Research Square

Preprints are preliminary reports that have not undergone peer review.
They should not be considered conclusive, used to inform clinical practice,
or referenced by the media as validated information.

Net zero weakens the land carbon sink but land-based mitigation compensates

Florian Humpenöder

humpenoeder@pik-potsdam.de

Potsdam Institute for Climate Impact Research (PIK) https://orcid.org/0000-0003-2927-9407

Michael Crawford

Potsdam Institute for Climate Impact Research (PIK)

Jens Heinke

Potsdam Institute for Climate Impact Research https://orcid.org/0000-0001-5256-0024

Kristine Karstens

Potsdam Institute for Climate Impact Research

Felicitas Beier

Potsdam Institute for Climate Impact Research (PIK)

Miodrag Stevanovic

Potsdam Institute for Climate Impact Research https://orcid.org/0000-0003-1799-186X

Laurin Köhler-Schindler

Potsdam Institute for Climate Impact Research (PIK)

Nico Bauer

Potsdam Institute for Climate Impact Research (PIK), Member of the Leibniz Association, Germany
https://orcid.org/0000-0002-0211-4162

Gabriel Abrahão

Potsdam Institute for Climate Impact Research (PIK) https://orcid.org/0000-0003-0336-6246

Elmar Kriegler

Potsdam Institute for Climate Impact Research https://orcid.org/0000-0002-3307-2647

Jan Dietrich

Potsdam Institute for Climate Impact Research https://orcid.org/0000-0002-4309-6431

Hermann Lotze-Campen

Potsdam Institute for Climate Impact Research https://orcid.org/0000-0002-0003-5508

Alexander Popp

Potsdam Institute for Climate Impact Research https://orcid.org/0000-0001-9500-1986

Physical Sciences - Article

Keywords:

Posted Date: November 3rd, 2026

DOI: https://doi.org/10.21203/rs.3.rs-11433237/v1

License: This work is licensed under a Creative Commons Attribution 4.0 International License.
Read Full License

Additional Declarations: There is **NO** Competing Interest.

Net zero weakens the land carbon sink but land-based mitigation compensates

Florian Humpenöder[1,*], Michael Crawford[1], Jens Heinke[1], Kristine Karstens[1,2], Felicitas Beier[1], Miodrag Stevanović[1], Laurin Köhler-Schindler[1], Nico Bauer[1], Gabriel Abrahão[1], Elmar Kriegler[1], Jan Philipp Dietrich[1], Hermann Lotze-Campen[1,2], Alexander Popp[1,3]

[1] Potsdam Institute for Climate Impact Research (PIK), Member of the Leibniz Association, Potsdam, Germany.

[2] Albrecht Daniel Thaer-Institute of Agricultural and Horticultural Sciences, Humboldt University of Berlin, Germany.

[3] Faculty of Organic Agricultural Sciences, University of Kassel, Witzenhausen, Germany.

[*] Correspondence and requests for materials should be addressed to Florian Humpenöder (humpenoeder@pik-potsdam.de).

Abstract

Land ecosystems absorb about a fifth of human CO_2 emissions, mostly because rising CO_2 stimulates plant growth[1]. National greenhouse gas inventories count this land carbon sink on managed land as anthropogenic. Mitigation pathways count only the land-use flux, the emissions and removals from land use. To match inventories, external sink estimates[2,3] are added to pathways afterwards. Here we compute both components inside the integrated assessment framework LPJmL-MAgPIE-REMIND for six CMIP7 scenarios, with the land's response to climate change and CO_2 included. In scenarios reaching net-zero CO_2 around mid-century, atmospheric CO_2 declines and the sink on managed land weakens. We show that the sink weakens later than in Grassi et al.[2] and does not become a source, unlike in Gidden et al.[3]. Land-based mitigation, such as afforestation, turns the land-use flux from a net emission today into net removals that by 2100 more than compensate for the weaker sink. Inventories count the sum of the sink and the land-use flux. In our net-zero scenarios, this sum peaks in 2050–2070, then loses about 25% by 2100. With our sink counted, net-zero CO_2 comes 2 to 7 years earlier than with the land-use flux alone, and at most 3 with either external estimate.

1. Introduction

Land ecosystems take up about a fifth of the CO_2 emitted by fossil fuels and land use: the Global Carbon Project's Global Carbon Budget (GCB)[1] puts this land carbon sink at 8.7 $GtCO_2\ yr^{-1}$ (2.4 $GtC\ yr^{-1}$) for 2015–2024, against emissions of 41.0 $GtCO_2\ yr^{-1}$. The sink is the carbon that vegetation and soils take up in response to rising atmospheric CO_2 and to climate change. It is reported separately from the emissions caused by land use[1,4]. Studies aligning pathways with inventories call this sink the indirect flux[2,3]. The sink also weakens once CO_2 stops rising. Photosynthesis responds to the atmospheric CO_2 concentration within months, whereas respiration by plants and soils follows the carbon stock over decades. When CO_2 stabilises or declines, respiration catches up and the net uptake ends (Fig. 1b), as experiments with Earth system models in which CO_2 stops rising or declines show[5–7].

In most mitigation scenarios of the Coupled Model Intercomparison Project Phase 7 (CMIP7), afforestation and reforestation (AR) supply the largest share of the land-based CO_2 removal; avoided deforestation and, where represented, peatland rewetting cut emissions[8]. Whether these removals add to the land carbon sink or make up for its decline has so far been examined only by passing the land-use information of a few scenarios from integrated assessment models (IAMs) to dynamic global vegetation models (DGVMs) or Earth system models[9–11]. None of these studies followed the removals and the sink together, across the scenarios, inside the IAM that projects their land use.

The distinction between the fluxes caused by land use and the sink underlies the two conventions for anthropogenic land fluxes (Fig. 1a). Bookkeeping models, which track carbon stocks after each land-use change, and IAMs both report the land-use flux: the emissions and removals caused by land-use change, wood harvest, regrowth and drained peatland. National greenhouse gas inventories report all fluxes on land they define as managed, which adds the sink on that land to the land-use flux[12,13]. In the comparison of bookkeeping models with inventories by Grassi et al.[14], the two conventions differ by 6.7 $GtCO_2\ yr^{-1}$ on average over 2000–2020. To compare national pledges with pathways, the gap is closed by adding an external estimate of the sink on managed land to IAM output, counting forest outside intact (undisturbed) forest as managed[1,14–16]. Grassi et al.[2] derived adjustment factors from the vegetation model LPJmL under the land use of the IAM IMAGE, for managed forest and for the shared socioeconomic pathway (SSP) scenarios SSP2-1.9 to SSP2-6.0. Gidden et al.[3] computed the indirect flux on managed forest with OSCAR, a land carbon-cycle emulator, for 914 pathways assessed in the IPCC Sixth Assessment Report (AR6), in five world regions. Across their pathway categories, the median of the sum inventories count, the land-use flux plus their estimate of the sink, is a net removal that peaks around mid-century and then shrinks as the sink weakens. Over 2020 to 2100 the gain in net removals from land use exceeds the loss of the sink in the 1.5 °C pathways with limited overshoot (C1) and the 2 °C pathways (C3), but not in those with higher overshoot (C2). Both external estimates are added afterwards to pathways that are usually computed without climate impacts, that is, without the response of yields, water and carbon densities (carbon stock per unit area) to the scenario's changing climate and rising CO_2. The estimates therefore cannot say which land classes carry the sink, and pathways computed without climate impacts have no sink of their own to compare the estimates with.

CMIP7 adds two reasons to quantify the land-use flux and the sink for the same scenario. First, its Earth system model simulations, mostly driven by CO_2 emissions[17,18], receive the scenarios' land use, harmonised with historical land-use data, not their land-use flux. The Earth system models compute the total net land flux themselves, the land-use flux plus the sink (the net land flux of the GCB). That flux can therefore be compared with the scenario's own total net land flux only if the IAM provides both parts. Second, comparing national pledges with the CMIP7 scenarios requires the inventory-aligned flux, which includes the sink on managed land. Yet IAMs run the CMIP7 scenarios without climate impacts[18], so the IAM side has no estimate of the sink.

Here we run an IAM, the land-use model MAgPIE[19] soft-coupled to the energy-economy model REMIND[20], for six of the seven scenarios of CMIP7's Scenario Model Intercomparison Project (ScenarioMIP): High (H-SSP3), Medium (M-SSP2), Medium-to-Low (ML-SSP2), Low (L-SSP2), Low-to-Negative (LN-SSP2) and Very Low (VL-SSP1). Climate impacts are included: the vegetation model LPJmL[21,22] supplies yields, water availability and carbon densities to MAgPIE through a one-way link, computed under bias-adjusted MRI-ESM2-0 climate and the CO_2 concentration of the nearest CMIP6 scenario[23,24], since climate projections for the CMIP7 scenarios are not yet available (Methods). The same IAM, without climate impacts, provides the CMIP7 marker scenario for VL-SSP1, the scenario the Earth system models run, under the name REMIND-MAgPIE[8]. We split each scenario's total net land flux, per land class and per simulation unit (the 200 spatial units on which MAgPIE allocates land), into the land-use flux and the CO_2-driven flux. The CO_2-driven flux is the change in carbon density in response to environmental change, here CO_2 together with climate change, on the projected land-use pattern; where it is negative, it is the sink defined above. The CO_2-driven flux is split between managed land and intact forest with the map that inventory harmonisation uses for forest[14,25], here applied to all land, so that all land outside intact forest counts as managed. Counting the land-use flux alone is the bookkeeping convention. Adding the CO_2-driven flux on managed land gives the inventory-aligned flux, and adding the CO_2-driven flux inside intact forest the total net land flux (Fig. 1a). We group the scenarios into three clusters, as the companion land-use assessment does[8]: weak policy (H-SSP3, M-SSP2), moderate transition (ML-SSP2) and ambitious mitigation (L-SSP2, LN-SSP2, VL-SSP1), the three scenarios that reach net-zero CO_2 around mid-century. Extended Data Table 1 compares this study with earlier work.

We find that under ambitious mitigation the sink on managed land weakens once atmospheric CO_2 stops rising, around the net-zero year, while the land-use flux turns from net emissions today into net removals that by 2100 more than make up for the weaker sink. Inventory-aligned net removals peak between 2050 and 2070, shrink by 22 to 27% by 2100 and by then come 56 to 86% from land use. This reproduces the peak and decline that Gidden et al.[3] found with OSCAR, now with a sink computed on the land areas that the model allocates. Unlike their estimate, which turns into a source, our CO_2-driven flux on managed land remains a sink through 2100. We also compare the external estimates of Grassi et al.[2] and Gidden et al.[3] with a sink computed inside the model that produced the scenarios: our sink weakens later than that of Grassi et al.[2].

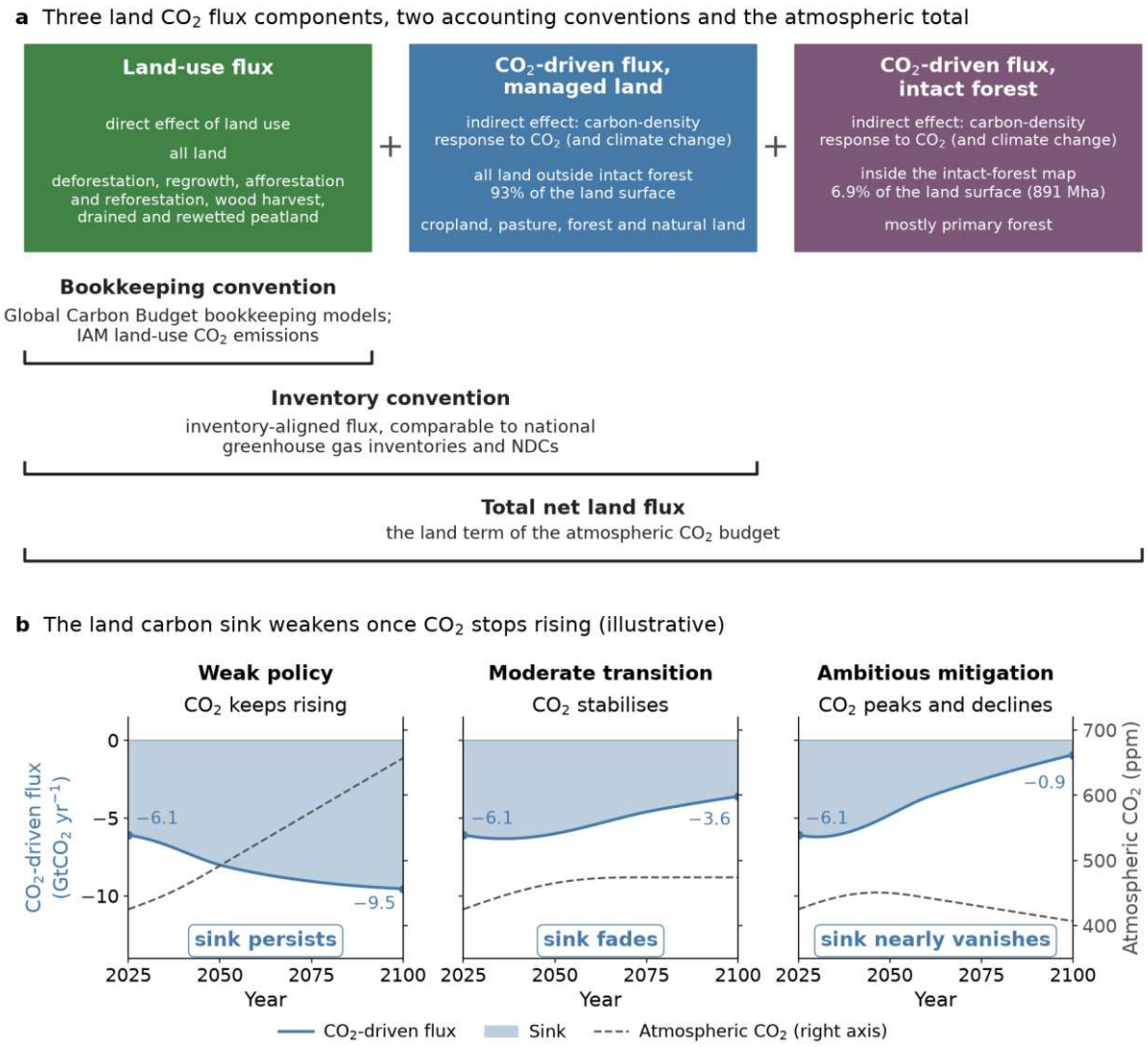


Figure 1. Three components of the total net land flux, and the CO_2-driven flux of an illustrative model under three CO_2 trajectories. (a) The three components of the total net land flux in LPJmL-MAgPIE-REMIND and how they add up. The bookkeeping convention counts the land-use flux alone. The inventory convention counts the inventory-aligned flux: the land-use flux plus the CO_2-driven flux on managed land. The total net land flux, the land term of the atmospheric CO_2 budget, is the inventory-aligned flux plus the CO_2-driven flux inside intact forest. Managed land follows the proxy used in inventory harmonisation (Methods). (b) The CO_2-driven flux on all land in an illustrative model whose parameters are fitted to the six scenarios' flux (Methods). The three stylised CO_2 trajectories (grey dashed, right axis) stand for the three scenario clusters: CO_2 keeps rising, levels off by 2075, or peaks around 2050 and then falls. The blue line is the flux (left axis; negative = sink, shaded blue), with its 2025 and 2100 values. In the model, uptake rises with CO_2, with diminishing returns; the response to climate change is folded into that CO_2 response (Methods). Of each year's uptake, 83% is released within a few years and 17% over about a century (fitted values, Methods). The sink is the part of the uptake not yet released. While CO_2 rises, uptake keeps running ahead of release; once CO_2 stops rising, release catches up and the sink shrinks.

