

“Afforestation and Its Limits: Integrating Soil Carbon and Biochar in Land-Based CDR Portfolios”

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1. Background and Objective

Carbon dioxide removal (CDR) is a key component of climate mitigation pathways consistent with the Paris Agreement. While deep emission reductions remain essential, most scenarios assessed by the IPCC require large-scale CDR deployment during the 21st century, ranging from approximately 150 to over 400 GtCO₂.

Among land-based options, afforestation is widely used due to its relatively low cost and scalability. However, its large-scale deployment creates significant trade-offs. Land is a scarce economic resource, and expanding forest area competes directly with agriculture, food production, and biodiversity conservation. When environmental protection constraints are imposed, the land available for afforestation becomes limited, reducing its overall mitigation potential.

From an economic perspective, land-based CDR deployment is a resource allocation problem under constraints. In integrated assessment models, land is allocated across competing uses based on relative returns, implying that mitigation options are selected not only by their carbon potential but also by their economic feasibility.

This raises an important question: can afforestation alone deliver the required level of CDR under land and economic constraints?

Alternative land-based CDR options, such as soil organic carbon (SOC) sequestration and biochar, offer additional mitigation potential without requiring large-scale land conversion. SOC is implemented within cropland through improved management practices, while biochar utilizes agricultural residues. These characteristics suggest that they may complement afforestation by reducing land competition and improving overall efficiency.

However, these options remain underrepresented in many integrated assessment frameworks, potentially leading to an over-reliance on land-intensive strategies.

Therefore, this study addresses two main questions:

1. Can afforestation alone meet CDR requirements under Paris-consistent pathways?

2. How do SOC sequestration and biochar complement afforestation under land and economic constraints?

To answer these questions, this study quantifies the carbon removal potential of afforestation alone and in combination with SOC and biochar, and compares the results with CDR requirements from IPCC AR6 mitigation pathways (C1–C3).

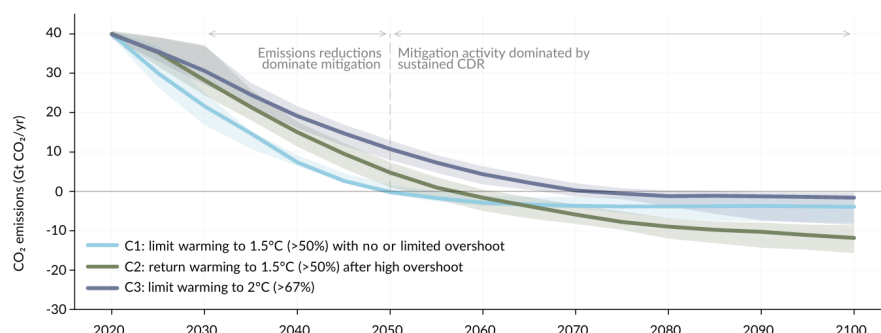


Table 1. Total CDR needed in the end of century (Gidden et al., 2024)

Scenario	Cumulative total CDR to 2100	Cumulative conventional CDR to 2100	Cumulative novel CDR to 2100
C1	190 (150,260)	140(120,180)	51(43,89)
C2	230 (190,250)	150(110,180)	64(40,120)
C3	330(260,440)	210(150,260)	140(79,270)

Fig 1. The median and interquartile ranges of carbon dioxide (CO₂) emissions (IPCC AR6, Gidden et al., 2024)

2. Methods

The analysis integrates the Asia–Pacific Integrated Model – Computable General Equilibrium (AIM-Hub) with the land-use allocation model AIM-PLUM. AIM-Hub simulates global economic activities, energy systems, and greenhouse gas emissions, while AIM-PLUM represents detailed land-use dynamics and agricultural production systems. Linking these models allows the analysis to capture interactions between economic drivers, land demand, and land-based mitigation strategies (Hasegawa et al., 2017).

Land-use allocation in AIM-PLUM is determined endogenously through a profit-maximization framework. Land is allocated across competing uses—cropland, pasture, forest, and unused land—based on relative economic returns, subject to technological and policy constraints. This structure captures opportunity costs and trade-offs between land-based mitigation and other economic activities.

Three land-based CDR options are explicitly represented: afforestation, soil organic carbon (SOC) sequestration, and biochar application.

Afforestation is implemented as a large-scale forest expansion program that utilizes only currently unused land. To avoid conflicts with food production and biodiversity conservation, cropland, pasture, existing forests, and protected areas are excluded from allocation. Biodiversity protection constraints are based on spatial datasets from the World Database on Protected Areas and Key Biodiversity Areas. The afforestation rate is set at 25 million hectares per year, consistent with previous land-based mitigation studies.

SOC sequestration is modeled as improved soil management practices applied exclusively to cropland and is restricted to land that remains cropland throughout the simulation period to ensure permanence. The methodological approach follows Kamasela et al. (2025), which estimates soil carbon accumulation rates under improved agricultural practices.

Biochar-based carbon removal is modeled using agricultural residues generated from crop production. Biomass availability is derived from crop output simulated by AIM-Hub, and biochar assumptions follow global estimates by Lefebvre et al. (2023). This approach links biochar deployment to existing agricultural systems without requiring additional land conversion.

