# Towards climate neutrality: A turning point in land-use history

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**"CDR has become a key function of land use and should be embraced as such. The complex interactions in the human and natural systems need to be addressed and integrated across scientific disciplines."**

### From emissions to removals

From its invention some 10,000 years ago, agriculture spread across the globe as population grew and people and knowledge migrated, only abated at times in some regions by epidemics or wars. Agriculture, but also the use of forest resources, e.g., for construction or smelting, became such massive forces of altering the landscape and depleting natural resources that Hans Carl von Carlowitz in 1713 wrote his book "Sylvicultura oeconomica", which introduced the concept of sustainability as the long-term responsible use of a natural resource.

In many tropical countries, the cumulative emissions from land use, land use change and forestry (LULUCF) by far surpass fossil emissions over the industrial era (IPCC, 2022a). Removals of CO2 are substantial: LULUCF associated with forests removes 3.5±1.0 GtCO2 per year globally (2012-2021 average), with a small net flux into the atmosphere from wood harvesting outdone by uptake of CO2 through afforestation and regrowth of forests following agricultural abandonment. But overall, emissions remain high and surpass removals by more than a factor of 2: LULUCF associated with deforestation, drainage and burning of organic soils, and other transitions emit 6.7±1.5 GtCO2, 0.8±0.3 GtCO2, and 0.6±0.5 GtCO2 per year, respectively (Fig. 1; Friedlingstein et al., 2022). The Glasgow leaders' declaration on forests and land use proposed at the UN Climate Change Conference in 2021 thus may have seemed as urgent as it was utopian when it reinforced earlier pledges to halt and reverse forest loss and land degradation within this decade.

When we look into the projections of socioeconomic models of the volume of CO2 removals from the atmosphere, we find that all illustrative mitigation pathways in the IPCC's 6th Assessment Report that are likely to limit warming to 2°C or lower use some form of Carbon Dioxide Removal (CDR), and the deployment levels required are high compared to those deployed today. Around net 3 GtCO2 per year should be removed on managed land (including re/afforestation) by 2050, with a similar amount through bioenergy with carbon

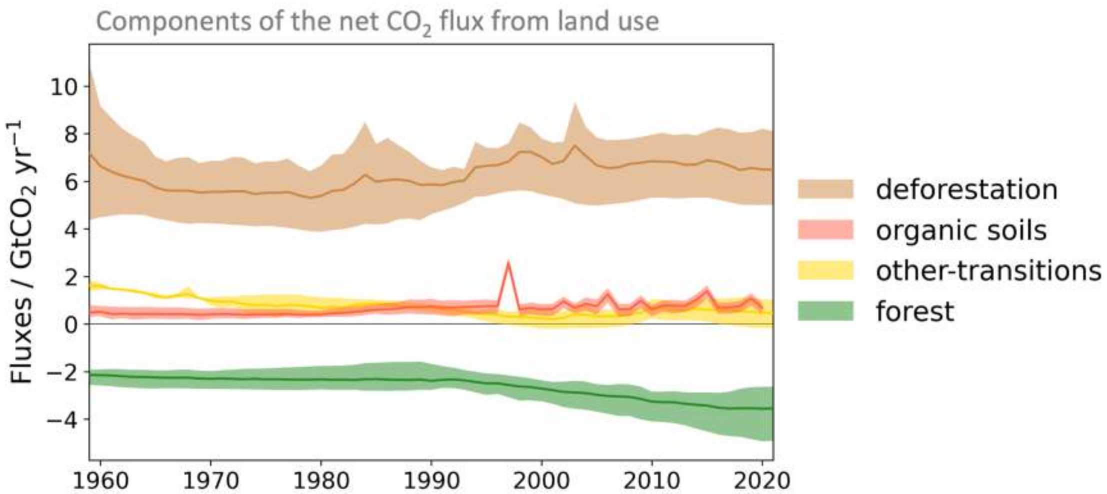


**Fig. 1:** Emissions and removals of CO2 associated with changes in land use and land management as simulated by bookkeeping models in the Annual Global Carbon Budget 2022 (based on data from Friedlingstein et al., 2022).

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capture and storage (IPCC, 2022b). After 10,000 years of releasing CO2 by clearing the land, humankind proposes to create massive sinks on land within the next few years.