2. Results

2.1 The land carbon sink weakens where mitigation lowers CO_2

The CO_2-driven flux is the change in vegetation and soil carbon density that LPJmL projects under the CO_2 concentration and climate of each scenario, evaluated on that scenario's land-use pattern from MAgPIE (Methods). LPJmL uses the CMIP6 climate of the representative concentration pathway (RCP) nearest to each scenario's own CO_2 outcome, since climate projections for the CMIP7 scenarios are not yet available (Methods; Fig. 2 panel titles). In 2025 the CO_2-driven flux is a sink of 6.4 $GtCO_2\ yr^{-1}$ on all land, of which 5.3 $GtCO_2\ yr^{-1}$ is on managed land and 1.1 inside intact forest (Fig. 2).

Under rising CO_2 the sink persists. In 2100 the CO_2-driven flux on all land is a sink of 8.5 $GtCO_2\ yr^{-1}$ in H-SSP3 (RCP6.0) and 7.9 in M-SSP2 (RCP4.5), with 6.6 to 7.2 $GtCO_2\ yr^{-1}$ on managed land and 1.3 inside intact forest. Where mitigation stops the rise of CO_2 the sink fades: 2.9 $GtCO_2\ yr^{-1}$ in L-SSP2 and 2.8 in ML-SSP2 (both RCP2.6; CO_2 peaks, then declines slightly), and 1.1 in both LN-SSP2 and VL-SSP1 (RCP1.9; CO_2 peaks and declines); of that 1.1, only 0.2 $GtCO_2\ yr^{-1}$ remains inside intact forest. The scenarios already differ at mid-century: in 2050 the sink is 8.2 $GtCO_2\ yr^{-1}$ in H-SSP3, 4.7 in LN-SSP2 and 4.8 in VL-SSP1.

Intact forest carries 9 to 18% of the sink in every scenario from 2025 to 2100, more than its 6.9% share of the land surface because the sink concentrates in forests. The rest is on land that inventories count as managed, in the vegetation of forest and of other natural land (natural vegetation outside forest) and in soils (Extended Data Fig. 1). The sink weakens because respiration by plants and soils catches up with photosynthesis once CO_2 stabilises or falls (Fig. 1b; Discussion). H-SSP3 has the highest CO_2 and the most warming of the six scenarios and still the largest sink, so the growth gain from CO_2 outweighs the carbon release from warming in our scenarios.

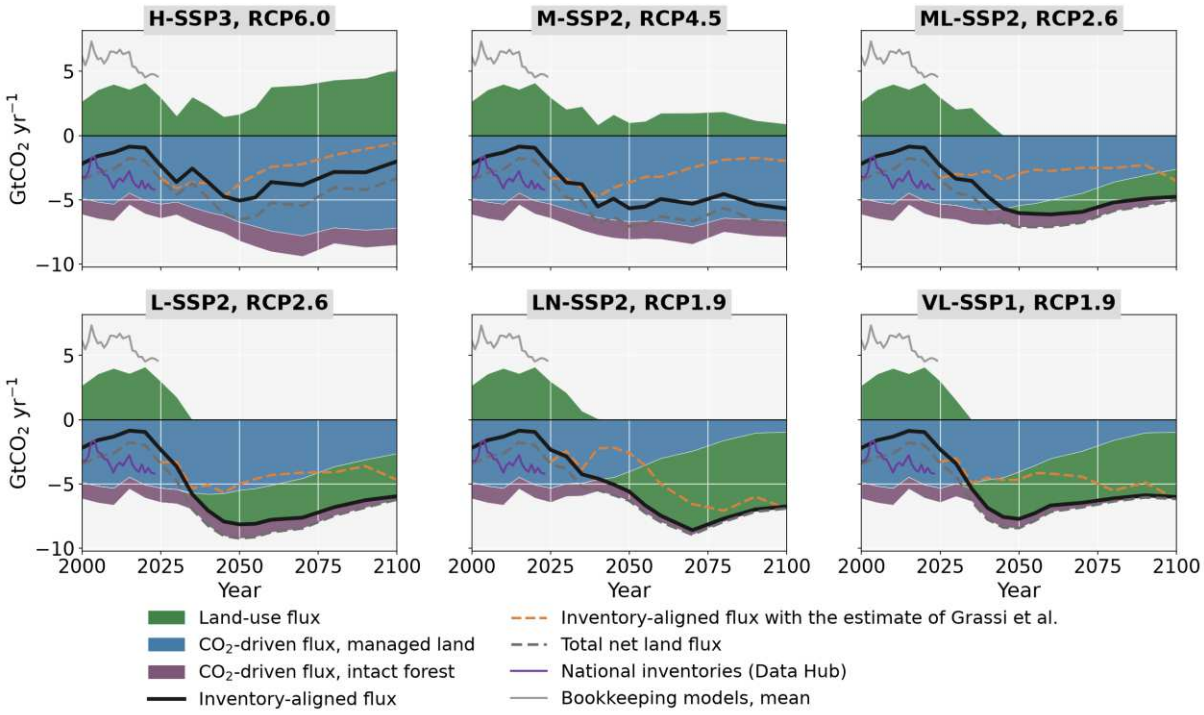


Figure 2. Land CO_2 flux 2000–2100 per scenario, with the RCP of each scenario's climate in the panel title ($GtCO_2\ yr^{-1}$; positive = net emissions, negative = net removals from the atmosphere). Stacked areas, from the zero line outward: CO_2-driven flux on managed land (blue), land-use flux on all land (green) and CO_2-driven flux inside intact forest (plum). Lines: the inventory-aligned flux (land-use flux plus the CO_2-driven flux on managed land; black); the inventory-aligned flux with the estimate of Grassi et al.[2], which covers managed forest only, in place of our CO_2-driven flux on managed land, from 2025 (orange dashed); and the total net land flux (sum of the three areas; grey dashed). Historical values in every panel: national inventories of land use, land-use change and forestry (LULUCF), as compiled in the LULUCF Data Hub[38] (v3.1.1; 2000–2023; purple) and the bookkeeping-model mean of the GCB[1] (2025 edition; 2000–2024; grey).

2.2 Mitigation turns the land-use flux into net removals

The land-use flux comprises land-use change, AR, wood harvest and the regrowth that follows it, regrowth on abandoned agricultural land, drained and rewetted peatland, and cropland management, including soil-carbon management. AR takes two forms: NPi/NDC AR, the area prescribed by countries' national policies implemented (NPi) or, in L-SSP2 and VL-SSP1, their nationally determined contributions (NDC); and carbon-price AR, added where a carbon price rewards the CO_2 that afforestation removes. For 2015–2024 our land-use flux lies below the bookkeeping models of the GCB[1] but within their uncertainty range (Extended Data Fig. 2a). In 2025 it is a net emission of about 3.0 $GtCO_2\ yr^{-1}$. It then diverges between the three clusters (Fig. 2, green; Fig. 3a), following how each scenario reallocates land between agriculture and forest (Fig. 3b).

Weak-policy scenarios. In H-SSP3 and M-SSP2 the land-use flux remains a net emission, +5.2 and +0.9 $GtCO_2\ yr^{-1}$ in 2100, with the conversion of other natural land (+3.2 and +0.7), permanent deforestation (+0.6 and +0.4) and emissions from drained peatland (+1.9 and +1.7) as its sources (Fig. 3a). Over 2025–2100 cropland expands by 657 Mha in H-SSP3 and 327 Mha in M-SSP2, at the expense of secondary forest, other natural land and primary forest (Fig. 3b). From 2030 H-SSP3 also drops its national land policies and releases the protected areas (Methods); by 2100 it keeps only 147 of its 196 Mha of NPi/NDC AR.

Moderate-transition scenarios. In ML-SSP2 the land-use flux turns into net removals of 0.6 $GtCO_2$ yr^{-1} by 2050 and 2.2 by 2100. Over 2025–2100 pasture declines by 220 Mha and carbon-price AR covers 132 Mha, while cropland still expands by 154 Mha (Fig. 3b).

Ambitious-mitigation scenarios. The land-use flux turns into larger net removals: by 2050 2.7 $GtCO_2$ yr^{-1} in L-SSP2, 1.6 in LN-SSP2 and 3.7 in VL-SSP1, and by 2100 3.3, 5.8 and 5.1 (Fig. 2). Over 2025–2100 pasture declines by 415, 583 and 563 Mha (Fig. 3b). By 2100 carbon-price AR covers 223 Mha in L-SSP2 and 455 Mha in VL-SSP1 as natural forest regrowth, and 724 Mha in LN-SSP2 as plantations[26], as configured for that scenario (Methods). In VL-SSP1, AR is confined to the tropics and its total area, the 196 Mha of NPi/NDC AR in place in 2025 included, is capped at 700 Mha, reached in 2090 (Fig. 3b shows the change since 2025). VL-SSP1, with its dietary transformation[27,28], in addition frees 224 Mha of cropland, and secondary forest and other natural land recover by 160 and 132 Mha. In ML-SSP2 and the ambitious-mitigation scenarios the net removals come mostly from AR, the end of deforestation and of other-natural-land conversion, and the rewetting of drained peatland.

In 2100 NPi/NDC AR removes 0.3 $GtCO_2$ yr^{-1} in H-SSP3 and 0.4 in M-SSP2. With carbon-price AR, all AR in 2100 removes 1.2 $GtCO_2$ yr^{-1} in ML-SSP2, 1.8 in L-SSP2, 3.0 in VL-SSP1 and 5.1 in LN-SSP2 (Fig. 3a). On natural land (primary forest, secondary forest and other natural land), regrowth removes more CO_2 than wood harvest emits: a net removal of 0.7 $GtCO_2$ yr^{-1} in 2025 and of 1.0 to 2.2 in 2100 in every scenario but H-SSP3 (Fig. 3a). Most of this regrowth is that of secondary forest already standing in 2025 and follows from its initial age structure. Regrowth on abandoned agricultural land adds to it (Methods). The scenarios differ in how much wood is harvested on natural land.

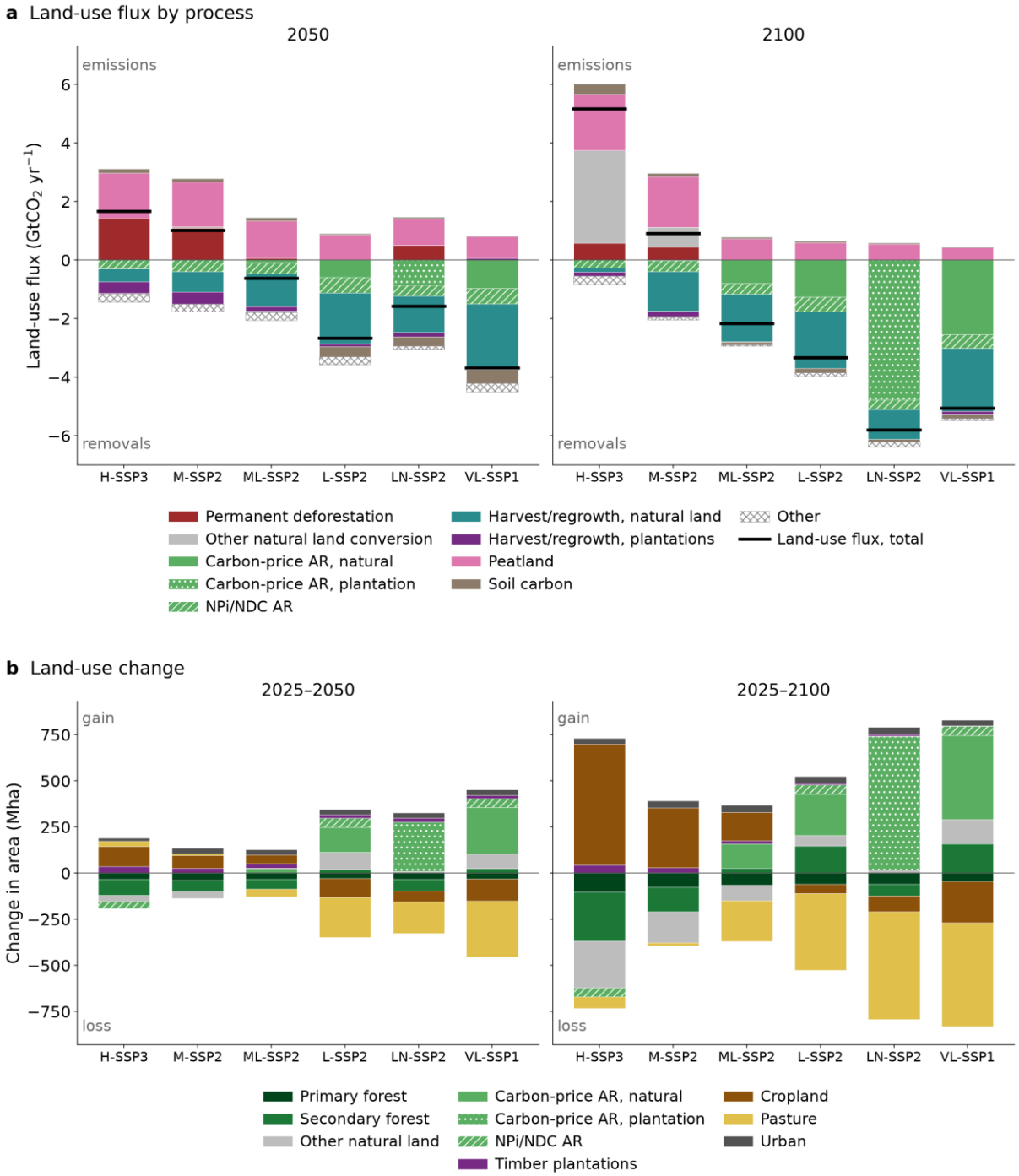


Figure 3. Land-use flux by process and land-use change, per scenario. (a) Land-use flux by process in 2050 and 2100 ($GtCO_2$ yr^{-1}; positive = emissions, negative = removals from the atmosphere); black line, total land-use flux. The two harvest/regrowth bars are net. On plantations, the harvest of timber plantations is netted against their regrowth. On natural land (primary forest, secondary forest and other natural land), harvest is netted against the regrowth of secondary forest and other natural land, which includes regrowth on abandoned land. Other: harvested wood products, cropland tree cover and a residual. (b) Change in the area of each land class from 2025 to 2050 and from 2025 to 2100 (Mha). In both panels, NPi/NDC AR is afforestation and reforestation prescribed by national policies (NPi) or nationally determined contributions (NDC). Carbon-price AR is established where the carbon price rewards the removal, on natural-vegetation growth curves or, in LN-SSP2, on plantation growth curves.

2.3 Inventory-aligned net removals peak in 2050–2070

The inventory-aligned flux is the model counterpart of what national inventories report (Fig. 1a; Fig. 2, black line; Fig. 4). In 2025 it is net removals of 2.3 $GtCO_2$ yr^{-1}. For 2015–2024 our inventory-aligned flux gives smaller net removals than the estimates for managed land from models, atmospheric inversions (fluxes inferred from measured CO_2 concentrations) and inventories (Methods; Extended Data Fig. 2, Extended Data Table 2).

In the ambitious-mitigation scenarios, inventory-aligned net removals rise to a peak and then decline, as in the aligned AR6 pathways[3] (Extended Data Fig. 3). The inventory-aligned flux peaks at 7.7 to 8.6 $GtCO_2$ yr^{-1} of net removals, in 2050 in L-SSP2 and VL-SSP1 and in 2070 in LN-SSP2, and loses 22 to 27% of that peak by 2100. Net removals from the land-use flux still grow or nearly hold over this period, while the sink on managed land weakens (Fig. 4). Land-based mitigation thus first adds to the inventory-aligned net removals and then offsets part of the weakening sink: until 2050 the sink's change offsets less than a third of the gain in net removals from land use. After 2050 the loss of the sink exceeds the gain in L-SSP2 and VL-SSP1 and offsets about three quarters of it in LN-SSP2. Over 2025–2100 the inventory-aligned flux still grows from 2.3 $GtCO_2$ yr^{-1} of net removals to 5.9 in L-SSP2, 6.7 in LN-SSP2 and 6.0 in VL-SSP1, but the loss of the sink offsets 43%, 50% and 54% of the gain in net removals from land use, respectively.

