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

Project title: Assessing technological resilience and regional interactions of sun-driven process chains for CO_2 removal (Project 1319)

Allocation period: 2024-07-01 to 2025-06-30

Project overview

To stabilize planetary temperature, large-scale deployment of negative emission technologies (NETs) for artificial CO_2 removal (CDR) will be necessary. However, the NET's interactions within the Earth system are not well constrained from a modeling perspective. Therefore, in the first two phases of the project *CITRONE*, we represented land-based process chains for artificial photosynthesis [NETPEC project, 1, 2] in the Max Planck Institute for Meteorology Earth System Model version 1.2-LR [MPI-ESM, 3] and scrutinized their implications on the Earth system (see report on second project phase). Our resulting study [4] highlights the pivotal role of the CDR process chain's efficiency for minimizing environmental impacts through land conversions. Following up on this result, we envisage to constrain the climatic envelope to NETPEC process chains in experiments with MPI-ESM-HR by identifying key climatic factors for technological efficiency. To support this objective, we will expand the number of external controls represented in the process chain's parametrization. We investigate the technological resilience of process chains with respect to climatic and forcing variability in equilibrium and scenario simulations. Minimizing land conversion by optimized CDR deployment is the second objective CITRONE III will address. Here, we establish an ensemble covering several option to prioritizing land cover change for CDR to quantify the potential of reducing land use conflicts through land management practices or constraints.

Report on the second project phase

In *CITRONE II*, we leveraged the representation of artificial photosynthesis for CDR (AP-CDR) in MPI-ESM as developed in *CITRONE I* [5] to "conduct and analyze a model ensemble that spans the technologically uncertain parameters and scenarios of the NETPEC approach" [6]. Here, we focus on reporting the computational aspects and primary results of our resulting study. Our manuscript further includes a comprehensive model description and discussion and we will provide it to DKRZ, once published or available as a preprint.

Ensemble design and resource utilization

We spent ~50% of utilized compute time on generating our study's core ensemble (Table 1). The ensemble's purpose was to scrutinize potential Earth system implications of AP-CDR along three pivotal uncertainty dimensions: the overall reliance on CDR, the spatial localization, and technological efficiency. We initially evaluated several scenario designs and eventually chose to include two options for each uncertainty dimension. For the first dimension, we investigate a high-CDR pathway that pushes the limits of scale-up [7] and the global reliance on CO_2 capture as implicitly contained in shared socio-economic pathway (SSP) 1-2.6 [8]. A globally spread-out and a localized AP-CDR deployment cover the second uncertainty dimension. The localization in the second case is according to individual coutries' past emission burdens [9]. An AP-CDR process chain based on present-day technology (direct air capture + industrial-scale electrolysis for CO_2 processing, both powered by photovoltaics) and the envisaged NETPEC process chain (direct air capture + photoelectrochemical CO_2 reduction, solar energy harvest only required for CO_2 capturing) span a range of technological uncertainty. The present-day technology scenario is particularly important for interpreting our results, as it quantifies the consequences of a CDR development that would fall short off expectations. We ran most of the CDR ensemble members until 2200 and some until 2300, to include an extended period of CDR scale-down and potential recovery of carbon stocks into our assessment.

Substantiating the results obtained from our core ensemble required thorough uncertainty quantification and sensitivity testing, with control simulations totaling to ~40% of compute time. We conducted two types of control experiments. A 400-year equilibrium control simulation with present day forcings contrasts results with internal model variability. Experiments along the core ensemble's emission and land use pathways but without explicit AP-CDR representation allowed to isolate CDR effects on the modeled Earth system from the system's generic response. We further performed sensitivity tests, which focus on thermal cooling through CO_2 fixation.

