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Attributing CO_2 effects in composite carbon management scenarios

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Marine carbon dioxide removal (mCDR) seeks to engineer durable storage of anthropogenic carbon emissions by leveraging the natural oceanic CO_2 sink. Development and early field testing of various mCDR technologies is currently underway, buttressing a range of industrial decarbonization efforts and land management-based interventions to mitigate legacy CO_2 emissions. The effectiveness of these individual approaches to reduce atmospheric CO_2 has lately received much attention, however, interactions between different ocean- and land-based CDR interventions and the dependence of CDR effectiveness on future fossil carbon emission scenarios have not yet been formally evaluated. We use numerical carbon cycle model frameworks to simulate CO_2 drawdown under composite CDR deployment scenarios and develop an analytical approach to attribute specific CO_2 reductions to individual co-occurring CDR interventions. We also use the analytical approach to evaluate the role of model biases by comparing simulations with the CYCLOPS carbon cycle box model and the cGENIE Earth System Model. Within each model domain, we systematically apply permutations of direct air capture (DAC), ocean alkalinity enhancement (OAE), direct ocean capture (DOC), and seaweed mariculture to quantify their individual and combined effects in the context of different background emission and decarbonization scenarios. Despite differences in carbon removal-timescales between CYCLOPS and cGENIE, both models show that each CDR intervention causes a distinct proportional CO_2 drawdown. As such, the simulated proportional CO_2 reduction of a composite scenario approximately equals the sum of the proportional CO_2 effects of all component interventions. In other words, each incremental emission reduction or CDR intervention causes an attributable percentage change in CO_2 relative to the counterfactual baseline scenario, where absolute CO_2 reductions from CDR and lowered net emissions are the exponential product of individual applications rather than the linear sum of isolated CO_2 effects. This analytic accounting of composite CDR efficacy can advance fair carbon credit attribution for independent CDR and decarbonization operators and inform global-scale monitoring, reporting and verification (MRV) of carbon management interventions.