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May 23, 2023

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Aligning IPCC scenarios to national land emissions inventories shifts global mitigation benchmarks

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Abstract:

Taking stock of global progress towards achieving the Paris Agreement requires consistently measuring aggregate national action against modelled mitigation pathways[1]. However, national GHG inventories (NGHGIs) and scientific estimates follow different accounting conventions for land-based carbon fluxes resulting in a large difference in current emission estimates[2,3], a gap which will evolve over time. Using state-of-the-art methodologies[4] and a land carbon cycle emulator[5], we establish a first estimate harmonizing IPCC-assessed emissions pathways with NGHGIs. We find that key global mitigation benchmarks such as net-zero timings or cumulative emissions to net-zero CO_2 appear more ambitious, that needed carbon removals from enhanced anthropogenic land-based sinks can be masked by weakened removals from natural processes, and that land-based carbon fluxes could ultimately become a source of emissions by 2100, when assessing scenarios using NGHGI conventions. Our results can inform the Global Stocktake[6] and highlight the need to enhance communication between the scientific and policy communities to enable a more robust interpretation of global scenarios for policy making in the future.

Main Text:

The 2021 UN climate change conference (COP26) marked a shift in the focus of climate policy from making pledges to implementation towards the long-term climate goal. Under the Paris Agreement, collective climate progress will be assessed through periodic Global Stocktakes (GSTs) in light of the best available science. In spring 2022 the first GST was launched[7] including a series of Technical Dialogues, which continued through COP27 in order to establish evaluation mechanisms amongst parties. Comparing current emissions trends from national greenhouse gas inventories and future targets in a collective benchmarking effort rooted in the best available mitigation science will be key for a rigorous, precedent-setting first GST and overall success of the Paris Agreement[6].

Countries have gradually increased the ambition of their national targets in response to the latest IPCC report findings[1,8]. Notably, a number of nations made long-term net-zero emission commitments in the run up to COP26[9], which for the first time brought the Paris Agreement long-term temperature goal within striking distance, although much of the assessed temperature reductions arose from long-term and non-binding promises rather than immediate climate action[10–12]. Global climate scenarios show that both deep near-term emissions reductions as well as enhancing anthropogenic land-based carbon sinks are needed to achieve net-zero emissions while also meeting the Paris temperature goal[13,14].

A key discrepancy exists, however, in how model-based scientific studies and national Greenhouse Gas Inventories (NGHGIs) account for the role of anthropogenic land-based carbon fluxes[4,15,16], with national inventories incorporating a broader scope of removals[2]. Prior studies[2–4] have quantified the magnitude of this difference in land-based carbon flux accounting at approximately 5.5-6.7 Gt CO_2 yr^{-1}. Critically, this conceptual difference hinders the comparability between aggregate targets set by countries and future mitigation benchmarks.

While this problem has been acknowledged in the most recent IPCC assessment[17] and raised by parties during the GST[18], the impact of this discrepancy on national and global benchmarks measuring the progress towards the goals of the Paris Agreement is still not well understood.

Here, we bridge this knowledge gap by aligning land-based CO_2 fluxes of scenarios assessed by the IPCC in its Sixth Assessment Report (AR6) with national GHG emissions inventories. We develop a novel approach to estimate large-quantity scenario ensembles of land-based fluxes consistent with national inventories building on previous efforts[4] and provide a translation tool aligning scenarios and national inventories for use in near-term policy making. We find that it is critical for nations to measure their collective progress in the GST against IPCC-consistent benchmarks using the same definitions for reporting land-based carbon fluxes in a like-for-like manner. Failing to do so means that key mitigation benchmarks can be erroneously estimated, with global net-zero CO_2 or GHG timings shifting by as much as 5 years in 1.5°C scenarios.

As such, our results also highlight the potential pitfalls of the dependence on land sinks in countries' climate target setting. We find that the gap between fluxes computed in each accounting framework reduces over time, confirming the robustness of the previously identified trend from a small set of scenarios[4]. However, we also observe that net land-based fluxes and removals are likely to be smaller under strong mitigation efforts than under current policies using the current NGHGI accounting framework, potentially masking needed carbon removals from land. Because of this, we find that land-use could become a net emitter of carbon at the end of the century under stringent mitigation pathways due to associated environmental feedbacks. Care thus needs to be taken when developing climate targets which depend strongly on land-based removals, which are currently proliferating in national long-term mitigation strategies[19], as current benefits from a carbon sink could translate to future mitigation burdens if land becomes a net source of CO_2.