Development and exploration consumed the remaining ~10% of compute time. The primary purpose of the development was to improve robustness and accuracy of parametrizations [Development I – III in Table 1] and of dynamic CDR deployment [Development IV]. All developments were successful and documented in [4]. With a couple of exploratory experiments, we confirmed that our envisaged work on impacts of external forcing variability on AP-CDR process chains will be numerically stable and technically feasible (see planned work below). The last quarter's share of the allocation will primarily serve for sensitivity experiments during the peer-review process of the publication on the first two phases of CITRONE [4] (Sensitivity II+). Specifically, this may involve the sensitivity of the results on land conversions to the underlying land use scenario, and significance testing of climatic effects with respect to internal model variability. In addition, the remainder will be used to work towards dynamic land use rules [5]. Data required to reproduce the results of our study including a set of restart files will be transferred to the the long-term archive at the end of this quarter.

***Table 1* | Approximate compute time utilization and purpose in CITRONE II.** One simulation year of our modeling setup corresponds to 2.2 – 2.4 node hours on the compute partitions, excluding data post-processing on shared partitions.

Experiment	***Purpose***	***Simulated years***
Development I	Debug and test thermal cooling through CO2 fixation	10
Development II	Calibrate land footprint of process chains	6
Development III	Include concentration-dependent CDR level-off to improve stability	240
Development IV	Debug and test second-order CDR deployment algorithm for enhanced CDR forcing accuracy	50
Spin-up 1850-2015	Initial state for impact study	165
Pathway controls	Quantify Earth system's forced response without explicit CDR	770

Equilibrium control	Quantify internal variability	400
Experiments with explicit and dynamic CDR through artificial photosynthesis	Evaluate Earth system effects across uncertainty dimensions: *(CDR and emission pathway)* x (*spatial deployment scenario)* x *(physical process chain characteristics and efficiencies)*	2590
Sensitivity I	Quantify sensitivity of results to thermal cooling through CDR	740
Sensitivity II+ (planned during peer-review)	Quantify sensitivity of results e.g. to land use scenario or details of the parametrization	740-1480
Exploration	Assess feasibility of work envisaged in CITRONE III	325
Total		6036-6776

Overview of our study's results and conclusions

Our model experiments demonstrate that globally and regionally, large-scale AP-CDR process chains mostly have negligible effects on climate and carbon cycle across a range of uncertainties [4, Figure 1]. The response of the global mean CO_2 concentration and surface air temperature (Figure 1a) indicates that none of the three uncertainty dimensions results in a different global climate in the periods of CDR scale-up (2069-2099) and constant CDR (2110-2139). However, spatially explicit AP-CDR induces significant changes in the surface energy balance in a small share of IPCC regions (Figure 1b). Except for the Kazakh Steppe and parts of Siberia, these impacts on the regional surface energy balance, as well as interactions with the surface moisture balance, do not lead to significant local changes in surface climate. Effects on carbon stocks are globally (Figure 1c) and regionally significant (not shown), but do not substantially diminish the removal potential of AP-CDR. They even get (over-)compensated over time in several experiments. Regional implications for the carbon cycle depend on the spatial scenario. For example, the localized scenario results in a higher carbon stock decrease in Central North America and Eastern Asia than the delocalized scenario, which in turn impairs carbon stocks in Northern South America more substantially. These effects propagate to the global scale (not shown). Thus, minimizing AP-CDR's environmental impacts is not only a matter of global localization versus delocalization. Alltogether, our study demonstrates low climatic and biospheric implications of AP-CDR process chains, which contrasts with substantial effects of many large-scale biomass-based CDR approaches.

While effects on climate and carbon cycle are small, CO_2 capturing, processing, and associated energy harvest still demand 0.46 to 2.82% of global land area, depending on process chain efficiencies [4, Figure 1d]. Technological efficiency dominate net land conversions globally, the spatial deployment additionally impacts land use regionally. Considering the core of northern and central Europe (NCE*) in the low-efficient, high-CDR simulations as an example (not shown), AP-CDR covers 17.6% of the region during the constant CDR period in the historic burden scenario. In contrast, land conversion in NCE* amounts to only 2.4% in the delocalized scenario. The implications of the historical burden-sharing scenario become even more evident when putting the land cover adjustments needed to accommodate AP-CDR into perspective. In the delocalized case, NCE* loses grass- and agricultural land only slightly above the Earth system's internal variability. In contrast, for CDR according to historic emission burdens, converted grasslands alone correspond to the equivalent of 37% of the European Union's agricultural area (∼48% of the region's entire area [9]) during the constant CDR period, which bears the potential for severe land use conflicts. This result highlights the central role of optimized process chain efficiencies for reducing this environmental burden. At the same time, the risks of relying extensively on DAC-type CDR chains also become evident.