By 2100 land use provides 56% of the inventory-aligned flux in L-SSP2 and 84 to 86% in LN-SSP2 and VL-SSP1. With the estimate of Grassi et al.[2] in place of ours, the share is 71% in L-SSP2 and 82 to 84% in LN-SSP2 and VL-SSP1. With the estimate of Gidden et al.[3], which turns into a source by 2100, land use is the only removal (Extended Data Table 3a).

Latin America alone provides 41 to 47% of the global inventory-aligned flux in 2100 in the ambitious-mitigation scenarios (Extended Data Table 3b; the land-use flux by region in Extended Data Table 3c).

Outside the ambitious-mitigation scenarios the sink on managed land still provides most of the inventory-aligned flux in 2100, but in ML-SSP2 land use comes close to half (46%), as its CO_2 levels off and its sink on managed land halves between 2025 and 2100. ML-SSP2's inventory-aligned flux peaks in 2060 and falls to 4.8 $GtCO_2$ yr^{-1} of net removals by 2100, less than in any ambitious-mitigation scenario. In the weak-policy scenarios the land-use flux remains net emissions, which the sink on managed land outweighs. M-SSP2's inventory-aligned flux ends at 5.7 $GtCO_2$ yr^{-1} of net removals in 2100, and H-SSP3's at 2.0, 60% below its own 2050 peak, since its land-use emissions cancel most of the sink. From weak policy to ambitious mitigation, inventory-aligned net removals thus shift from the sink on managed land, which follows CO_2, to land use, whose net removals are exposed to reversal.

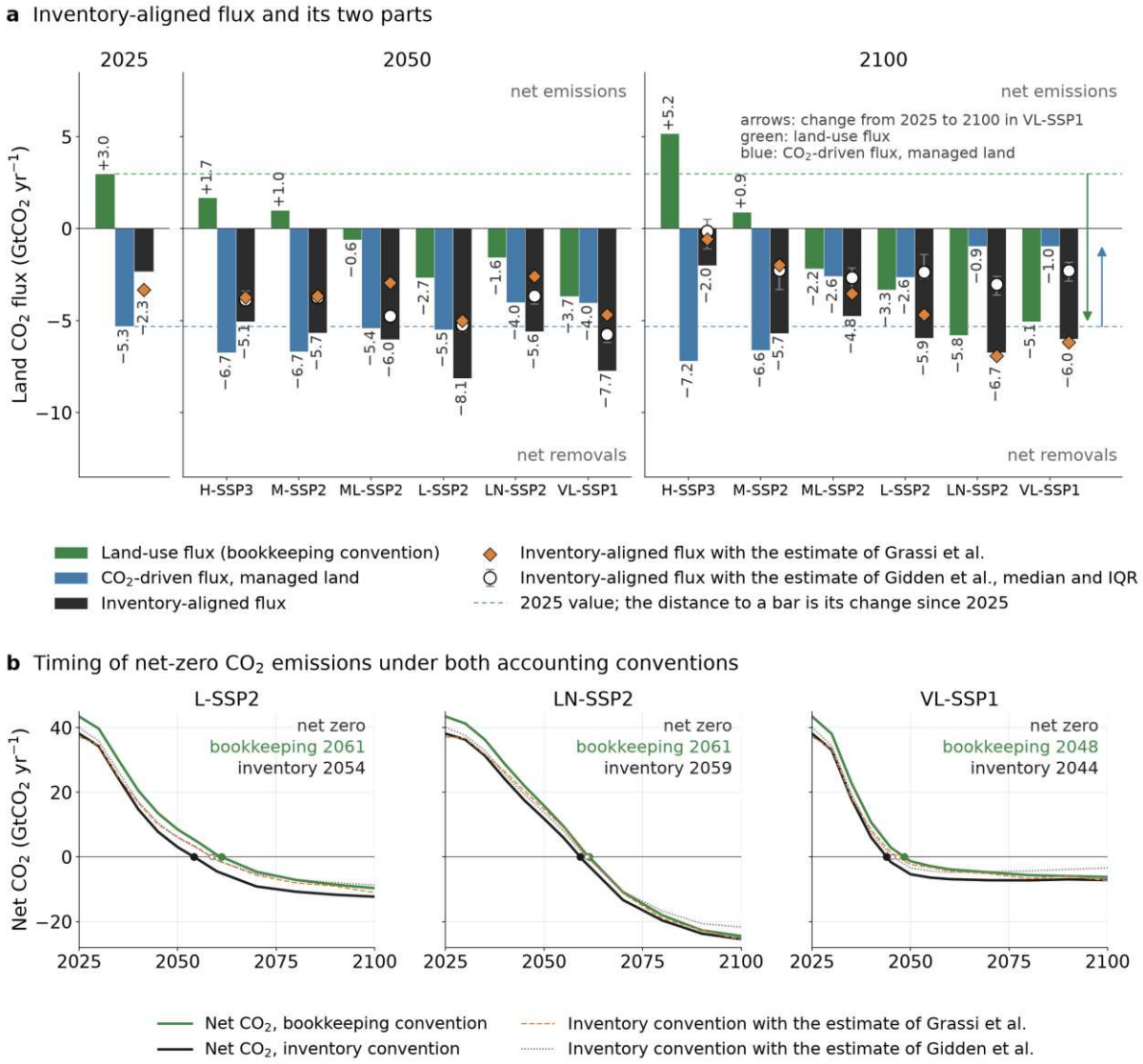


Figure 4. Components of the inventory-aligned flux and timing of net-zero CO_2 emissions ($GtCO_2\ yr^{-1}$; positive = net emissions, negative = net removals from the atmosphere). (a) Land-use flux, CO_2-driven flux on managed land and their sum, the inventory-aligned flux, in 2025 and per scenario in 2050 and 2100. Markers show the inventory-aligned flux with an external estimate in place of our CO_2-driven flux: diamonds, the estimate of Grassi et al.[2] for each scenario's RCP; circles and whiskers, the estimate of Gidden et al.[3], median and interquartile range of the AR6 climate category matched to each scenario (Methods; none for 2025). Both external estimates cover managed forest only, ours all managed land (Extended Data Table 3d). Dashed lines mark the 2025 value of the land-use flux and of the CO_2-driven flux on managed land; the distance from a line to a bar is that part's change since 2025, shown by the arrows for VL-SSP1 in 2100. (b) Net CO_2 emissions from all sectors from 2025 to 2100 for L-SSP2, LN-SSP2 and VL-SSP1, the three scenarios that reach net-zero CO_2 around mid-century. The land sector is counted in two ways: with the land-use flux (bookkeeping convention) or with the inventory-aligned flux (inventory convention). Thin lines, the inventory convention with each external estimate in place of ours. Dots mark the year of net zero, interpolated linearly between time steps.

2.4 Under net zero, our sink loses less than either external estimate by 2050

Under ambitious mitigation, our sink on managed land weakens later than the external estimate of Grassi et al.[2] and, unlike that of Gidden et al.[3], does not become a source. Both external estimates cover managed forest only[2,14], whereas ours also covers other natural land and the soils of all managed land. We replace our sink by each external estimate and keep our land-use flux (Fig. 4a, markers). With the estimate of Grassi et al., taken for the RCP of each

scenario's climate (Extended Data Table 4), this inventory-aligned flux gives larger net removals than ours in 2025, but about 3.0 $GtCO_2$ yr^{-1} smaller in 2050 in the ambitious-mitigation scenarios (Fig. 4a, diamonds). With our sink, the inventory-aligned net removals peak in 2070 in LN-SSP2 and in 2050 in VL-SSP1 and then decline. With the estimate of Grassi et al., this decline does not appear: in 2100 the net removals of both scenarios are at or near their largest value (Fig. 2, orange dashed line). By 2050 the estimate of Grassi et al.[2] has lost 63% of its 2025 value of 6.3 $GtCO_2$ yr^{-1} under RCP2.6 and 84% under RCP1.9, whereas our sink on managed land keeps at least 76% in every scenario. On managed forest alone, the scope of both external estimates, our estimate is well below that of Grassi et al.[2] in 2025 but about equal to or larger than it in 2050 (Extended Data Table 3d).

The estimate of Gidden et al., computed with the OSCAR emulator, does not stay a sink as ours does: by 2100 it turns into a source in the AR6 climate categories matched to the ambitious-mitigation scenarios, of 2.8 $GtCO_2$ yr^{-1} in the category matched to LN-SSP2 and VL-SSP1 (Methods; Extended Data Table 3d). By 2050 it keeps 68 to 83% of its 2020 value in those categories (it has none for 2025), against 79 to 108% for our sink. With it, the three ambitious-mitigation scenarios keep only 2.3 to 3.0 $GtCO_2$ yr^{-1} of inventory-aligned net removals in 2100, against 5.9 to 6.7 with ours (Fig. 4a, circles).

The sink that is counted also sets the date of net-zero CO_2, the year in which a scenario's CO_2 emissions from all sectors, land included, reach zero (Fig. 4b). Under the inventory convention, which counts our sink on managed land, the ambitious-mitigation scenarios reach net zero 2 to 7 years earlier than under the bookkeeping convention, which counts the land-use flux only. With either external estimate in place of ours, the gain shrinks to at most 3 years.

3. Discussion

3.1 Implications for inventory alignment and CMIP7

The global stocktake under the Paris Agreement compares pathways with national greenhouse gas inventories. The comparison requires adding an estimate of the sink on managed land to the land-use flux of these pathways[2,3,29]. We compute that sink inside the IAM rather than adding an external estimate afterwards, so the external estimates can be compared with ours. Both cover managed forest only, and under ambitious mitigation both have lost a larger share of their sink than ours by 2050. The estimate of Grassi et al.[2] exceeds ours today; by mid-century it falls short of ours on managed land and at most about equals it on managed forest. The estimate of Gidden et al.[3] becomes a source by 2100, whereas ours remains a sink (Extended Data Table 3d). Pathways aligned with an external estimate also carry a land-use flux computed without climate impacts, whereas in our scenarios the response of yields and carbon densities to climate change and rising CO_2 changes the land-use flux itself. Compared with the same six scenarios run without climate impacts for ScenarioMIP[8], the land-use flux is a larger net removal or a smaller net emission in every scenario, by 0.3 to 0.8 $GtCO_2$ yr^{-1} in 2050 and 0.3 to 2.1 in 2100 (Supplementary Table 2). The gain comes from stronger regrowth

in all six scenarios and from less deforestation in the weak-policy scenarios, both found earlier[30] for MAgPIE under RCP2.6.

For CMIP7, the decomposition provides a reference for the Earth system models, which compute the total net land flux themselves from the scenarios' land use[17,18]. For VL-SSP1 these models use the land use of this framework's marker scenario[8] as processed by Land-Use Harmonization 3 (LUH3), which harmonises it with historical land-use data[18,31]. The total net land flux that the Earth system models compute for VL-SSP1 can therefore be compared with ours, the sum of our land-use flux and CO_2-driven flux. The comparison is approximate, because the marker land use was computed without climate impacts (Supplementary Tables 2 and 3) and then processed by LUH3, so it differs from the land use in this study.

3.2 Net-zero targets count on a sink that fades

For climate policy the key point is that the net removals that inventories count for land do not stay what they are today. Today the sink on managed land is larger than the net emissions from land use, so the land counts as a net removal only because of the sink. Under ambitious mitigation, by 2100 half or more of the net removals come from land use (Fig. 4a). The land sector accounted for about a quarter of the emission reductions pledged in the first round of NDCs (2015–2016)[32], often without a quantified target[33]. The sink weakens once CO_2 stops rising, so pledges and net-zero targets that count on today's net removals from land count on a component that fades. In the ambitious-mitigation scenarios the net removals that inventories count peak in 2050–2070, then shrink by 22 to 27% by 2100 (Fig. 2). The sink also brings the net-zero date forward, by 2 to 7 years with our estimate and by at most 3 years with either external estimate (Fig. 4b). Countries set their net-zero targets in inventory terms, whereas pathways give the net-zero year in bookkeeping terms, so a target has to be compared with the pathway's net-zero year in inventory terms, as Gidden et al.[3] concluded for the AR6 pathways. VL-SSP1, for example, reaches net-zero CO_2 in 2048 under the bookkeeping convention and in 2044 under the inventory convention, so a net-zero target is compared with 2044.

The net removals from land use that compensate for the weaker sink require land and are exposed to disturbance and reversal[34]. In our scenarios they rest on 272 (L-SSP2) to 725 Mha (LN-SSP2) of AR added between 2025 and 2100, carbon-price and NPi/NDC AR together, as plantations in LN-SSP2 and as natural regrowth in L-SSP2 and VL-SSP1 (Fig. 3b), and on avoided deforestation and peatland rewetting. All of it must be maintained beyond 2100. Disturbances such as drought, fire and pest outbreaks, whose risk to forest carbon grows with warming[35], threaten the carbon of the sink and of land use alike. Neither form of AR is harvested or converted in the ambitious-mitigation scenarios, but plantations and natural regrowth differ for biodiversity: regrowth of native forest extends and connects habitat, a plantation does not, and AR on this scale can take areas of high importance for biodiversity[36].

3.3 Limitations

Three limitations bound these results. First, all six scenarios come from one framework, LPJmL-MAgPIE-REMIND, and LPJmL's carbon densities are driven by the climate of one climate model, MRI-ESM2-0, and the CO_2 concentration of the nearest CMIP6 scenario,

which for LN-SSP2 lacks its overshoot (Methods; Extended Data Table 4). One framework and one climate model cannot quantify the spread of the sink across models, nor how much net removal from land use another IAM would produce for the same scenarios. The weakening of the sink itself, on which the result rests, follows from falling CO_2 rather than from the model: it appears in Earth system models with and without a coupled nitrogen cycle[5–7]. In ISIMIP3b, where IMAGE and MAgPIE were run under five climate models, the choice of climate model explained almost none of the spread in the projected land-use pattern[24].

Second, LPJmL 4 has no nitrogen cycle, and carbon-only models[22] tend to respond more strongly to CO_2; the estimate of Grassi et al.[2] rests on the same LPJmL generation. LPJmL's present-day sink is nevertheless comparable with independent estimates, if on the low side. Its potential natural-vegetation sink, the sink LPJmL computes with no land use, is close to the uncorrected DGVM land sink of the GCB (Extended Data Fig. 4), and our total net land flux lies within the range of remote-sensing estimates and below the atmospheric inversions (Methods).

Third, managed land is a matter of definition. We count all land outside intact forest as managed, applying the intact-forest map of Grassi et al.[14,37] to all land classes, whereas the inventory harmonisation it comes from applies it to forest only, and both external estimates cover managed forest only. On managed forest alone, with soil carbon attributed to forest in proportion to its area, our inventory-aligned net removals decline less after their peak: by 0 to 13% by 2100, against 22 to 27% on all managed land (Extended Data Table 3d). The map is static and has no intact class outside forest, so intact other natural land counts as managed here (Methods). A narrower definition, MAgPIE's own managed land classes (secondary and planted forest, cropland, pasture and urban land) in place of the map, leaves 1.2 instead of 3.2 $GtCO_2\ yr^{-1}$ of the vegetation part of today's sink on managed land.

