



Regional perspective of terrestrial carbon dioxide removal on land-atmosphere coupling and heat extremes

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Terrestrial carbon dioxide removal (CDR), including afforestation and reforestation (A/R) and other land-based approaches, is a key element of climate mitigation pathways consistent with the Paris Agreement. While the mitigation potential and Earth system responses to terrestrial CDR deployment have been increasingly explored, its influence on land-atmosphere coupling and temperature extremes remains underexplored, particularly at regional scales. Understanding these processes is essential for evaluating both synergies and trade-offs associated with land-based mitigation strategies, including potential implications for biogeophysical co-benefits, resilience, and permanence.

Here, we present a spatio-temporal explicit analysis of how terrestrial CDR pathways modify land-atmosphere coupling and associated hot extremes across regions and seasons. The analysis is based on emission-driven simulations from the fully coupled MPI Earth System Model and considers a range of future scenarios that include both stylized large-scale terrestrial CDR deployment and more realistic mitigation pathways developed within CDRSynTra, LAMACLIMA, and RESCUE projects. This scenario diversity allows us to explore the robustness, plausibility, and potential non-linearities of land-atmosphere responses to terrestrial CDR. The scenarios considered include large-scale A/R aligned with national pledges, transformation pathways characterized by global sustainability and global inequality, and climate stabilization pathways with and without temperature overshoot that rely on portfolios of multiple CDR approaches.

We apply various land-atmosphere coupling diagnostics, such as measures of soil-moisture control on latent and sensible heat fluxes, and relate these to hot-day and heatwave metrics over land to assess the processes linking surface fluxes, moisture availability, and temperature extremes. By explicitly focusing on regional responses, the analysis captures spatial heterogeneity in land-atmosphere feedbacks that is not apparent in global-mean assessments. Seasonal variability (e.g., during spring and summer) and different future time horizons (near-, mid-, and late-century; before and after overshoot), are considered to assess the sensitivity of land-atmosphere coupling processes to the timing and magnitude of the application of terrestrial CDR.

Identifying regions where terrestrial CDR strongly modifies land–atmosphere coupling and heat extremes can help highlight hotspots for targeted monitoring and evaluation by indicating where observations and diagnostics are most relevant for tracking biophysical responses and emerging risks. Analyses indicate that regions such as Scandinavia, West Asia, and Northeast China exhibit contrasting responses, where changes in heat extremes coincide with shifts in soil-moisture control and evaporative cooling, and where observational coverage of surface fluxes remains limited. Such regional insights can also inform the assessment of where terrestrial CDR deployment may be associated with co-benefits, and where land–atmosphere feedbacks could pose challenges or limitations, including adaptation-relevant impacts on heat stress and labor productivity. Overall, this work helps fill a key gap in current assessments by explicitly linking terrestrial CDR deployment to land–atmosphere coupling and heat extremes at regional scales, and by providing a process-based assessment framework that can support risk-aware evaluation of land-based CDR strategies and be extended to other terrestrial CDR approaches.