Aligning Global Pathways with National Inventories

Global mitigation pathways play a critical role in informing climate policies and targets that are in line with international climate goals. These pathways are typically generated by integrated assessment models (IAMs) which capture transitions in anthropogenic energy and land-use systems consistent with stated global climate policy objectives. It is not possible to directly compare IAM results with national inventories used to assess progress under the UNFCCC, however, due to differences in how land-based fluxes are accounted.

Because it is practically difficult to separate anthropogenic and natural fluxes through observations, national inventories follow IPCC reporting conventions for land-use, land-use change, and forestry (LULUCF) emissions[20] and separate anthropogenic (i.e., managed) and natural fluxes using an area-based approach[21] with managed land-areas determined by individual nations[22]. Emissions scenarios on the other hand are calibrated against data from detailed global carbon cycle models that model and account for natural from anthropogenic fluxes separately by design[5,23,24]. IAM pathways mainly include direct human-induced emissions and removals (e.g., land use changes, harvest, regrowth), while NGHGIs submitted by countries to the UNFCCC generally include a wider definition of managed land area as well as most of the indirect removals on that land caused by environmental changes[2,25] (e.g., the CO_2 fertilization effect). As a result, best estimates of present-day anthropogenic fluxes from bookkeeping models used by IAMs indicate that the land sector is a net source of emissions[3], whereas NGHGIs collectively report it as a net sink[26], resulting in fundamentally different perspectives of the role of land-based removals at present and in the future when viewed in isolation.

To disentangle the direct and indirect components of land-based carbon fluxes and better harmonize removals with definitions used in NGHGIs, we use a reduced complexity climate model with explicit treatment of the land-use sector, OSCAR[5], one of the models used by the Global Carbon Project[3]. Of the 1202 pathways that passed IPCC vetting, 914 provide sufficient land-use change data to allow us to fill this information gap and enable alignment between pathways and inventories. We find an alignment factor of 4.4 ± 1.0 Gt CO_2 yr^{-1} average over the 2000-2020 time period, which is in line with existing estimates[2,5]. A full description of the calculation approach is provided in the Methods.

Across both 1.5°C and 2°C scenarios (Fig. 1A, definitions in Methods), LULUCF emissions pathways aligned with NGHGIs show a strong increase in the total land sink until around mid-century. However, the 'NGHGI alignment gap' (Fig. 1B) decreases over this period, converging in the 2050-2060s for 1.5°C scenarios and 2070s-2080s for 2°C scenarios. The convergence is primarily a result of the simulated stabilization and then decrease of the CO_2-fertilization effect as well as background climate warming reducing the overall effectiveness of the land sink, which in turn affects the indirect removals considered by NGHGIs. These dynamics lead to land-based emissions reversing their downward trend in most NGHGI-aligned scenarios by mid-century, and result in the LULUCF sector becoming a net-source of emissions by 2100 in about 25% of both 1.5°C and 2°C scenarios.

Global and Regional Ambition Implications

The downward adjustment of emission pathways to align with national inventories in combination with the changing dynamics of indirect LULUCF removals results in revisions to emissions benchmarks derived from scenarios (Supplementary Table 1, Supplementary Figure 1). Taken together, we find these effects advance the time by when net-zero CO_2 emissions in scenarios are achieved by around 2-5 years for both 1.5°C and 2°C scenarios (Fig. 2A), and 2030 emission reductions relative to 2020 are enhanced by about 5 percentage points for both pathway categories. When incorporating the additional land removals considered by NGHGIs, the assessed cumulative net CO_2 emissions to global net-zero CO_2 also decreases systematically by 15-18% for both 1.5°C and 2°C scenarios (Fig. 2B).