## The new role of land use on our way to climate neutrality

The IPCC's latest assessment report no longer discusses the "if", but "how" of CDR within ambitious mitigation strategies. Although it remains irrevocable that deep, persistent cuts in emissions are needed, CDR becomes more prominent and imminent. The roles of CDR are to compensate for residual emissions from 'hard-to-transition' sectors, such as methane and nitrous oxide from agriculture, and to create net-negative emissions in the long-term (Fig. 2). But as global CO2 emissions since the Paris Agreement did not notably decrease, apart from a one-year drop attributable to a severe pandemic, CDR is also seen as increasingly needed to accelerate near-term mitigation. Near-term employment, however, relies on land: It is the terrestrial vegetation that currently provides 99.9% of CDR with its ready-to-use CDR methods such as re/afforestation, restoration of wetlands, peatlands and degraded forests, soil carbon uptake or forestry with usage in long-lived wood products (Smith et al., 2023). Some of the novel CDR methods projected to play a major role in future mitigation pathways, like bioenergy with carbon capture and storage (BECCS), will add further pressure on land.

It may seem utopian that we create such large sinks, when Brazil recently saw the largest rates of deforestation in the last decade (Silva Junior et al., 2021), and when the COVID-19 pandemic reduced monitoring capacities and legal enforcement to reduce tropical deforestation (Friedlingstein et al., 2022). But it could be that, just like the ideas proposed by Carlowitz after the severe lack of natural resources impeded human well-being and economic prosperity leading to the "forest transition" in many parts of Europe, the unprecedented urgency of mitigation efforts might now lead to a transformation of the landscape to large-scale deployment of CDR. CDR adds one more function to the already extensive multifunctionality of the vegetated landscape, which we rely on to create food and fiber, provide recreational value, and control air and water quality.

## New research approaches

Does this turning point in land use history mean a turning point in our research approaches is needed? In several aspects, recent developments in our current modeling tools will serve us well in tackling the role of land use as a CDR method. For example, land surface and Earth system models have continuously been improved to not only capture land cover changes such as deforestation, but also various types of land management, such as wood harvesting and irrigation. Management changes were long assumed as more subtle, as they did not lead to changes in the vegetation type - after all, a forest remained a forest even if it was harvested. Yet management effects on carbon stocks are of similar magnitude as those of land cover changes (Erb et al., 2018). Land surface and Earth system models have further been improved to capture land management serving CDR purposes, including representations of dedicated bioenergy plants or forestry with long-lived wood product usages. This increases their unique potential to provide an assessment of

