Interference in the Earth system through terrestrial carbon dioxide removal: numerical simulations of trade-offs, risks and opportunities

Abstract

Dissertation of Vera Heck, Potsdam Institute for Climate Impact Research,
Institute for Geography, Humboldt-Universität zu Berlin

Terrestrial carbon dioxide removal (tCDR) strategies are being discussed as options to counteract anthropogenic global warming. In particular policy makers now increasingly consider targeted land use change such as afforestation and biomass plantations as options to extract carbon from the atmosphere. In light of this, it is important to understand sustainability limits and implications of tCDR in the context of Earth system dynamics.

This thesis provides a comprehensive model based assessment of biogeochemical and hydrological side-effects of large-scale biomass plantations and afforestation in the context of planetary boundaries, delimiting a safe operating space for humanity. Simulations with a dynamic global vegetation model (LPJmL) indicate considerable biogeochemical and hydrological consequences of biomass plantations which are even larger than those of historical agricultural land use. In particular, biomass plantations on current agricultural land use areas show a 22% increase in net primary productivity compared to natural vegetation on the same area, which drives other alterations in regional and global carbon and water cycles.

Additionally, land use scenarios of biomass plantations are developed with a multi-objective optimisation model under consideration of regional environmental constraints and evaluated against the global planetary boundaries for biogeochemical flows, biosphere integrity, land system change and freshwater use. This shows clear trade-offs between planetary boundaries and tCDR. Respecting environmental constraints according to the planetary boundary framework yields almost zero tCDR potential. The transgression of regional environmental constraints into a zone of increasing risk of triggering feedbacks at the planetary scale can provide considerable annual net carbon extraction rates of 1.4 GtC - 6.9 GtC, depending on the biomass conversion pathway and the timely operationalisation of large-scale carbon capture and storage plants.

The importance of co-evolutionary dynamics of the Earth's carbon cycle and societal interventions through tCDR is demonstrated with a conceptual modelling approach in the context of carbon-related planetary boundaries. It becomes apparent that focussing on climate change without an integrated trade-off assessment may lead to navigating the Earth system out of the safe operating space due to collateral transgression of other boundaries. The success of tCDR depends on the degree of anticipation of climate change, the potential tCDR rate and the underlying emission pathway.

Integrating population growth and changing food demands while minimising carbon and biodiversity loss demonstrates opportunities and limitations for terrestrial carbon sequestration. Without substantial improvements of crop and livestock productivities, feeding 9 billion people diminishes opportunities for tCDR. Higher productivities, however, combined with the displacement of agricultural production into concentrated regions of high productivity yield sustainable terrestrial carbon sequestration potentials of up to 98 GtC.