3.4 Conclusions and outlook

Net-zero CO_2 emissions weaken the land carbon sink, and land-based mitigation compensates. Under ambitious mitigation the net removals from land use first add to the inventory-aligned net removals and after mid-century mostly make up for the weakening sink, so the inventory-aligned net removals peak in 2050–2070 and lose about 25% of that peak by 2100. In scenarios where CO_2 keeps rising the sink does not fade, but there the land-use flux stays a net emission. Two consequences follow for pathway assessment and research. First, computing the sink inside the framework rather than adding an estimate afterwards changes what an aligned pathway shows, in two ways. With the land's response to climate change and rising CO_2 included, the land-use flux itself becomes a larger net removal. And the estimate chosen sets when the sink of an aligned pathway weakens: under ambitious mitigation the estimate of Grassi et al.[2] weakens mostly before 2050, ours mostly after. Aligned with it, our ambitious-mitigation scenarios have about 3.0 $GtCO_2\ yr^{-1}$ smaller net removals in 2050, and net zero in inventory terms comes at most 2 years before the bookkeeping date instead of 2 to 7 years (Fig. 4b). Second, where the sink on managed land ends up by 2100 in LN-SSP2 and VL-SSP1 is open: our estimate leaves a sink of just under 1 $GtCO_2\ yr^{-1}$, whereas the estimate

of Gidden et al.[3] turns into a source of 2.8 $GtCO_2$ yr^{-1} as CO_2 declines (Extended Data Table 3d). A multi-IAM, multi-climate-model version of this decomposition, together with inventories and model estimates that separate the land-use flux from the CO_2-driven flux consistently, would turn the result from a single-framework result into a quantity with an assessed range.

4. Methods

4.1 Model framework

We use the LPJmL-MAgPIE-REMIND framework: MAgPIE and REMIND are soft-coupled, and LPJmL supplies MAgPIE's biophysical inputs through a one-way link. MAgPIE[19,39] is a global, recursive-dynamic, partial-equilibrium land-use model that meets region-specific demand for plant- and animal-based commodities, timber and bioenergy at minimum production cost, subject to biophysical, technological and policy constraints. Rising demand is met through land expansion, yield increases from investment in research, irrigation expansion and trade. Being recursive-dynamic, MAgPIE optimises one time step at a time, in five-year steps from 1995 to 2060 and ten-year steps to 2100. A flux reported for a year is the annual mean over the time step that ends in that year, and "today" in the text is the 2025 time step. Socio-economic inputs are provided at country level and aggregated to the twelve world regions on which demand is resolved (codes and countries in Supplementary Table 1). Biophysical inputs at 0.5° are aggregated to 200 simulation units, on which land is allocated. MAgPIE tracks cropland (crop area, fallow, tree cover), pasture, primary forest, secondary forest, planted forest (carbon-price AR, NPi/NDC AR, timber plantations), urban land and other natural land. Each class carries vegetation, litter and soil carbon pools, except that crop area and fallow have no litter pool and urban land carries soil carbon only. Land CO_2 fluxes are computed per simulation unit and summed over each region's simulation units for reporting.

LPJmL[21,22,40], a dynamic global vegetation model, supplies MAgPIE's biophysical inputs through a one-way link. LPJmL simulates vegetation dynamics, biogeochemistry and hydrology, including photosynthesis, respiration, mortality and fire, at 0.5° and a daily time step[22,41,42]. LPJmL 4.0.004[21], run for natural vegetation without a nitrogen cycle, provides vegetation, litter and soil carbon densities and water availability. The area that can carry forest is derived from these densities in pre-processing: the 0.5° cells where the vegetation carbon density of natural vegetation is at least 20 tC ha^{-1}. LPJmL 5.2.001[22], run for crops and grassland, provides crop and pasture yields and irrigation water requirements. LPJmL outputs are computed once per CMIP6 climate scenario of ISIMIP3b[23,24], under the climate of MRI-ESM2-0 and that scenario's atmospheric CO_2 concentration, and supplied to MAgPIE as fixed cellular inputs; each CMIP7 scenario takes the nearest one (see below). Before use, all LPJmL inputs are smoothed over time with a spline (four degrees of freedom per century) and harmonised to one history, observation-based climate (GSWP3-W5E5) until 2010 and MRI-ESM2-0 SSP3-7.0 until 2025, from which each scenario's climate continues[43]. Smoothing leaves the fade to mid-century unchanged: the sink computed from the unsmoothed SSP1-1.9

densities on a fixed land area keeps 69% of its 2020s value in the 2040s, against 72% with the smoothed and harmonised densities. After mid-century the unsmoothed sink falls faster than the processed one used here, so the post-peak loss of inventory-aligned net removals we report would be larger without smoothing. These densities set the carbon stocks of natural vegetation that MAgPIE's CO_2 price acts on, and their change over time, applied to the projected land-use pattern, gives the CO_2-driven flux.

Secondary and planted forest, cropland tree cover and other natural land are resolved by age class. Their vegetation carbon density rises with stand age along Chapman–Richards growth curves, parameterised by climate zone for natural regrowth and for plantations[26], towards the LPJmL density of the simulation unit[44], and their litter carbon density rises linearly over the first 20 years to the LPJmL value. Primary forest takes the LPJmL densities directly. Secondary forest starts in 1995 from the observed age-class distribution of forests[44]. Soil organic carbon in the top 30 cm is modelled with IPCC stock-change factors[45]. The steady-state density of each land use is the LPJmL soil carbon density under natural vegetation, scaled on cropland by factors for crop type, irrigation, tree cover and soil-carbon management. The actual density closes 15% of its gap to the steady-state density each year. Below 30 cm, every land use keeps the LPJmL density under natural vegetation. Timber demand rises with population and income and is supplied by timber plantations, secondary and primary forest and other natural land[44]. Carbon in industrial roundwood enters wood-product pools that decay with half-lives of 2 to 60 years, whereas carbon in fuelwood is released at harvest. Peatland CO_2, CH_4 and N_2O fluxes are computed from the areas of intact (never drained), drained and rewetted peatland by land use and climate zone[46], with emission factors from the IPCC Wetlands Supplement for tropical and boreal peatland and from Tiemeyer et al.[47] for temperate peatland.

REMIND[20,48] is a global, multi-region, intertemporal-optimal energy-economy model solving a non-linear welfare-maximisation problem on the same twelve-region scheme. REMIND and MAgPIE share population, GDP and first-generation bioenergy assumptions and are soft-coupled. REMIND passes greenhouse gas prices and the regional production of purpose-grown lignocellulosic biomass that MAgPIE has to supply. MAgPIE returns the price of that biomass, land-based greenhouse gas emissions and land-use costs. Each scenario runs six REMIND and five MAgPIE iterations. The land results reported here come from the final MAgPIE iteration, and the net CO_2 emissions (Fig. 4b) from the final REMIND iteration, which takes that MAgPIE iteration's land fluxes. The land CO_2 flux passed to REMIND is the land-use flux only. Inside MAgPIE the carbon price also acts on the CO_2-driven change in carbon density (see below).

4.2 Scenario implementation

ScenarioMIP for CMIP7 defines seven scenarios (Table 1 of Van Vuuren et al.[18]), each named after its emission trend: High (H), High-to-Low (HL), Medium (M), Medium-to-Low (ML), Low (L), Low-to-Negative (LN) and Very Low (VL). One nominated IAM quantifies each scenario as its marker model, and the Earth system models receive the marker scenario's emissions and land use, each harmonised with historical data[18]. The marker implementations

draw on the shared socioeconomic pathway (SSP) narratives[49], with their demographic and economic drivers recently updated[18], as the scenario names indicate (H-SSP3, M-SSP2). We produce six of them with the LPJmL-MAgPIE-REMIND framework. H-SSP3 rolls back current policies; M-SSP2 continues today's policies; ML-SSP2's emissions decline from 2040 to net-zero CO_2 in 2100; L-SSP2 keeps warming likely below 2 °C; LN-SSP2 returns to 1.5 °C by 2100 after a high overshoot; and VL-SSP1 limits warming to 1.5 °C with an overshoot "as low as plausible". All six share SSP2 settings and current policies until 2025. The seventh scenario, HL-SSP5, the second member of the moderate-transition cluster, is not part of this run set because its SSP5 parameter sets had not been validated in LPJmL-MAgPIE-REMIND in time. Running one framework across all six scenarios keeps the decomposition internally consistent, so the differences reported here are one framework's land response throughout.

The same framework provides the VL-SSP1 marker, under the name REMIND-MAgPIE[8]. In the marker scenarios, climate impacts are held at their 2025 level. Here, climate impacts are included: yields, water availability and carbon densities follow each scenario's climate and CO_2 concentration to 2100. The climate is bias-adjusted MRI-ESM2-0 from ISIMIP3b[23]. MRI-ESM2-0 has an equilibrium climate sensitivity at the median of the five ISIMIP3b models[50], covers all forcing tiers used here and is one of the five climate models in the ISIMIP3b land-use sensitivity work[24]. The CMIP7 scenarios are mapped to the nearest CMIP6 forcing available in ISIMIP3b (Extended Data Table 4), so LN-SSP2 and VL-SSP1 share one climate. The mapping preserves the qualitative CO_2 shape of each scenario (rising, stabilising, peaking and declining), except that it does not reproduce the overshoot of LN-SSP2 and gives ML-SSP2, whose own CO_2 levels off near 490 ppm, a forcing that peaks and then declines slightly.

MAgPIE applies the greenhouse gas prices from REMIND to land emissions from 2035 in L-SSP2, LN-SSP2 and VL-SSP1, from 2045 in ML-SSP2 and not at all in H-SSP3 and M-SSP2. For CO_2, the price applies to the net emissions from vegetation and litter carbon of primary forest, secondary forest and other natural land, whether they result from land use or from the CO_2-driven change in carbon density, and to peatland emissions; soil carbon is not priced. Drained peatland can then be rewetted at a cost[46], on up to 2% of the drained area per year. Carbon-price AR is established where the reward for its expected sequestration[51] outweighs establishment and opportunity costs. The reward values half of the carbon the new forest is projected to take up within 50 years at the expected carbon price, the other half being withheld as a buffer against the risk of reversal. Carbon-price AR is confined to land that can carry forest under the scenario's climate, limited to 3% per year of the part of that land not yet under forest, excluded from boreal regions in all scenarios and confined to the tropics in VL-SSP1, and protected from later conversion. Two AR design settings matter for the results. LN-SSP2 is configured to implement carbon-price AR as plantations (timber-plantation growth curves but no harvest, no area cap), with the reward for it phased in linearly from zero in 2040 to its full value in 2050. ML-SSP2, L-SSP2 and VL-SSP1 implement carbon-price AR as natural-vegetation regrowth, and VL-SSP1 in addition caps total AR, NPi/NDC AR included, at 700 Mha. Extended Data Table 4 lists the land settings that differ between the scenarios.

4.3 Flux decomposition

We define the land-use flux as the carbon flux attributable to human use of land: land-use change (deforestation, AR, plantation establishment), management (wood harvest, drained and rewetted peatland, cropland management including soil-carbon management) and the resulting succession dynamics of secondary forest, planted forest and abandoned agricultural land. We define the CO_2-driven flux as the carbon flux attributable to the change in the carbon density of each land class that LPJmL projects under the evolving CO_2 and climate, applied to the land-class areas MAgPIE projects. The land-use flux is the model's land response to demand, policy and climate impacts, which act through yields and water. The CO_2-driven flux is the response of the carbon densities to climate change and CO_2, evaluated on that land-use pattern.

The flux for each MAgPIE time step is computed with magpie4, MAgPIE's R reporting package, from the carbon stock $C = A \cdot \rho$, the product of area A and carbon density ρ, for each simulation unit, land class and pool of vegetation and litter, and by age class where the land class has them (see above). The stock change of soil carbon is split differently (see below). For vegetation and litter, each difference over a time step is the value at the previous time step minus the value at the current one, so that an emission is positive. The stock change is then split into an area term $\Delta A \cdot \rho(t + \Delta t)$, which is the land-use flux, and a density term $A(t + \Delta t) \cdot \Delta \rho$ plus the interaction term $\Delta A \cdot \Delta \rho$, which together are the CO_2-driven flux. The two parts add up to the total stock change exactly. Because the split is computed by age class, stand ageing (area moving between age classes) counts as land-use flux, while the vegetation and litter density of an age class changes only with LPJmL's response to CO_2 and climate. Regrowing forest therefore grows towards a density that rises with CO_2, so the CO_2-enhanced part of its uptake counts as land-use flux, as in the transient-density bookkeeping of the GCB since its 2025 edition[1]; the inventory-aligned flux is unaffected. How large that CO_2-enhanced part is can be read from the same six scenarios run without climate impacts for ScenarioMIP[8], which share the code and settings of ours, hold the LPJmL inputs at their 2025 values and end up with the same carbon prices. The land-use flux differs between the two sets by 0.3 to 0.8 $GtCO_2\ yr^{-1}$ in 2050 and 0.3 to 2.1 in 2100 (Discussion; Supplementary Table 2). The part of this difference that comes from the higher densities of regrowing stands rather than from their areas, obtained by recomputing our land-use flux with the densities of the no-impact set, is 0.3 to 0.4 $GtCO_2\ yr^{-1}$ in 2050 and 0.6 to 0.8 in 2100 in the ambitious-mitigation scenarios. Moving that density part from the land-use flux to the sink lowers the share of land use in the 2100 inventory-aligned flux from 56% to 43% in L-SSP2, from 86% to 76% in LN-SSP2 and from 84% to 75% in VL-SSP1 (Extended Data Table 3a). Peatland fluxes, computed from emission factors, belong entirely to the land-use flux. The land-use flux is partitioned further by process (deforestation, conversion of other natural land, wood harvest, regrowth by land class, harvested wood products, peatland, soil carbon, residual), and the CO_2-driven flux by land class and by pool (vegetation and litter together, and soil). The soil stock change cannot be split into an area term and a density term in the same way, because a converted hectare keeps its soil carbon density at first and only gradually approaches a new steady-state density. In the top 30 cm, the steady-state density of each hectare is the LPJmL density under natural vegetation scaled by the stock-change factor of its land use. The part of the soil stock change

that comes from the LPJmL density, which responds to CO_2 and climate, is the CO_2-driven flux. The part that comes from the stock-change factor, which changes when land use changes or when crop type, irrigation, tree cover or soil-carbon management change on cropland, is the land-use flux. Because the soil stock closes only 15% of the gap to its steady-state density each year, both parts include effects that appear in later time steps. Below 30 cm, where every land use keeps the density under natural vegetation, all of the change is CO_2-driven. The CO_2-driven soil term is reported as one pool over all land classes.

4.4 Illustrative model of the CO_2-driven flux

The model behind Fig. 1b is illustrative and enters no part of the analysis. Carbon uptake, gross primary production (GPP), rises with the logarithm of CO_2 (a log-linear β factor, whose definitions Walker et al.[52] review), $GPP(C) = GPP_0\,[1 + \beta \ln(C/C_0)]$, without delay and with diminishing returns. The uptake is split between a fast and a slow carbon pool, each holding a share of the uptake and releasing its stock at a fixed turnover time. The flux plotted is the total release minus GPP (negative = sink). $GPP_0 = 115$ GtC yr^{-1} and $C_0 = 285$ ppm are fixed. β, the two shares and the two turnover times were fitted by least squares to the CO_2-driven flux on all land of the six scenarios over 2005–2100. Each scenario is driven by the CO_2 concentration of the CMIP6 scenario under which LPJmL computed its carbon densities (Extended Data Table 4). The fit gives $\beta = 0.26$, 83% of the uptake released with a turnover time of 2.5 years (the data are five-year means, so this value is not resolved) and 17% with a turnover time of 104 years, at a root-mean-square error of 0.7 $GtCO_2$ yr^{-1}. The fit describes the flux and is not a carbon-cycle model: the flux it is fitted to also carries the response to climate change, which the fit folds into β, so β is an effective whole-biosphere value, and the two pools stand for fast and slow release rather than for identified carbon pools. At constant CO_2 each stock converges on its share of GPP times its turnover time, so release equals uptake and the flux vanishes: the flux is non-zero only while CO_2 changes. The three CO_2 trajectories in Fig. 1b are stylised and stand for the three scenario clusters rather than being taken from the scenarios.

