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Estimates of Deglacial Land Biosphere Carbon Stock Changes – A Model Sensitivity Study

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The sign and magnitude of deglacial changes in the land biosphere carbon stock (Δland) are uncertain. Estimates range from releases of 200-400 GtC (Zimov et al., 2006, Science; Zech et al., 2011, Climate of the Past) to uptakes as high as 1300 GtC over the deglacial period (Adams et al., 1990, Global and Planetary Change). Recent estimates locate Δland around an uptake of 300-400 GtC (Ciais et al., 2012, Nature Geoscience; Menviel et al., 2017, Paleoceanography). These studies invoke ocean δ^{13}C measurements in an isotopic mass balance for the ocean, land, and atmosphere following earlier studies (e.g. Shackleton, 1977, in: The fate of Fossil Fuel CO_2 in the Ocean). However, the exchange of carbon and isotopes with the geosphere through ocean-sediment interactions and weathering is neglected.

We quantify the impact of sediment/weathering fluxes on estimates of Δland using the Bern3D model by conducting pulse-release and deglacial (“LGM-PI”) sensitivity experiments in combination with observational constraints.

In the pulse-release experiments, “land carbon” is removed instantaneously from the model atmosphere. Experiments are done in a “closed” and “open system” configuration, where either sediment/weathering fluxes are neglected or enabled. These experiments permit us to elucidate the response time scales and the influence of the weathering/sediment fluxes on the isotopic mass balance approach.

Initially, the $\delta^{13}CO_2$ perturbation of the atmosphere is removed much faster than the CO_2 perturbation itself as gross exchange with the ocean and land biosphere dilutes the isotopic signal. On multi-millennial to 100-kyr timescales, the ^{13}C perturbation is removed by weathering/sediment exchanges. Over timescales such as the deglacial, sediment/weathering interactions further mitigate the isotopic perturbation, leading to an underestimation of the initial change by 20-30% when relying on a closed system assumption.

Many processes potentially affected past isotope evolution. For the LGM-PI sensitivity experiments, we apply in a factorial setting idealized changes in Δland, remineralization depth (oceanic org. C), $CaCO_3$/org. C export ratio (oceanic alkalinity), wind stress forcing (circulation), and organic weathering rates on land (weathering/burial changes) in addition to standard LGM forcings (GHG, orbital, ice-sheet and albedo, coral reef regrowth, fresh water pulses). Observational and reconstructed $\delta^{13}C_{atm}$, $\delta^{13}C_{DIC}$, marine $[CO_3^{2-}]$, and atmospheric CO_2 are used as targets for the results.

Response sensitivities from the factorial experiments are used to build simple substitute models. In a Monte-Carlo framework, combinations of the idealized forcings that match the targets within their uncertainties are sought. Promising combinations are checked and further investigated using the Bern3D model. This allows us to explore a large space of process combinations.

The data-constraint results clearly indicate that the land carbon stock increased over the deglacial, rendering suggestion of a larger land carbon stock at the LGM compared to the late Holocene very unlikely. Further, Δland seems to have been larger than 300-400 GtC when considering ocean-sediment interactions and observational and reconstructed constraints, possibly more in the range of 500 to 1000 GtC.