Overall, our study provides novel evidence indicating that, within the scope and limitations of our modeling approach, DAC-like process chains targeting liquid or solid products cause negligible impacts on climate and do not induce carbon emissions from the biosphere that would substantially offset their removal potential. At the same time, our results suggest that associated land conversions could lead to substantial target conflicts in a world overly reliant on CDR. Minimizing adverse consequences requires high technological efficiency, keeping the overall CDR need low through plausible emission reductions, and limiting excessive expectations on CDR. Therefore, reducing the reliance on yet unrealized technological advancements is vital in light of the growing evidence of all costs of CO_2 removal.

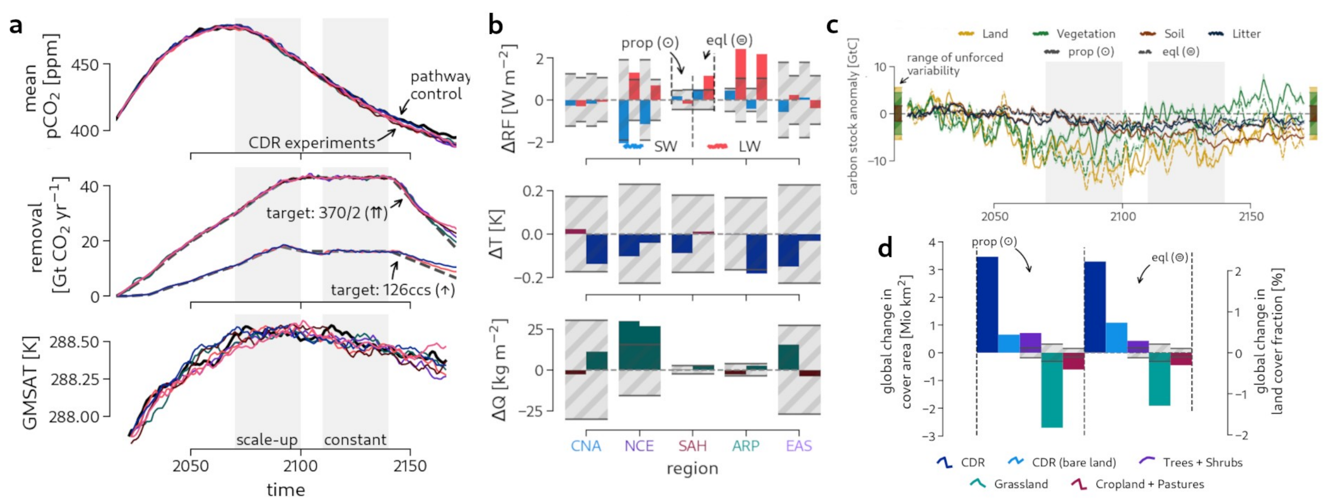

Figure 1 | Overview of results on Earth system implications of AP-CDR process chains obtained during CITRONE II. a*, Global mean responses of the surface CO2 concentration, sink product pools, and surface air temperature (SAT) in individual CDR experiments along the three uncertainty dimensions and in the mean pathway control.* ***b****, Mean regional anomalies in radiative short- and long-wave forcing (ΔRF), SAT (ΔT), and soil moisture (ΔQ) in selected IPCC regions [11] during the period of constant AP-CDR. Panels visualize results for the high-efficiency process chain, high-CDR world, and both spatial scenarios (eql – spread-out deployment, prop – localized according to emission burden). Shading indicates the range of internal model variability.* ***c****, Response of global carbon stocks for the same experiment.* ***d****, Global land conversions induced by spatial AP-CDR. Depicted experiments are as in* ***b****,* ***c*** *but for the process chain with low overall efficiency.*