4.5 Managed land, intact forest and the inventory-aligned flux

Managed land is all land outside intact forest. Inventory harmonisation takes intact forest, forest in which remote sensing detects no human activity, as the proxy for the forest that countries do not count as managed[1,14,53]. We apply the same proxy to all land, so cropland, pasture, urban land, other natural land and all forest outside intact forest count as managed, protected areas included. The map is that of Grassi et al.[14]: the intact forest landscapes of Potapov et al.[25] for 2013, with the national maps of Canada and Brazil and an adjustment for Russia, at 0.5° (our sums: 899 Mha intact and 3,382 Mha non-intact forest), summed to the 200 simulation units. In each simulation unit and time step the intact area is assigned to primary forest first and any remainder to secondary forest, each capped by the class area, so that deforested intact land becomes managed. The map is static and has no intact class outside forest, so intact other natural land counts as managed. In 2025 intact forest covers 891 Mha, 6.9% of the 12,986 Mha land surface (841 Mha primary and 51 Mha secondary forest). The other 3,186 Mha of forest, planted forest included, are managed forest; Extended Data Fig. 5

shows the split by region. MAgPIE's own class split (secondary and planted forest, cropland, pasture and urban land as managed) is not used for this purpose because it does not match the inventories' definition.

Both external estimates cover managed forest only, for reasons Grassi et al.[2] give: models place most of the sink in forest, many non-Annex I countries report only forest land and deforestation, and no proxy comparable to intact forest separates managed from unmanaged land outside forest. We therefore also give our estimate on managed forest alone (Extended Data Table 3d). Because the CO_2-driven soil term is one pool over all land classes (see above), the estimate is the vegetation term of managed forest plus the simulation unit's soil term scaled by that forest's share of the unit's land, the same rule as for intact forest below.

The CO_2-driven flux inside intact forest is computed per simulation unit as the vegetation term of primary and secondary forest scaled by the intact share of each class, plus the soil term of all classes scaled by the intact share of the simulation unit's land, which assumes the same soil term per hectare inside and outside intact forest. The CO_2-driven flux on managed land is the remainder, so that the two sum to the total per simulation unit, region and year. The inventory-aligned flux is the land-use flux on all land plus the CO_2-driven flux on managed land; the total net land flux adds the intact-forest term. All three are reported for the twelve regions and the World. Extended Data Table 5 maps the components to the IPCC land-use categories[54]. The net-zero years quoted in Results (Fig. 4b) are computed from our framework's net CO_2 emissions: fossil and industrial CO_2 net of removals outside the land sector, such as bioenergy with carbon capture and storage, plus a land term, which is the land-use flux. For the inventory convention the CO_2-driven flux on managed land is added. Net zero is interpolated linearly between time steps.

4.6 Observational benchmarks

Three sets of benchmarks are used (Extended Data Fig. 2). Bookkeeping land-use change emissions and the DGVM land sink are from the 2025 edition of the GCB[1]: the annual series of BLUE[55], OSCAR[56] and LUCE[57] and their mean, the GCB's ±1σ uncertainty of land-use change emissions, and the DGVM ensemble mean SLAND, computed on pre-industrial land cover[4,58] and corrected for replaced sinks and sources[59], for 2000–2024, taken from its data release[60]. Extended Data Fig. 4 also shows the uncorrected SLAND. The inventory-convention benchmarks are the country-level LULUCF fluxes of the LULUCF Data Hub[38] (v3.1.1, the 2025 inventory release, described by Melo et al.[53]), aggregated to the twelve MAgPIE regions and the World for 2000–2023, and the decadal values of Table S11 of the GCB 2025 supplement for 2005–2014 and 2015–2024: gap-filled inventories (missing country-years filled statistically), bookkeeping models plus the DGVM sink in managed forest, and atmospheric inversions masked to managed land. The net land flux from atmospheric inversions for 2015–2024 (mean and ±1σ across 14 inversion systems) is from the GCB, and the remote-sensing-based net land flux for 2000–2019 from Randerson et al.[61]. All benchmarks are expressed in $GtCO_2\ yr^{-1}$ (those published in $GtC\ yr^{-1}$ multiplied by 44/12); net removals from the atmosphere are negative in every figure and table. For the regional comparison over 2000–2020 (Extended Data Table 2) we use the country-level

fluxes harmonised by Grassi et al.[14,37]: the bookkeeping models of Houghton and Nassikas (H&N), BLUE and OSCAR, with the emissions from drained organic soils added to BLUE and OSCAR as in the harmonisation (H&N includes them), and the ensemble mean sink of the TRENDY v11 DGVM intercomparison in managed and intact forest (their non-intact and intact forest), aggregated to the twelve regions with the same mapping. The estimate of Grassi et al.[2] enters as their five-yearly adjustment factors under SSP2 with each RCP (Extended Data Table 4), which the authors provided for the ten IPCC AR6 regions (their paper reports five) and which we mapped to our twelve regions with madrat[43], the R framework that prepares MAgPIE's input data. Grassi et al.[2] mark their estimate as more uncertain after 2050. The estimate of Gidden et al.[3,62], computed with the OSCAR emulator for the AR6 pathways, enters as the median across the pathways of each AR6 climate category at the World level, with the interquartile range for 2050 and 2100 (Fig. 4; Extended Data Table 3d). Each scenario's global warming is computed from its full emission pathway, REMIND's energy and industry emissions together with MAgPIE's land emissions, with the reduced-complexity climate model MAGICC7 in the probabilistic setup of the AR6 climate assessment[63]. MAGICC7 computes the atmospheric CO_2 concentration with its own land and ocean carbon cycle, so the CO_2 and warming paths of the scenarios do not depend on the CO_2-driven flux of LPJmL. Each scenario is matched to the category that the AR6 rules give for its own MAGICC7 warming (the probabilities of exceeding warming levels from 1.5 to 4 °C at peak warming and in 2100): C7 for H-SSP3 (96 pathways), C6 for M-SSP2 (80), C5 for ML-SSP2 (185), C3 for L-SSP2 (231) and C2 for LN-SSP2 and VL-SSP1 (106). VL-SSP1 peaks at 1.7 °C in this run, more than the limited overshoot of C1 allows.

The LPJmL potential natural vegetation sink, the sink the land would supply if it were entirely natural vegetation under each scenario's climate, is computed from the same LPJmL carbon densities as the CO_2-driven flux (change of the natural-vegetation carbon density, vegetation, litter and soil together, times land area) and compared with SLAND for the historical period (Extended Data Fig. 4).

4.7 Evaluation against observational estimates

Each of the three quantities, the land-use flux, the CO_2-driven flux on managed land and the inventory-aligned flux, has a reference estimate (Extended Data Fig. 2; by region for 2000–2020 in Extended Data Table 2). Period means weight each model time step by the number of its years inside the period. The land-use flux lies below the bookkeeping models of the GCB[1] (2025 edition): net emissions of 3.6 $GtCO_2\ yr^{-1}$ for 2015–2024 against 5.8 (BLUE), 4.7 (OSCAR) and 4.6 (LUCE), mean 5.0, but within the GCB's uncertainty of ±2.6. Over 2000–2020 and against the bookkeeping models harmonised by Grassi et al.[14] (Extended Data Table 2), the land-use flux is below them in Latin America (0.6 against 2.0 $GtCO_2\ yr^{-1}$) and sub-Saharan Africa (0.8 against 1.4) and a small net emission where they give a small net removal or none, in China, Europe and the United States.

The inventory-aligned flux is compared with national inventories and with a bookkeeping plus DGVM estimate (Extended Data Fig. 2b). That estimate is the GCB's translation of the bookkeeping models to the inventory definition: their land-use change emissions plus the

DGVM sink in managed forest[1]. For 2015–2024 our net removals average 1.5 $GtCO_2$ yr^{-1}, rising from about 0.9 in the 2015 and 2020 time steps to 2.3 in the 2025 step, which Results use as today's value. The decadal mean is smaller than every estimate for managed land: 1.9 from the bookkeeping plus DGVM estimate, 2.5 from atmospheric inversions and 3.8 from the inventories[1]. Our 2025 step alone, 2.3, lies between the bookkeeping plus DGVM estimate and the inversions. The gap to the inventories is not specific to our framework: the bookkeeping plus DGVM estimate falls short of them too. What is specific is where our two parts sit. Our land-use flux is a smaller net emission than the bookkeeping models give, 3.6 against their mean of 5.0 $GtCO_2$ yr^{-1}, and our CO_2-driven flux on managed land a smaller sink than the DGVM sink in managed forest, 5.1 against 6.9; the two differences largely cancel. That DGVM sink includes non-forest land in grid cells with forest for most DGVMs[14], whereas ours covers all managed land explicitly. On managed forest alone our sink is 2.1 $GtCO_2$ yr^{-1}, with which the inventory-aligned flux would be a net emission of 1.5 $GtCO_2$ yr^{-1}. The regional comparison over 2000–2020 with the harmonisation of Grassi et al.[14] shows the same gap to the bookkeeping plus DGVM estimate (Extended Data Table 2).

The total net land flux, net removals of 2.4 $GtCO_2$ yr^{-1} over 2000–2019, lies within the remote-sensing estimate of Randerson et al.[61], 2.9 ± 2.6 $GtCO_2$ yr^{-1}, and, at 2.5 over 2015–2024, below the GCB's own total of 3.6, the corrected DGVM sink net of the bookkeeping emissions, and below its inversion ensemble[1], 4.8 ± 1.1 $GtCO_2$ yr^{-1}.

4.8 Use of large language models

Generative AI tools (Claude, Anthropic, Opus 5 and Fable 5 models, accessed through Claude Code) were used to assist with drafting, language editing and consistency checking of the manuscript text, to support the literature search and the checking of references against Crossref and DataCite, and to write and check code for data processing, figure generation and verification. No data, results, references or figure content were generated by AI: all scenario results, analyses and interpretations are the authors' own, all AI-assisted output was reviewed and verified by the authors, and the authors take full responsibility for the accuracy, integrity and originality of the work.

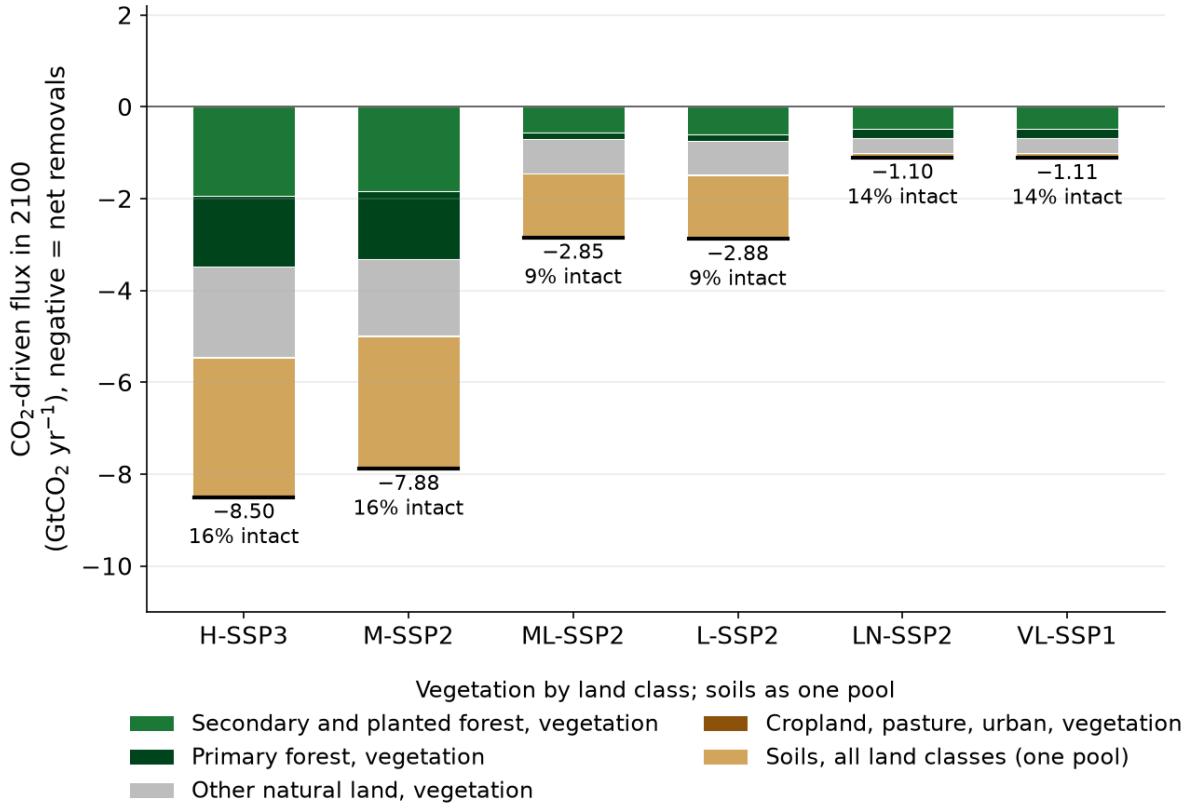
Extended Data

Extended Data Table 1 | Positioning of this study against four strands of literature

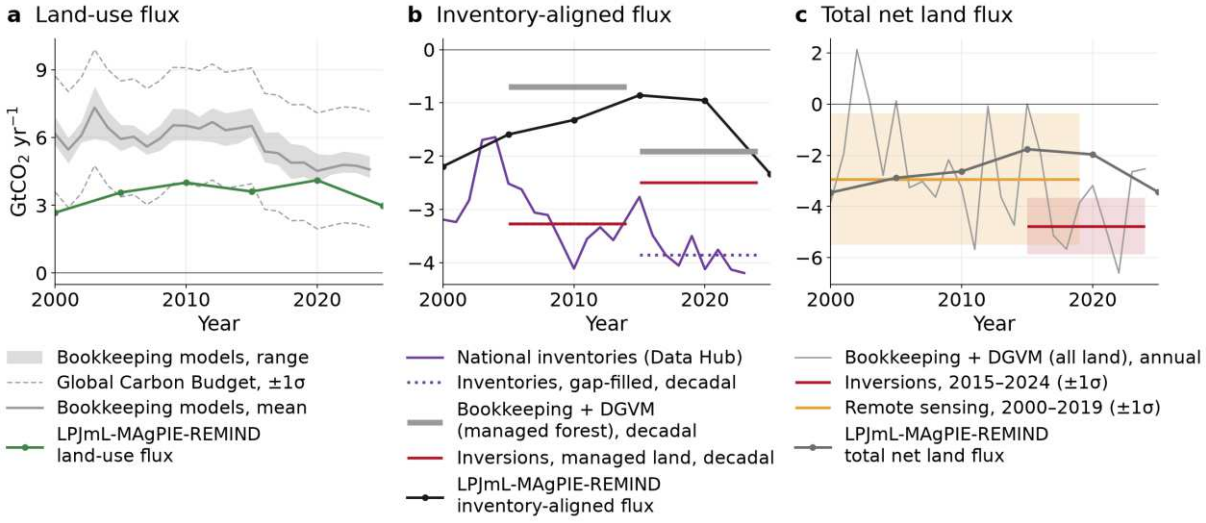
	Grassi et al.[2]	Gidden et al.[3]	LASC studies[12,56,65]	Offline land-use forcing[9,10,66]	ESM overshoot[5,6,11]	This study
Land carbon model	LPJmL with IMAGE land use, adjusted for each IAM's forest area	OSCAR emulator, probabilistic	bookkeeping models and DGVMs	DGVMs or ESMs forced with IAM land use	ESMs	LPJmL carbon densities inside MAgPIE
Link to IAM land use	internal in IMAGE, post hoc for other	external, from aggregate land cover	none (historical land use)	external, one-way	none (idealised CO_2) or	internal: the densities drive land allocation, carbon pricing and

	Grassi et al.[2]	Gidden et al.[3]	LASC studies[12,56,65]	Offline land-use forcing[9,10,66]	ESM overshoot[5,6,11]	This study
	IAMs				external, one-way	reporting
Resolution	0.5° grid, reported for five regions; 2013 intact-forest map	five world regions	grid or world regions	grid	grid	computed on 200 simulation units, reported for 12 regions
Land classes	managed forest only	managed forest only	all land, natural vs managed	model-specific	model-specific	eleven classes and sub-classes, partly by age class; peatland; managed land vs intact forest
Scenarios	SSP2-1.9 to SSP2-6.0 and SSP2 baseline	914 AR6 pathways	past	one or a few scenarios	overshoot and net-negative experiments	six CMIP7 ScenarioMIP scenarios
IAM climate impacts	in IMAGE only	not used; OSCAR recomputes the land-use flux	not applicable	as in each IAM (on in IMAGE)	not applicable	on (yields, water, carbon densities)
Flux partition	land-use vs CO_2-driven, managed forest	land-use vs CO_2-driven, managed forest	land-use, CO_2-driven, LASC	total land response	total land response; CO_2 fertilisation vs climate change in one study[11]	land-use by process; CO_2-driven by class, pool, managed vs intact
Primary output	adjustment of IAM pathways to inventories	inventory-aligned net-zero timing; aligned net removals peak by mid-century, then decline	historical land-use emissions and LASC	land carbon uptake or loss under IAM land use	sink response to CO_2 decline	land-use flux and sink on managed land for the same scenario; bookkeeping and inventory conventions from one framework

The four strands address how land carbon under land use responds to CO_2 and climate: prospective inventory alignment of IAM pathways (Grassi et al.[2] and Gidden et al.[3], one column each), historical loss of additional sink capacity (LASC), offline simulations of dynamic global vegetation models (DGVMs) or Earth system models (ESMs) with IAM land use, and the carbon-cycle response to overshoot in ESMs. ScenarioMIP marker scenarios are produced by different IAMs; the IAM used here provides the VL-SSP1 marker, without climate impacts and under the name REMIND-MAgPIE, and here runs all six scenarios with climate impacts (Methods).