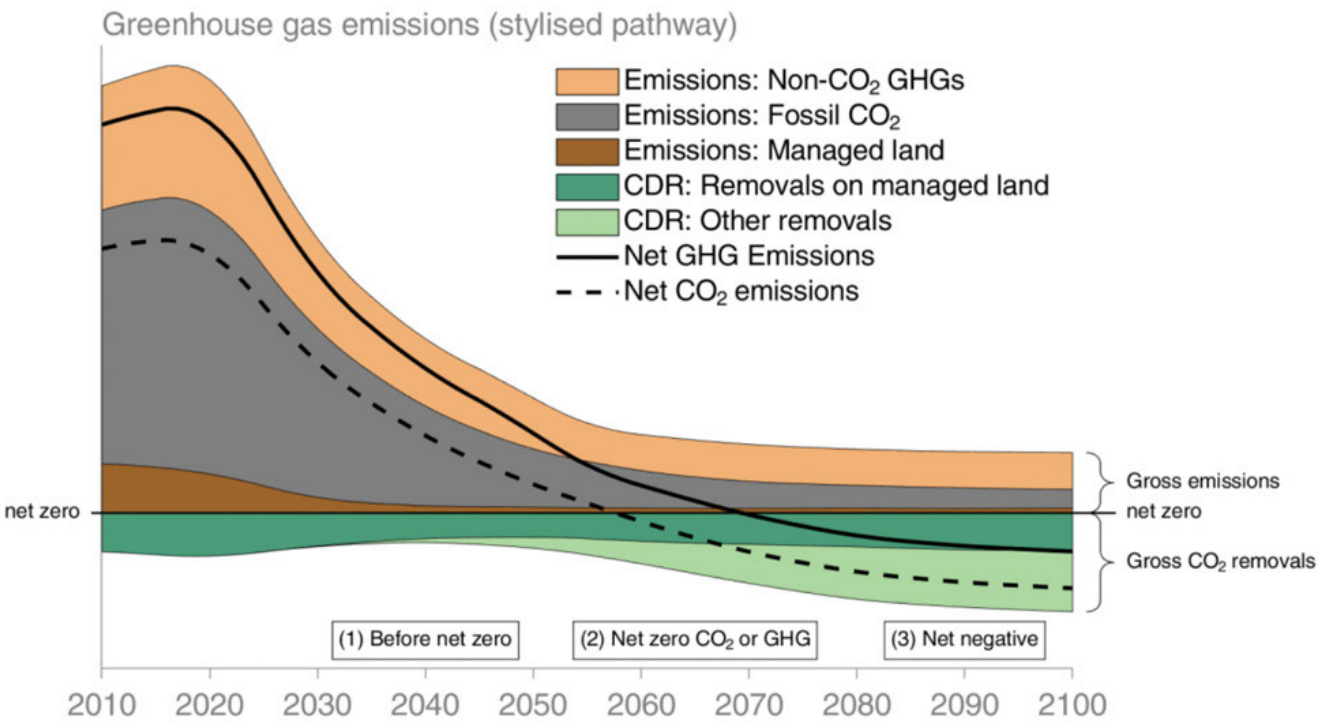


**Fig. 2.** Stylized pathways showing the role of Carbon Dioxide Removal in ambitious global or national mitigation strategies (IPCC, 2022b).

the full climate impacts of CDR, as it is well known in science that through the exchange of energy, water, and momentum between the land surface and atmosphere, climate may be substantially altered through land use change, and not just locally, but even in distant areas (Pongratz et al., 2021). This perspective is still largely missing in the greenhouse gas-focused political realm.

However, in many aspects, novel approaches will be needed. If large swaths of land are transformed for other uses, the resulting changes in climate – global climate, but also local climate including water and energy fluxes – will impact the capability of that land to provide food, fiber, CDR, or other ecosystem services. These interactions between climate impacts and impacts on other ecosystem services are currently largely untested because socioeconomic modeling that simulates land use changes is uncoupled from the Earth system models that investigate associated climate changes. Similarly, the lack of human behavior, decision-making, and other social processes in the current global climate projections impedes the depiction of feedbacks between harmful climate impacts and the adoption of more aggressive mitigation (Beckage et al., 2020), which are also important aspects relevant to land-based CDR. While not all questions need a full coupling of Earth system, socioeconomic, and other human system models to be addressed (van Vuuren et al., 2016), the linkages between these systems remain largely unexplored in current modeling frameworks. The AIMES working group on Modeling Earth System and Human interactions (MESH) seeks to identify significant feedbacks between human and Earth systems and facilitate the development of new methods and scenarios for coupling Earth system, socioeconomic, and other human system models.

Coupled models of natural and human systems would be an important, but not the sole, building block in the integrative assessment that CDR requires. A large range of literature discusses sustainability and feasibility challenges, such as food security, biodiversity, and land rights (IPCC, 2022b). Correspondingly, the challenges around assessing CDR potentials have moved from determining the technical limits of CO2 uptake to determining realistic implementation potentials that avoid conflicts over resources such as water or land, take societal processes into account, are ecologically sustainable, and are socially, economically and politically feasible. Consequently, research now aims to provide a common assessment framework, in close exchange with the public, industry, and politics, allowing us to evaluate CDR methods across all these dimensions, compare them against each other, and additionally evaluate trade-offs with other sustainability goals. First steps in this direction have been taken in national contexts (e.g., Förster et al., 2022) and will be generalized (Pongratz et al., 2022).

CDR has become a key function of land use and should be embraced as such. The complex interactions between human and natural systems need to be addressed and integrated across scientific disciplines. While research has rightly highlighted the conflicts that can arise when land is used for many purposes, a complementary focus on creating synergies between land's many functions is a key opportunity that will be essential to understand and take advantage of the appreciable potentials of CDR in a sustainable way. ▫

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