Abstract

Limiting the global average temperature increase to 1.5°C by the end of the century will most likely require climatically-relevant amounts of carbon dioxide removal (CDR), also known as negative emissions. There are many ways of achieving negative emissions, ranging from ecosystem restoration to industrial processes, but their efficacy at scale remains uncertain. Negative emissions technologies entered mainstream climate mitigation discourse via integrated assessment models (IAMs), which featured bioenergy with carbon capture and storage (BECCS) as a means to both carbon removal and energy generation. In the IAM literature, negative emissions technologies (NETs) are key to meeting the exigencies of cost-optimized climate mitigation, which include a more gradual phaseout of fossil fuels, continued GDP growth, and rising energy consumption. The planetary-scale CDR featured in those studies prompts discussions of the implied side effects on food, energy, and water systems and the Earth system more broadly. The planetary boundaries framework delineates a safe operating space for human activity by identifying thresholds for several Earth system processes. The goal of this study is to estimate an upper bound for the rate of CDR while remaining within those biophysical limits. The negative emissions from a portfolio of technologies are maximized subject to constraints which describe three planetary boundaries—blue water, green water, and land-system change—and a cap on total energy use. The portfolio of NETs includes BECCS, direct air carbon capture and storage (DACCS), enhanced mineral weathering (EW), and afforestation/reforestation (AR). The model, formulated as a linear program, estimates a maximum rate of negative emissions within planetary boundaries of 30 $GtCO_2\ yr^{-1}$, which is on the same order of magnitude as negative emissions rates from IAMs. The NETs portfolio generated by the model has substantial impacts on planetary boundaries, which implies that the NETs portfolios in IAMs would have impacts of similar scale. In contrast to the results of IAM studies which depend on BECCS and DACCS to achieve most of the negative emissions, the NETs portfolio in this study depends on AR to deliver half of the total negative emissions. The high proportion of AR in the model output is needed to make progress towards the safe side of the land-system change planetary boundary. Overall, this study presents an alternative framework for modelling carbon dioxide removal that results in characteristically different portfolios of NETs compared to those in IAMs.