Extended Data Fig. 1. CO_2-driven flux in 2100 by land class ($GtCO_2$ yr^{-1}; positive = net emissions, negative = net removals from the atmosphere). Vegetation (LPJmL vegetation and litter carbon) by land class: secondary and planted forest, cropland, pasture and urban (below 0.05 $GtCO_2$ yr^{-1}), primary forest and other natural land. Soils (LPJmL soil carbon) are one pool over all land classes (Methods). Black line and number: total CO_2-driven flux, with the share inside intact forest.



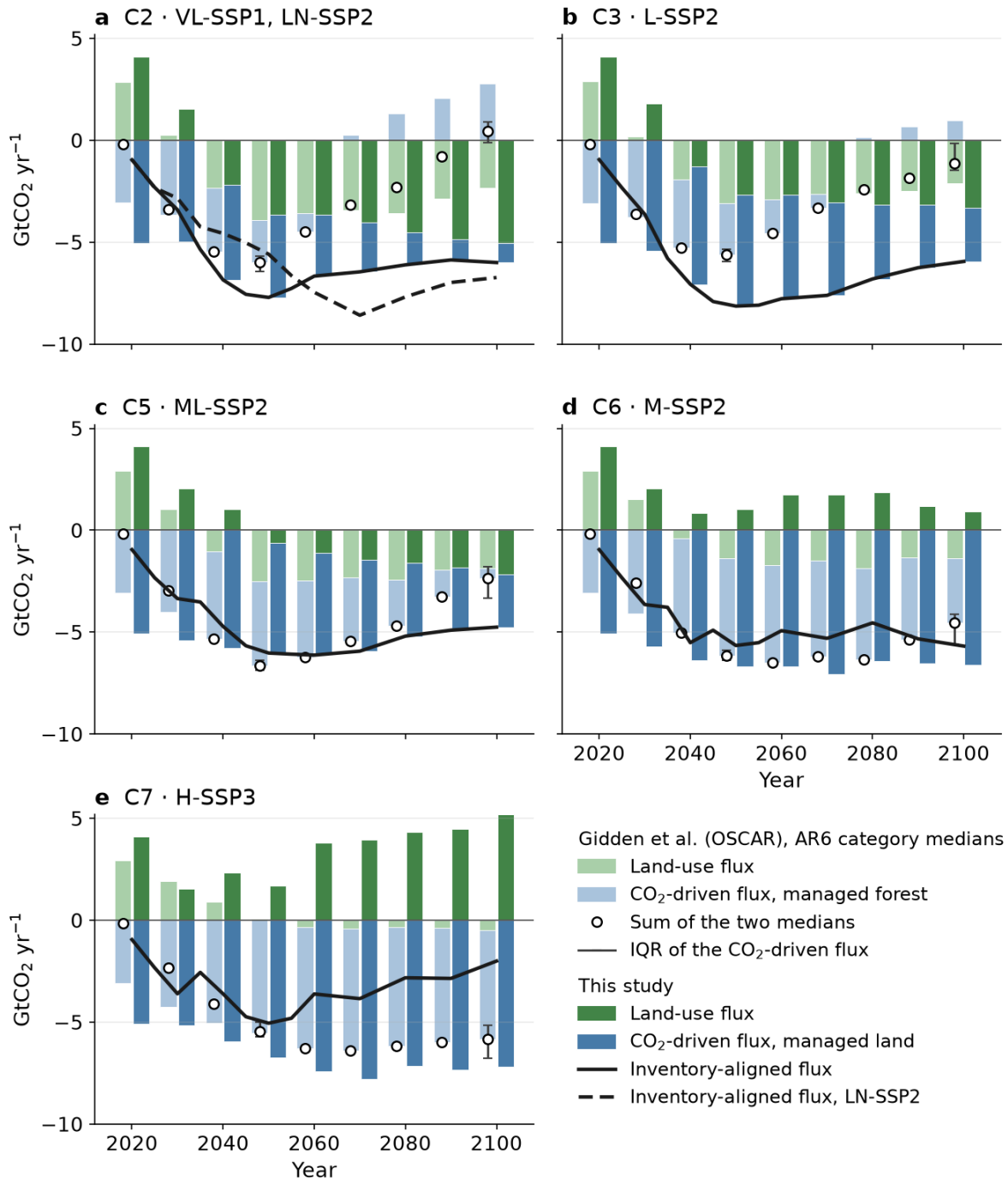
Extended Data Fig. 2. Land-use flux, inventory-aligned flux and total net land flux against observational estimates, 2000–2025 ($GtCO_2$ yr^{-1}; positive = net emissions, negative = net removals from the atmosphere; LPJmL-MAgPIE-REMIND values from M-SSP2). Model values are five-year means, plotted at the end year of each time step. (a) Land-use flux against the bookkeeping models of the GCB[1] (2025 edition; range of BLUE, OSCAR and LUCE, their mean, and the GCB's ±1σ uncertainty of land-use change emissions, dashed). (b) Inventory-aligned flux against national inventories (LULUCF Data Hub[38] v3.1.1, annual) and the decadal values in Table S11 of the GCB[1]: gap-filled inventories, bookkeeping models plus the DGVM sink in managed forest, and atmospheric inversions on managed land. (c) Total net land flux against the bookkeeping-plus-DGVM net

flux, atmospheric inversions for 2015–2024 (line and ±1σ) and the remote-sensing estimate of Randerson et al.[61] for 2000–2019 (line and ±1σ).

Extended Data Table 2 | Regional means of the three quantities and their benchmarks, 2000–2020

Region	land-use flux (this study)	bookkeeping models	CO_2-driven flux on managed land (this study)	DGVM sink in managed forest	inventory-aligned flux (this study)	bookkeeping + DGVM	national inventories
CAZ	+0.12	+0.16 (+0.10 to +0.28)	−0.68	−0.45	−0.56	−0.29	+0.02
CHA	+0.48	+0.00 (−0.17 to +0.33)	−0.28	−0.33	+0.20	−0.32	−0.96
EUR	+0.40	−0.20 (−0.36 to −0.03)	−0.11	−0.25	+0.29	−0.44	−0.35
IND	+0.16	+0.06 (−0.01 to +0.14)	−0.08	−0.09	+0.08	−0.03	−0.28
JPN	−0.01	−0.02 (−0.03 to −0.01)	−0.02	−0.04	−0.03	−0.07	−0.08
LAM	+0.65	+1.98 (+1.51 to +2.35)	−1.06	−1.18	−0.41	+0.80	+0.43
MEA	+0.01	+0.05 (+0.02 to +0.07)	−0.08	−0.01	−0.06	+0.04	−0.01
NEU	+0.03	−0.02 (−0.03 to +0.00)	−0.06	−0.06	−0.03	−0.08	−0.10
OAS	+1.32	+1.56 (+1.27 to +1.79)	−0.63	−0.85	+0.69	+0.71	+0.35
REF	−0.28	−0.04 (−0.32 to +0.11)	−0.58	−1.01	−0.86	−1.05	−1.43
SSA	+0.77	+1.39 (+1.19 to +1.55)	−1.13	−1.66	−0.36	−0.27	+0.20
USA	+0.13	−0.11 (−0.37 to +0.02)	−0.30	−0.49	−0.17	−0.60	−0.98
World	+3.77	+4.81 (+3.06 to +6.10)	−5.00	−6.42	−1.23	−1.62	−3.19

The three quantities from LPJmL-MAgPIE-REMIND are the columns marked “this study”; the benchmarks each is compared with are in the columns to its right ($GtCO_2$ yr^{-1}; positive = net emissions, negative = net removals from the atmosphere). Land-use flux against the bookkeeping models as harmonised by Grassi et al.[14] (Houghton and Nassikas, BLUE and OSCAR with organic-soil emissions; mean and range); CO_2-driven flux on managed land, which also covers other natural land and non-forest soils, against the TRENDY v11 DGVM ensemble mean sink in managed (non-intact) forest of the same study, a smaller area; inventory-aligned flux against bookkeeping plus that DGVM sink and against the national inventories of the LULUCF Data Hub[38] (v3.1.1, 2025 inventory release). LPJmL-MAgPIE-REMIND values weight each model time step by its years inside 2000–2020 (Methods); the Grassi et al.[14] model data are of GCB 2022 vintage.



Extended Data Fig. 3. The inventory-aligned flux of the AR6 pathways aligned by Gidden et al.[3] against this study, 2020–2100 ($GtCO_2$ yr^{-1}; positive = net emissions, negative = net removals from the atmosphere). Each panel sets one AR6 climate category against the scenario matched to it (Methods): C2 and VL-SSP1 and LN-SSP2 (a), C3 and L-SSP2 (b), C5 and ML-SSP2 (c), C6 and M-SSP2 (d), C7 and H-SSP3 (e). Per decade, the light bars are, across the category's pathways, the median land-use flux and the median estimate of Gidden et al.[3] for the sink on managed forest, and the open circles the sum of the two medians; the whiskers at 2050 and 2100 add the interquartile range of that estimate to the median land-use flux. The dark bars are the land-use flux and the CO_2-driven flux on managed land of this study, and the black line their sum, the inventory-aligned flux. In panel a the bars and the solid line are VL-SSP1 and the dashed line is LN-SSP2, which is matched to the same category. In C2 the sum of the medians turns from 6.0 $GtCO_2$ yr^{-1} of net removals in 2050 into 0.4 of net emissions by 2100, because the estimate of Gidden et al.[3] becomes a source of 2.8 as CO_2 declines; our inventory-aligned flux ends at 6.0 to 6.7 of net removals.

Extended Data Table 3 | Land CO_2 flux by region, and our estimate of the sink against the external estimates ($GtCO_2$ yr^{-1})

(a) Share of the inventory-aligned flux from land use in 2100 under each estimate of the sink, World

Scenario	our estimate, managed land	our estimate, managed forest	our estimate, CO_2-enhanced regrowth in the sink	Grassi et al.	Gidden et al., median (IQR)
L-SSP2	56%	75%	43%	71%	141% (123% to 240%; C3)
LN-SSP2	86%	89%	76%	84%	192% (161% to 225%; C2)
VL-SSP1	84%	88%	75%	82%	222% (177% to 276%; C2)

(b) Inventory-aligned flux; 2020 from the model, 2016–2020 from the inventories, 2100 per scenario

Region	2020 model	2016–2020 inventories	H-SSP3	M-SSP2	ML-SSP2	L-SSP2	LN-SSP2	VL-SSP1
CAZ	−0.44	−0.08	−0.69	−1.09	−0.10	−0.16	−0.43	−0.48
CHA	+0.07	−1.26	−0.73	−0.79	−0.48	−0.57	−0.79	−0.46
EUR	+0.24	−0.27	+0.05	+0.01	−0.10	−0.16	−0.20	−0.18
IND	+0.07	−0.41	+0.03	−0.08	−0.03	−0.08	−0.12	−0.08
JPN	−0.03	−0.06	−0.05	−0.04	−0.04	−0.04	−0.05	−0.04
LAM	−0.20	+0.05	−2.27	−2.10	−2.17	−2.44	−3.12	−2.85
MEA	−0.14	−0.01	−0.14	−0.12	+0.03	+0.02	+0.12	+0.12
NEU	−0.04	−0.09	−0.05	−0.06	−0.04	−0.05	+0.00	+0.00
OAS	+0.63	+0.32	+1.55	+0.39	−0.41	−0.60	−0.70	−0.52
REF	−0.89	−1.11	−1.27	−1.17	−1.06	−1.19	−0.70	−0.80
SSA	+0.10	+0.09	+1.71	−0.39	−0.23	−0.39	−0.55	−0.61
USA	−0.32	−0.97	−0.14	−0.25	−0.12	−0.28	−0.19	−0.10
World	−0.95	−3.80	−2.01	−5.69	−4.76	−5.95	−6.74	−6.00

(c) Bookkeeping convention (land-use flux only); 2025, and 2100 per scenario

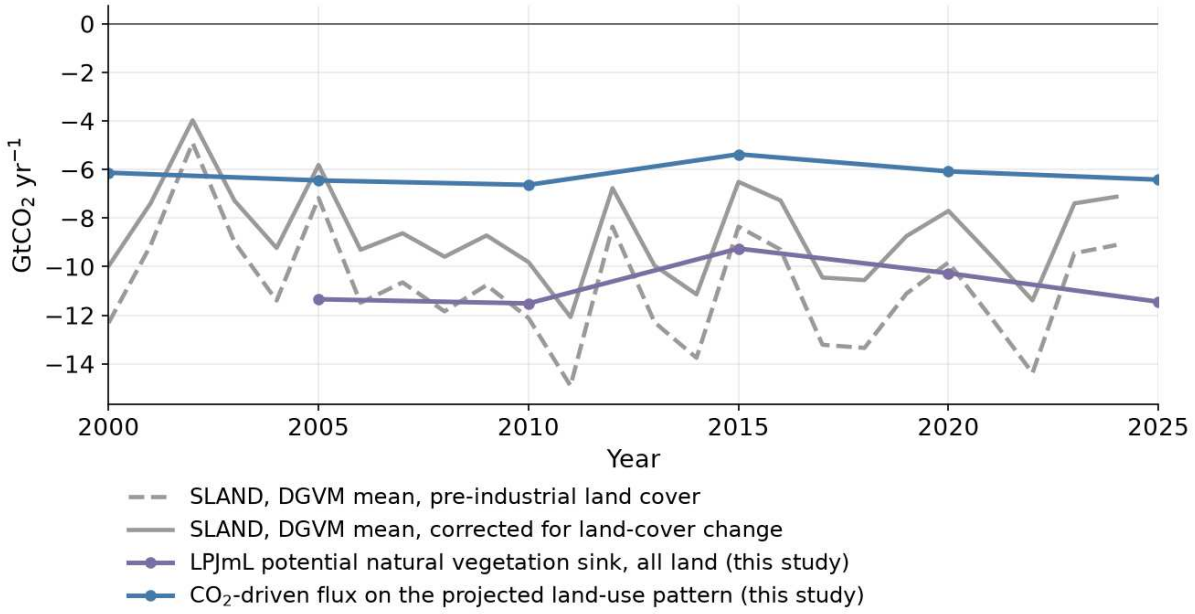
Region	2025	H-SSP3	M-SSP2	ML-SSP2	L-SSP2	LN-SSP2	VL-SSP1
CAZ	+0.11	+0.28	+0.04	+0.00	−0.06	−0.04	−0.07
CHA	+0.17	−0.26	−0.33	−0.27	−0.36	−0.71	−0.39
EUR	+0.30	+0.23	+0.19	+0.03	−0.02	−0.12	−0.09
IND	+0.08	+0.09	−0.07	−0.06	−0.11	−0.14	−0.10
JPN	−0.02	−0.02	−0.02	−0.03	−0.03	−0.05	−0.04
LAM	+0.34	−0.19	−0.29	−1.25	−1.49	−2.58	−2.32
MEA	+0.00	+0.01	+0.00	+0.01	+0.00	+0.00	+0.00
NEU	+0.02	+0.04	+0.03	+0.02	+0.01	+0.01	+0.01
OAS	+1.50	+2.33	+0.84	−0.20	−0.39	−0.71	−0.53
REF	−0.25	−0.10	−0.11	−0.28	−0.40	−0.32	−0.41
SSA	+0.67	+2.66	+0.63	−0.14	−0.31	−0.92	−0.99
USA	+0.06	+0.11	+0.00	+0.00	−0.16	−0.20	−0.11