All scenarios are evaluated under a business-as-usual socioeconomic pathway corresponding to SSP2, where land-use demand evolves with population, economic growth, and dietary change. Environmental protection constraints are maintained throughout to prevent land conversion in biodiversity-rich areas.

For each CDR option, cumulative carbon removal are calculated over 2020–2100 and compared with cumulative CDR requirements under IPCC AR6 mitigation pathways (C1–C3) (IPCC, 2023; Gidden et al., 2024).

3. Preliminary Results

3.1 Afforestation alone may be insufficient to meet carbon dioxide removal requirements under low-emission pathways

Under the business-as-usual socioeconomic pathway with environmental protection constraints, afforestation delivers approximately 180 GtCO₂ of cumulative carbon sequestration by 2100. This potential is achieved through a sustained afforestation program that expands forest area exclusively on currently unused land at a global rate of 25 million hectares per year.

These results suggest that afforestation alone may be sufficient to meet CDR requirements in mitigation pathways with relatively low reliance on carbon removal, such as the C1 category of IPCC AR6 scenarios. In these pathways, deep emission reductions occur early, and cumulative CDR demand remains relatively modest.

However, afforestation alone appears insufficient to meet the higher CDR requirements associated with more carbon-removal-intensive pathways. In C2 and C3 pathways, cumulative CDR demand reaches approximately 190–400 GtCO₂ over the 21st century. Under such conditions, the afforestation potential estimated in this study falls short of the required removal levels.

These findings highlight an important limitation of relying exclusively on afforestation as the primary land-based CDR strategy. When environmental protection constraints prevent the conversion of cropland and biodiversity-rich ecosystems, the available land area for forest expansion becomes limited. As a result, the achievable carbon removal potential of afforestation may be substantially lower than the levels assumed in some mitigation scenarios.

3.2 Contributions of soil organic carbon and biochar in lower-emission pathways

The integration of additional land-based CDR options significantly increases total carbon removal potential. Soil organic carbon sequestration on cropland contributes approximately 139 GtCO₂ of cumulative carbon removal by 2100. Biochar deployment using agricultural residues provides an additional 149 GtCO₂ of cumulative removal.

When afforestation, SOC sequestration, and biochar are combined, total carbon removal reaches approximately 480 GtCO₂ by the end of the century. In terms of annual removal rates, the combined portfolio provides approximately 6–8 GtCO₂ per year during much of the century.

Although afforestation remains the dominant contributor to cumulative carbon sequestration, SOC and biochar provide important near- and medium-term contributions. Because SOC sequestration can be implemented directly within agricultural systems and biochar production utilizes existing biomass residues, these options can be deployed without requiring additional land conversion.

This diversified portfolio approach aligns with recent analyses of CDR deployment pathways. Gidden et al. (2024) note that insufficient near-term emission reductions combined with reliance on a limited set of conventional CDR options could necessitate the rapid deployment of novel CDR technologies during the latter half of the century. Integrating SOC sequestration and biochar into land-based mitigation strategies may reduce the need for large-scale deployment of more expensive or technologically uncertain CDR options.

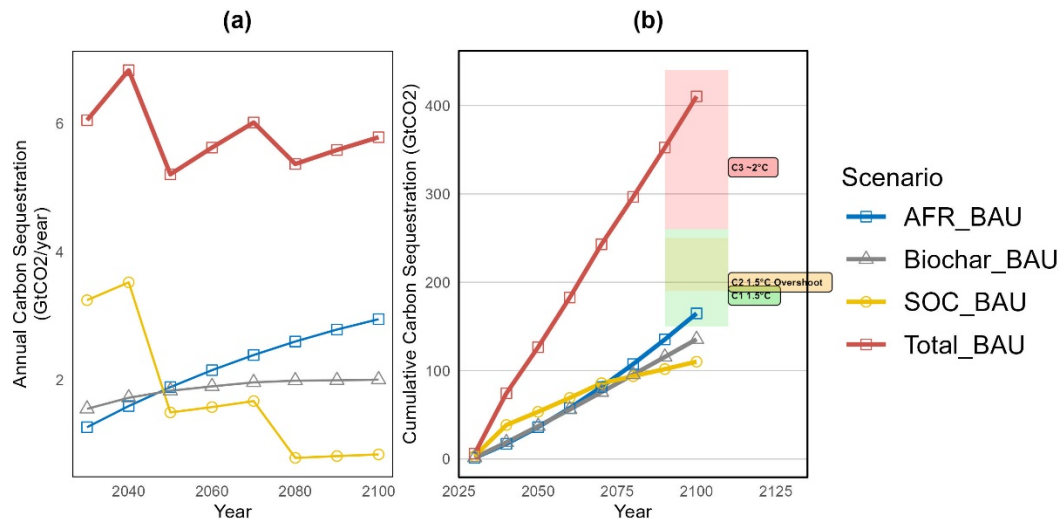


Fig 2. Global carbon sequestration potential from afforestation, soil organic carbon, and biochar in this study: (a) annual and (b) cumulative potentials, compared with emission trajectories and CDR levels required in Gidden et al. (2024)

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