dioxide removal but no NET area. This approach isolates effects through land use (change) through land-based negative emissions from those by agricultural land use transitions. The NETPEC surface type interacts with the local surface physics and carbon cycle.* ***Successful validation of the extended model (b-e).*** *Globally realized negative emissions converge precisely to the target irrespective of spatial and temporal scenario (b), same goes for the atmospheric CO_2 concentration (c). Arrows indicate the ideal expectations. Spatial negative emissions in a weighting scenario following transient projections of gross domestic product (d). Effects of NETPEC devices on surface albedo in an experiment with solar-driven negative emissions in deserts. Data: [4, 11].*

Intermediate results for highly efficient land use scenarios show little climatic impacts of NETPEC devices through altered surface balances [Fig, 2a, b]. Land carbon stock impacts are spatially heterogeneous and scenario-dependent, requiring further investigation. The results further highlight the sensitivity of intra-annual negative emission variability to the spatial configuration [Fig 2c, d].

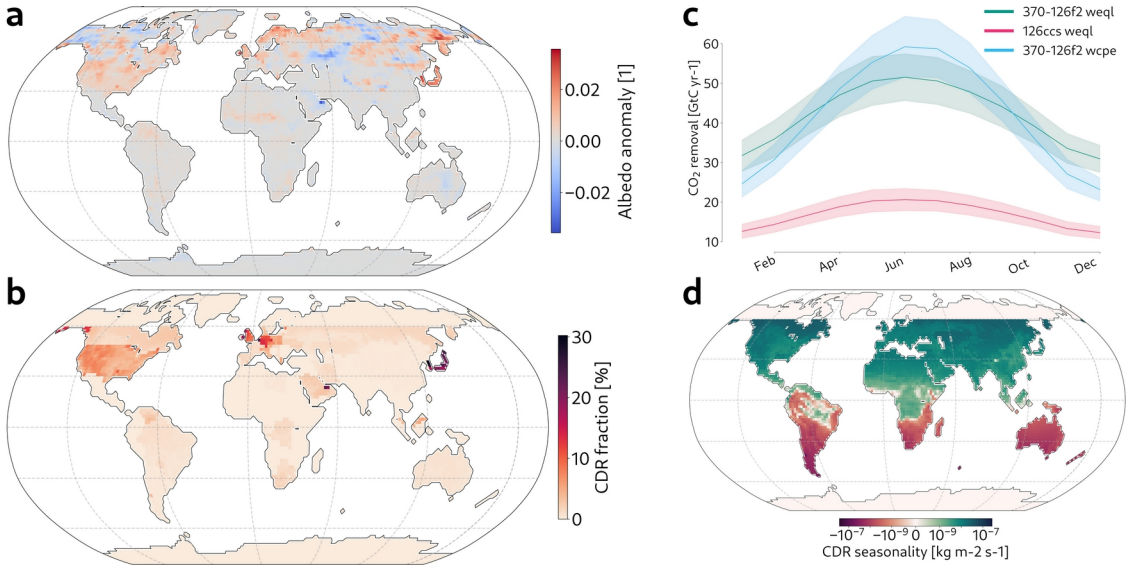

Figure 2: ***NETPEC impacts for a highly efficient–low land use scenario.*** *Small albedo shifts compared to the control simulation (a) in regions with large CDR cover fraction (b) do not propagate into significant climate anomalies. Spatial deployment weights follow the cumulative past per-capita CO_2 emission burden [10]. The temporal negative emission target is derived from future scenarios [11] and follows roughly half of the residual emissions between the shared socioeconomic pathway (SSP) 1-2.6 and SSP3-7.0. The multi-annual mean seasonality depends on the interplay of seasonality irradiance, spatial configuration, and withdrawal target (c). This is mainly explained by the land cover distribution, illustrated by the difference at global annual maximum (May) and minimum (December) negative emissions in an experiment with spatially homogeneous deployment target (d).*