Region	2025	H-SSP3	M-SSP2	ML-SSP2	L-SSP2	LN-SSP2	VL-SSP1
World	+2.98	+5.18	+0.91	−2.17	−3.32	−5.80	−5.05

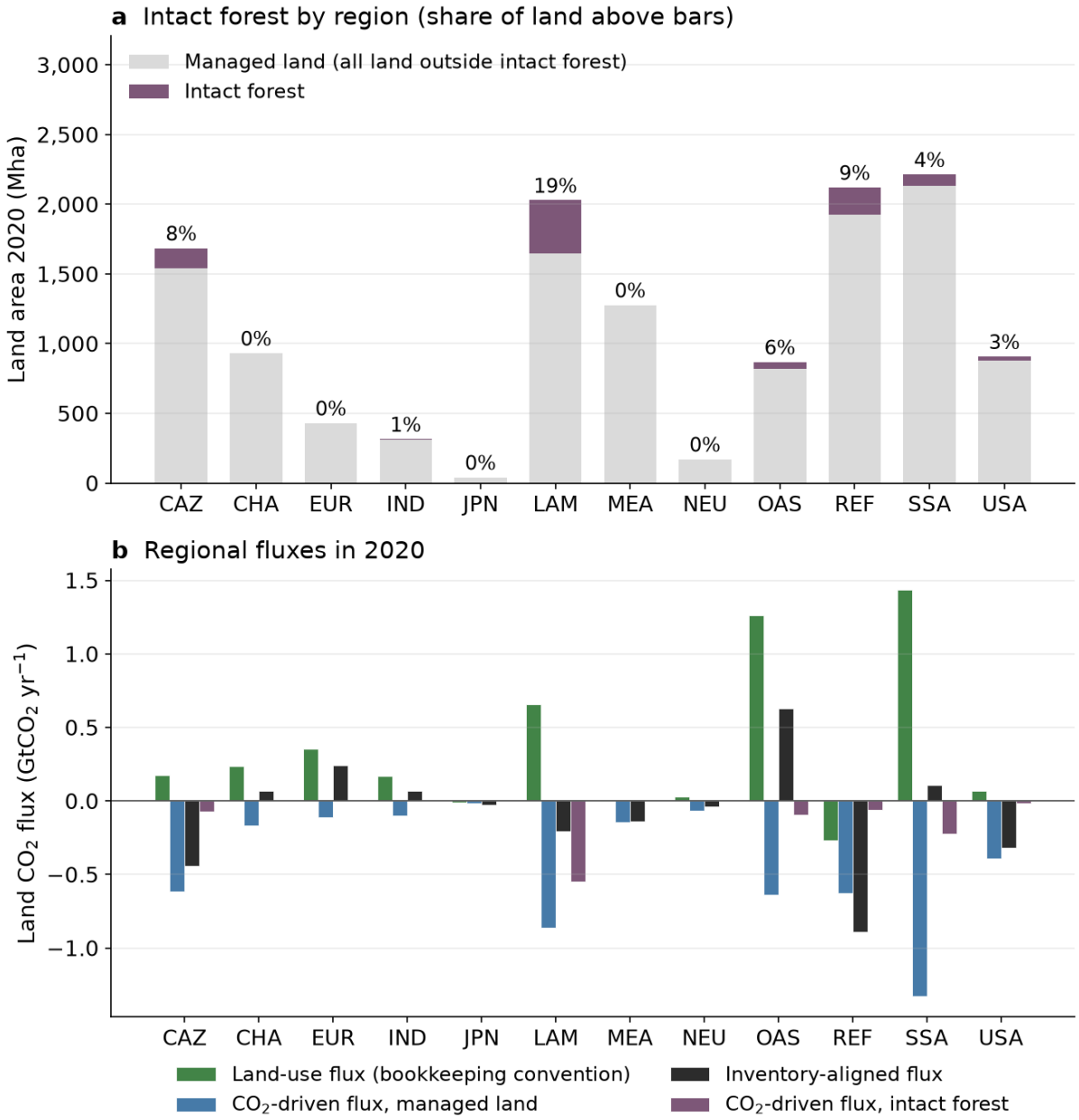
(d) Our estimate of the sink on managed land and on managed forest against the estimates of Grassi et al.[2] and Gidden et al.[3], World

Year	Scenario	our estimate, managed land	our estimate, managed forest	Grassi et al.	ratio, ours to Grassi et al.	Gidden et al. (category)
2020	all	−5.06	−2.15	−5.58	0.91	−3.07 to −3.10 (C2 to C7)
2025	all	−5.32	−2.16	−6.30	0.84	not available
2050	H-SSP3	−6.73	−2.78	−5.42	1.24	−5.53 (C7)
2050	M-SSP2	−6.67	−2.76	−4.67	1.43	−4.75 (C6)
2050	ML-SSP2	−5.42	−2.16	−2.34	2.32	−4.14 (C5)
2050	L-SSP2	−5.48	−2.30	−2.34	2.34	−2.55 (C3)
2050	LN-SSP2	−4.02	−1.69	−1.00	4.02	−2.08 (C2)
2050	VL-SSP1	−4.04	−1.77	−1.00	4.04	−2.08 (C2)
2100	H-SSP3	−7.18	−3.03	−5.76	1.25	−5.33 (C7)
2100	M-SSP2	−6.60	−2.88	−2.89	2.28	−3.16 (C6)
2100	ML-SSP2	−2.59	−1.03	−1.36	1.91	−0.50 (C5)
2100	L-SSP2	−2.63	−1.12	−1.36	1.93	+0.97 (C3)
2100	LN-SSP2	−0.94	−0.70	−1.12	0.84	+2.77 (C2)
2100	VL-SSP1	−0.95	−0.68	−1.12	0.85	+2.77 (C2)

Positive = net emissions, negative = net removals from the atmosphere. (a) The land-use flux divided by the land-use flux plus each estimate of the sink: ours on managed land, on managed forest and with the CO_2-enhanced growth of regrowing forest counted in the sink rather than in land use (Methods), and the estimates of Grassi et al.[2] and Gidden et al.[3] (median and interquartile range of the matched category); above 100% the estimate is a source. (b) Land-use flux plus CO_2-driven flux on managed land (all land outside intact forest), with the national inventories of the LULUCF Data Hub[38] (v3.1.1) averaged over 2016–2020, the five years the 2020 model value covers, and aggregated to the same regions. (c) Land-use flux only. (d) Both external estimates cover managed forest only, so our estimate is also given on managed forest alone: its vegetation, plus soil carbon by that forest's share of each simulation unit's land. On that scope our inventory-aligned flux loses 13% (L-SSP2), 11% (LN-SSP2) and 0% (VL-SSP1) of its peak net removals by 2100, against 27%, 22% and 22% on managed land. The ratio is our estimate on managed land over the estimate of Grassi et al. The estimate of Gidden et al.[3] is the median across the pathways in the AR6 climate category matched to each scenario (Methods), in 2020 the range across these categories; Gidden et al.[3] report no 2025 value. Values up to 2025 are from M-SSP2. Values are inventory-aligned, not inventory-compliant: twelve world regions, one global model's carbon densities and emission factors, no country methodologies.



Extended Data Fig. 4. The LPJmL potential natural vegetation sink on all land (the sink the land would supply if it were entirely natural vegetation) and the CO_2-driven flux on the projected land-use pattern, 2000–2025, against the DGVM ensemble mean SLAND of the GCB[1] (2025 edition) in two forms: as published, corrected for land-cover change (replaced sinks and sources[59]), and uncorrected, on pre-industrial land cover. $GtCO_2\ yr^{-1}$; positive = net emissions, negative = net removals from the atmosphere; the potential sink from 2005, SLAND to 2024.



Extended Data Fig. 5. Intact forest and regional fluxes in 2020. (a) Land area by region (Supplementary Table 1), split into managed land and intact forest, with the intact share of the region's land above the bars. (b) Regional land-use flux, CO_2-driven flux on managed land, their sum, the inventory-aligned flux, and the CO_2-driven flux inside intact forest, in 2020 ($GtCO_2\ yr^{-1}$; positive = net emissions, negative = net removals from the atmosphere), with the bars, colours and labels of Fig. 4. The intact-forest map (Methods) covers 62% of the world's primary forest in 2020: 75% in REF, 71% in LAM, 62% in CAZ, 50% in SSA, 45% in OAS and 43% in USA.

Extended Data Table 4 | Land-related settings that differ between the six scenarios

	H-SSP3	M-SSP2	ML-SSP2	L-SSP2	LN-SSP2	VL-SSP1
Population and income	SSP3	SSP2	SSP2	SSP2	SSP2	SSP1
Climate forcing (MRI-ESM2-0)	ssp460 (RCP6.0)	ssp245 (RCP4.5)	ssp126 (RCP2.6)	ssp126 (RCP2.6)	ssp119 (RCP1.9)	ssp119 (RCP1.9)
Greenhouse gas price on land	none	none	from 2045	from 2035	from 2035	from 2035

	H-SSP3	M-SSP2	ML-SSP2	L-SSP2	LN-SSP2	VL-SSP1
emissions						
Carbon-price AR	none	none	natural regrowth, outside boreal regions	natural regrowth, outside boreal regions	plantations, reward phased in 2040–2050, outside boreal regions	natural regrowth, tropics only; total AR at most 700 Mha
NPi/NDC land policies	NPi, dropped from 2030	NPi	NPi	NDC	NPi	NDC
Protected areas	WDPA, released from 2030	WDPA	WDPA	WDPA	WDPA	WDPA and biodiversity hotspots
Biodiversity constraint	none	none	none	no net BII loss per biome from 2030	no net BII loss per biome from 2050	BII of 0.7 by 2100, from 2030
Diet and food waste	projected	projected	projected	projected	projected	EAT-Lancet diet and food waste at most 20% of demand, 2025–2070
Semi-natural vegetation on cropland	none	none	none	none	none	20% by 2070
Tree cover on cropland	none	none	none	1% by 2050	2% by 2070, plantation growth	3% by 2050
Soil-carbon management on cropland	none	none	none	10% by 2050	20% by 2070	30% by 2050

From the MAgPIE configuration of each scenario. AR, afforestation and reforestation; NPi, national policies implemented; NDC, nationally determined contributions; WDPA, World Database on Protected Areas; BII, Biodiversity Intactness Index. The NPi/NDC land policies set the AR area and the minimum forest and other natural land. Settings shared by all six scenarios are described in Methods.

Extended Data Table 5 | Flux components mapped to IPCC land-use categories, World, 2020

Category and model component	2020
Forest land remaining forest land, land use (secondary-forest regrowth, wood harvest, plantation regrowth and shifting cultivation)	+0.92
Land converted to forest land, afforestation and reforestation regrowth (carbon-price and NPi/NDC)	−0.37
Forest land converted to other land, deforestation	+1.42
Cropland and grassland, land use (soil carbon change, cropland tree cover)	+0.19
Drained peatland net of rewetting (organic soils, reported by inventories under the draining land use)	+1.42
Harvested wood products, storage minus release	−0.27
Other natural land, land use (conversion and regrowth; vegetated, not the IPCC Other land)	+0.82
Residual, land use	−0.02

Category and model component	2020
Managed land, CO_2-driven, vegetation	−3.12
Managed land, CO_2-driven, soils (soil pool times managed-land area share)	−1.94
Sum of managed-land categories (inventory-aligned)	−0.95
Intact forest, CO_2-driven, vegetation (not in inventories)	−0.79
Intact forest, CO_2-driven, soils (not in inventories)	−0.23
Total net land flux	−1.97

LPJmL-MAgPIE-REMIND, M-SSP2; $GtCO_2\ yr^{-1}$; positive = emissions, negative = removals from the atmosphere. Land converted to forest land holds removals only and forest land converted to other land emissions only; the other rows and the sums are net. Land-use components are from the MAgPIE land-use-change accounting; CO_2-driven components are the LPJmL density change, split between managed land and intact forest (Methods) with soils as one pool allocated by area share. Harvested wood products (storage minus release) are part of the land-use flux. For comparison, the 2025 release of the LULUCF Data Hub[38] gives World LULUCF net removals of 3.8 $GtCO_2\ yr^{-1}$ for 2016–2020, the five years the 2020 model value covers. The compilation of Grassi et al.[14] gives net removals of 1.9 $GtCO_2\ yr^{-1}$ for 2000–2020 and, for its bookkeeping models, net emissions of 4.8 $GtCO_2\ yr^{-1}$.

5. References

1. Friedlingstein, P. et al. Global Carbon Budget 2025. *Earth Syst. Sci. Data* **18**, 3211–3288 (2026). https://doi.org/10.5194/essd-18-3211-2026
2. Grassi, G. et al. Critical adjustment of land mitigation pathways for assessing countries' climate progress. *Nat. Clim. Change* **11**, 425–434 (2021). https://doi.org/10.1038/s41558-021-01033-6
3. Gidden, M. J. et al. Aligning climate scenarios to emissions inventories shifts global benchmarks. *Nature* **624**, 102–108 (2023). https://doi.org/10.1038/s41586-023-06724-y
4. Canadell, J. G. et al. Global Carbon and other Biogeochemical Cycles and Feedbacks. In *Climate Change 2021: The Physical Science Basis* 673–816 (Cambridge Univ. Press, 2021). https://doi.org/10.1017/9781009157896.007
5. Koven, C. D. et al. Multi-century dynamics of the climate and carbon cycle under both high and net negative emissions scenarios. *Earth Syst. Dyn.* **13**, 885–909 (2022). https://doi.org/10.5194/esd-13-885-2022
6. Park, S.-W. & Kug, J.-S. A decline in atmospheric CO_2 levels under negative emissions may enhance carbon retention in the terrestrial biosphere. *Commun. Earth Environ.* **3**, 289 (2022). https://doi.org/10.1038/s43247-022-00621-4
7. Sanderson, B. M. et al. flat10MIP: an emissions-driven experiment to diagnose the climate response to positive, zero and negative CO_2 emissions. *Geosci. Model Dev.* **18**, 5699–5724 (2025). https://doi.org/10.5194/gmd-18-5699-2025
8. Popp, A. et al. Land-use, emissions, and sustainability futures across ScenarioMIP-CMIP7: a multi-model assessment. Preprint at https://doi.org/10.5281/zenodo.22304777 (2026).
9. Krause, A. et al. Large uncertainty in carbon uptake potential of land-based climate-change mitigation efforts. *Glob. Change Biol.* **24**, 3025–3038 (2018). https://doi.org/10.1111/gcb.14144
10. Harper, A. B. et al. Land-use emissions play a critical role in land-based mitigation for Paris climate targets. *Nat. Commun.* **9**, 2938 (2018). https://doi.org/10.1038/s41467-018-05340-z
11. Melnikova, I. et al. Impact of bioenergy crop expansion on climate–carbon cycle feedbacks in overshoot scenarios. *Earth Syst. Dyn.* **13**, 779–794 (2022). https://doi.org/10.5194/esd-13-779-2022
12. Pongratz, J., Reick, C. H., Houghton, R. A. & House, J. I. Terminology as a key uncertainty in net land use and land cover change carbon flux estimates. *Earth Syst. Dyn.* **5**, 177–195 (2014). https://doi.org/10.5194/esd-5-177-2014
13. Grassi, G. et al. Reconciling global-model estimates and country reporting of anthropogenic forest CO_2 sinks. *Nat. Clim. Change* **8**, 914–920 (2018). https://doi.org/10.1038/s41558-018-0283-x
14. Grassi, G. et al. Harmonising the land-use flux estimates of global models and national inventories for 2000–2020. *Earth Syst. Sci. Data* **15**, 1093–1114 (2023). https://doi.org/10.5194/essd-15-1093-2023

15. Schwingshackl, C. et al. Differences in land-based mitigation estimates reconciled by separating natural and land-use CO_2 fluxes at the country level. *One Earth* **5**, 1367–1376 (2022). https://doi.org/10.1016/j.oneear.2022.11.009
16. Obermeier, W. A. et al. Differences and uncertainties in land-use CO_2 flux estimates. *Nat. Rev. Earth Environ.* **6**, 747–766 (2025). https://doi.org/10.1038/s43017-025-00730-6
17. Sanderson, B. M. et al. The need for carbon-emissions-driven climate projections in CMIP7. *Geosci. Model Dev.* **17**, 8141–8172 (2024). https://doi.org/10.5194/gmd-17-8141-2024
18. Van Vuuren, D. P. et al. The Scenario Model Intercomparison Project for CMIP7 (ScenarioMIP-CMIP7). *Geosci. Model Dev.* **19**, 2627–2656 (2026). https://doi.org/10.5194/gmd-19-2627-2026
19. Dietrich, J. P. et al. MAgPIE - An Open Source land-use modeling framework, version 4.11.0. Zenodo https://doi.org/10.5281/zenodo.15862748 (2025).
20. Luderer, G. et al. REMIND - REgional Model of INvestments and Development, version 3.5.2. Zenodo https://doi.org/10.5281/zenodo.17210406 (2025).
21. Schaphoff, S. et al. LPJmL4 – a dynamic global vegetation model with managed land – Part 1: Model description. *Geosci. Model Dev.* **11**, 1343–1375 (2018). https://doi.org/10.5194/gmd-11-1343-2018
22. von Bloh, W. et al. Implementing the nitrogen cycle into the dynamic global vegetation, hydrology, and crop growth model LPJmL (version 5.0). *Geosci. Model Dev.* **11**, 2789–2812 (2018). https://doi.org/10.5194/gmd-11-2789-2018
23. Lange, S. Trend-preserving bias adjustment and statistical downscaling with ISIMIP3BASD (v1.0). *Geosci. Model Dev.* **12**, 3055–3070 (2019). https://doi.org/10.5194/gmd-12-3055-2019
24. Molina Bacca, E. J. et al. Future land-use pattern projections and their differences within the ISIMIP3b framework. *Earth Syst. Dyn.* **16**, 753–801 (2025). https://doi.org/10.5194/esd-16-753-2025
25. Potapov, P. et al. The last frontiers of wilderness: Tracking loss of intact forest landscapes from 2000 to 2013. *Sci. Adv.* **3**, e1600821 (2017). https://doi.org/10.1126/sciadv.1600821
26. Braakhekke, M. C. et al. Modeling forest plantations for carbon uptake with the LPJmL dynamic global vegetation model. *Earth Syst. Dyn.* **10**, 617–630 (2019). https://doi.org/10.5194/esd-10-617-2019
27. Bodirsky, B. L. et al. A food system transformation pathway reconciles 1.5 °C global warming with improved health, environment and social inclusion. *Nat. Food* **6**, 1133–1152 (2025). https://doi.org/10.1038/s43016-025-01268-y
28. Beier, F. D. et al. Planetary boundaries under a land-based climate change mitigation scenario with a food demand transformation: a modelling study. *Lancet Planet. Health* **9**, 101249 (2025). https://doi.org/10.1016/S2542-5196(25)00087-7
29. Grassi, G. et al. Improving land-use emission estimates under the Paris Agreement. *Nat. Sustain.* **8**, 579–581 (2025). https://doi.org/10.1038/s41893-025-01565-1
30. Humpenöder, F. et al. Land-use and carbon cycle responses to moderate climate change: implications for land-based mitigation? *Environ. Sci. Technol.* **49**, 6731–6739 (2015). https://doi.org/10.1021/es506201r
31. Chini, L. & Hurtt, G. Land-Use Harmonization 3 Future Scenario VL v1.1 for ScenarioMIP (LUH3-VL v1.1). Zenodo https://doi.org/10.5281/zenodo.19353397 (2026).
32. Grassi, G. et al. The key role of forests in meeting climate targets requires science for credible mitigation. *Nat. Clim. Change* **7**, 220–226 (2017). https://doi.org/10.1038/nclimate3227
33. Fyson, C. L. & Jeffery, M. L. Ambiguity in the Land Use Component of Mitigation Contributions Toward the Paris Agreement Goals. *Earth's Future* **7**, 873–891 (2019). https://doi.org/10.1029/2019ef001190
34. Windisch, M. G. et al. Hedging our bet on forest permanence for the economic viability of climate targets. *Nat. Commun.* **16**, 2460 (2025). https://doi.org/10.1038/s41467-025-57607-x
35. Anderegg, W. R. L. et al. Climate-driven risks to the climate mitigation potential of forests. *Science* **368**, eaaz7005 (2020). https://doi.org/10.1126/science.aaz7005
36. Prütz, R. et al. Biodiversity implications of land-intensive carbon dioxide removal. *Nat. Clim. Change* **16**, 155–163 (2026). https://doi.org/10.1038/s41558-026-02557-5
37. Grassi, G. et al. Harmonising the land-use flux estimates of global models and national inventories for 2000–2020: background data. Zenodo https://doi.org/10.5281/zenodo.7650360 (2023).
38. Melo, J. et al. The LULUCF Data Hub: translating global land use emissions estimates into the national GHG inventory framework, version 3.1.1. Zenodo https://doi.org/10.5281/zenodo.18352395 (2026).
39. Dietrich, J. P. et al. MAgPIE 4 – a modular open-source framework for modeling global land systems. *Geosci. Model Dev.* **12**, 1299–1317 (2019). https://doi.org/10.5194/gmd-12-1299-2019

40. Schaphoff, S. et al. LPJmL4 – a dynamic global vegetation model with managed land – Part 2: Model evaluation. *Geosci. Model Dev.* **11**, 1377–1403 (2018). https://doi.org/10.5194/gmd-11-1377-2018
41. Sitch, S. et al. Evaluation of ecosystem dynamics, plant geography and terrestrial carbon cycling in the LPJ dynamic global vegetation model. *Glob. Change Biol.* **9**, 161–185 (2003). https://doi.org/10.1046/j.1365-2486.2003.00569.x
42. Bondeau, A. et al. Modelling the role of agriculture for the 20th century global terrestrial carbon balance. *Glob. Change Biol.* **13**, 679–706 (2007). https://doi.org/10.1111/j.1365-2486.2006.01305.x
43. Dietrich, J. P. et al. madrat: May All Data be Reproducible and Transparent (MADRaT), version 3.30. Zenodo https://doi.org/10.5281/zenodo.7886302 (2023).
44. Mishra, A. et al. Estimating global land system impacts of timber plantations using MAgPIE 4.3.5. *Geosci. Model Dev.* **14**, 6467–6494 (2021). https://doi.org/10.5194/gmd-14-6467-2021
45. Karstens, K. et al. Management-induced changes in soil organic carbon on global croplands. *Biogeosciences* **19**, 5125–5149 (2022). https://doi.org/10.5194/bg-19-5125-2022
46. Humpenöder, F. et al. Peatland protection and restoration are key for climate change mitigation. *Environ. Res. Lett.* **15**, 104093 (2020). https://doi.org/10.1088/1748-9326/abae2a
47. Tiemeyer, B. et al. A new methodology for organic soils in national greenhouse gas inventories: Data synthesis, derivation and application. *Ecol. Indic.* **109**, 105838 (2020). https://doi.org/10.1016/j.ecolind.2019.105838
48. Baumstark, L. et al. REMIND2.1: transformation and innovation dynamics of the energy-economic system within climate and sustainability limits. *Geosci. Model Dev.* **14**, 6571–6603 (2021). https://doi.org/10.5194/gmd-14-6571-2021
49. O'Neill, B. C. et al. The roads ahead: Narratives for shared socioeconomic pathways describing world futures in the 21st century. *Glob. Environ. Change* **42**, 169–180 (2017). https://doi.org/10.1016/j.gloenvcha.2015.01.004
50. Meehl, G. A. et al. Context for interpreting equilibrium climate sensitivity and transient climate response from the CMIP6 Earth system models. *Sci. Adv.* **6**, eaba1981 (2020). https://doi.org/10.1126/sciadv.aba1981
51. Humpenöder, F. et al. Investigating afforestation and bioenergy CCS as climate change mitigation strategies. *Environ. Res. Lett.* **9**, 064029 (2014). https://doi.org/10.1088/1748-9326/9/6/064029
52. Walker, A. P. et al. Integrating the evidence for a terrestrial carbon sink caused by increasing atmospheric CO_2. *New Phytol.* **229**, 2413–2445 (2021). https://doi.org/10.1111/nph.16866
53. Melo, J. et al. The LULUCF Data Hub: translating global land use emissions estimates into the national GHG inventory framework. Preprint at https://doi.org/10.5194/essd-2025-631 (2026).
54. IPCC. 2006 IPCC Guidelines for National Greenhouse Gas Inventories, Prepared by the National Greenhouse Gas Inventories Programme. Volume 4: Agriculture, Forestry and Other Land Use (eds Eggleston, H. S. et al.) (IGES, 2006).
55. Hansis, E., Davis, S. J. & Pongratz, J. Relevance of methodological choices for accounting of land use change carbon fluxes. *Glob. Biogeochem. Cycles* **29**, 1230–1246 (2015). https://doi.org/10.1002/2014gb004997
56. Gasser, T. et al. Historical CO_2 emissions from land use and land cover change and their uncertainty. *Biogeosciences* **17**, 4075–4101 (2020). https://doi.org/10.5194/bg-17-4075-2020
57. Qin, Z. et al. Global spatially explicit carbon emissions from land-use change over the past six decades (1961–2020). *One Earth* **7**, 835–847 (2024). https://doi.org/10.1016/j.oneear.2024.04.002
58. Walker, A. P. et al. Harmonizing direct and indirect anthropogenic land carbon fluxes indicates a substantial missing sink in the global carbon budget since the early 20th century. *Plants People Planet* **7**, 1123–1136 (2025). https://doi.org/10.1002/ppp3.10619
59. O'Sullivan, M. et al. An improved approach to estimate the natural land carbon sink. *npj Clim. Atmos. Sci.* **9**, 29 (2026). https://doi.org/10.1038/s41612-025-01302-7
60. Global Carbon Project. Supplemental data of Global Carbon Budget 2025. ICOS Carbon Portal https://doi.org/10.18160/GCP-2025 (2026).
61. Randerson, J. T. et al. The weak land carbon sink hypothesis. *Sci. Adv.* **11**, eadr5489 (2025). https://doi.org/10.1126/sciadv.adr5489
62. Gidden, M. et al. Dataset for Gidden et al. 2023 Updated AR6 Mitigation Benchmarks using National Emissions Inventories, version 2. Zenodo https://doi.org/10.5281/zenodo.10158920 (2023).

63. Kikstra, J. S. et al. The IPCC Sixth Assessment Report WGIII climate assessment of mitigation pathways: from emissions to global temperatures. *Geosci. Model Dev.* **15**, 9075–9109 (2022). https://doi.org/10.5194/gmd-15-9075-2022
64. Humpenöder, F. et al. Data and code for: Net zero weakens the land carbon sink but land-based mitigation compensates, version 1.0. Zenodo https://doi.org/10.5281/zenodo.23448553 (2026).
65. Obermeier, W. A. et al. Modelled land use and land cover change emissions – a spatio-temporal comparison of different approaches. *Earth Syst. Dyn.* **12**, 635–670 (2021). https://doi.org/10.5194/esd-12-635-2021
66. Brovkin, V. et al. Effect of anthropogenic land-use and land-cover changes on climate and land carbon storage in CMIP5 projections for the twenty-first century. *J. Clim.* **26**, 6859–6881 (2013). https://doi.org/10.1175/JCLI-D-12-00623.1

6. Data and code availability

Data availability

The data behind every figure and table, the MAgPIE, REMIND and MAGICC7 output of the six scenarios restricted to the variables this study uses, and their run configurations are archived on Zenodo (https://doi.org/10.5281/zenodo.23448553)[64]. The six scenarios run without climate impacts, the comparison set of the Discussion and Methods, are the REMIND-MAgPIE submissions to ScenarioMIP[8] and are available in the ScenarioMIP database (https://scenariomip.apps.ece.iiasa.ac.at/); the variables used for the comparison are included in the same archive. Full reports with further variables are available from the corresponding author upon request. The benchmark data are available from the LULUCF Data Hub[38], the GCB data release[60], Grassi et al.[37] and Gidden et al.[62].

Code availability

The scenarios were run with MAgPIE 4.11.0 (https://doi.org/10.5281/zenodo.15862748) and REMIND 3.5.2 (https://doi.org/10.5281/zenodo.17210406) on input-data revision 4.119, generated with madrat (https://doi.org/10.5281/zenodo.7886302), using inputs from LPJmL 4.0.004 for natural vegetation and LPJmL 5.2.001 for crops and pasture. The reports were generated with magpie4 2.41.0, the R package that produces MAgPIE's standard reporting, in the version used for the ScenarioMIP runs, extended by the intact-forest split and the inventory-aligned flux. This extension, the R data pipeline and the Python scripts for the benchmark data and the figures are archived with the data on Zenodo (https://doi.org/10.5281/zenodo.23448553)[64]. The archive also holds the REMIND output that drove the final MAgPIE iteration of each scenario, so these iterations can be rerun without REMIND. MAgPIE, REMIND, LPJmL, magpie4 and madrat are open source (https://github.com/magpiemodel/magpie, https://github.com/remindmodel/remind, https://github.com/PIK-LPJmL/LPJmL, https://github.com/pik-piam/magpie4, https://github.com/pik-piam/madrat).

7. Acknowledgements

We thank Giacomo Grassi for providing the adjustment factors of Grassi et al. for the ten IPCC AR6 regions, and Thomas Gasser for his advice on the decomposition of the carbon stock change into area and density terms.

8. Funding

F.B. was funded by the European Union's Horizon Europe programme under grant agreement no. 101183367 (NEWPATHWAYS), and M.S. by the NGFS VI project (grant no. 94196b).

9. Author contributions

F.H. designed the study, ran the coupled scenarios, analysed the results, made the figures and wrote the manuscript. M.C. developed the flux decomposition and its data pipeline. J.H. provided the LPJmL simulations. K.K. and F.B. prepared the LPJmL outputs as MAgPIE inputs. J.P.D. ensured model and code quality. M.S. supported the MAgPIE part of the coupled scenarios. N.B. and G.A. supported the REMIND part of the coupled scenarios. L.K.-S. coordinated the ScenarioMIP process at PIK and ran the REMIND-MAgPIE scenarios without climate impacts submitted to the ScenarioMIP database. A.P., H.L.-C. and E.K. supervised the work. All authors contributed to the LPJmL-MAgPIE-REMIND framework or to the ScenarioMIP scenarios and provided feedback on the manuscript.

10. Competing interests

The authors declare no competing interests.

Supplementary Files

This is a list of supplementary files associated with this preprint. Click to download.

- SUPPLEMENTARYINFORMATION.docx