Although key emissions benchmarks appear to be more ambitious when measured in the same methodological framework as national inventories, this does not imply that the amount of global effort to achieve key climate outcomes needs to increase. First and foremost, all land-use fluxes (direct and indirect) are included in the physical climate models used by the IPCC, meaning the temperature outcomes of each pathway is the same even if flux components are accounted for differently by models and inventories. When considering the additional land sink in national inventories, multiple dynamics interact that affect the above mitigation outcomes, including the change in historical emission baseline, the enhanced anthropogenic land sink compared to what was reported by IAMs, and declining sequestration in that additional sink.

The majority of countries use the net land CO_2 flux reported in NGHGIs as a basis to assess compliance with their NDCs and track progress of their long-term emission reduction strategies under the Paris Agreement[2,27,28] as well as prior climate pacts[29]. Aligning benchmarks from global pathways to NGHGIs is critical, therefore, to compare aggregate national targets with emission levels from scenarios assessed by the IPCC. Historically, NDCs have been compared to scenario-based estimates of needed emissions reductions by either aligning pathways to NGHGIs with simple offsetting methods[1] or excluding LULUCF emissions entirely due to definitional issues[9] and large uncertainties in LULUCF-based NDC quantification[27]. Comparing our results to one of the most recent aggregate NDC estimates[1] adjusted for base year differences between models and inventories (Fig. 3A, see Methods), we find that the gap between unconditional NDCs and a median 2°C outcome is approximately 18% larger when using NGHGI-aligned pathways, while our assessment of the gap between unconditional NDCs and a median 1.5°C outcome is around 4% smaller (Supplementary Figure 2). Notably, under the NGHGIs reporting framework, estimates of needed progress in anthropogenic emissions reductions risk being masked by natural sink enhancement in the near term. Our results highlight the need to incorporate a dynamic estimation of this correction term for other mitigation benchmarks, because the impact of this correction term depends critically on the strength of mitigation in the underlying IAM pathway, which explains our finding a reduction in the 1.5°C gap versus an increase in the assessed 2°C gap above.

Harmonizing pathways to inventories, i.e., including indirect carbon removals and different definitions of managed forests, can affect how equitable mitigation action is understood, as around ~60% of the historical NGHGI adjustment falls in Non-Annex I countries[26]. From a global perspective, there is almost no change in effort for 1.5°C pathways - that is, the difference in decadal emission reductions between the two accounting frameworks is small. Regionally, though, developed countries see a modest increase in 2030 emissions reductions when adjusting pathways to NGHGIs, whereas most developing regions see a modest decrease (Fig. 3B, Supplementary Figure 3). In 2°C pathways, the NGHGI adjustment results in more stringent 2020-2030 emissions reductions globally compared to the unadjusted pathways. This strengthening most directly affects emissions reductions in regions with large, forested area such as Latin America and Russia, while also decreasing projected emissions reductions in the OECD and Asia, after accounting for indirect effects. The African region sees on average marginally weakened emissions reductions by 2030. Our results span both positive and negative values across many regions, indicating strong uncertainty in changes to regional mitigation from incorporating NGHGI-based removals, but also highlight the potential complexities when setting both equitable and ambitious climate targets based on national inventories.

Implications for Land-Based Carbon Removals

Scenarios assessed by the IPCC in AR6 show that a combination of deep near-term gross emissions reductions and medium-term net carbon removal from the atmosphere are needed to reach net-zero and eventually net-negative CO_2 emissions to limit warming in line with the Paris Agreement temperature goal. In most 1.5°C and 2°C pathways, hundreds of gigatonnes of CO_2 are removed over the course of this century, with ultimate levels dependent on the strength of near-term mitigation action[17]. However, scenarios lacked key information needed to estimate land-based removals (c.f., footnote 53 in ref.[17]) and to align their LULUCF projections with NGHGIs. Because our assessment explicitly accounts for carbon stored in land reservoirs, we are also able to account for land-based removals consistently across scenarios to estimate total land-based carbon dioxide removal (CDR).

We find that the role of different CDR options transitions strongly over the course of the century in mitigation pathways. Scenarios see a marked increase by 2030 in CDR from the LULUCF sector, resulting in around 30% higher removals of CO_2 by 2030 compared to 2020 levels in 1.5°C pathways and 20% higher removals in 2°C pathways (Fig. 4A). Taken together with technical CDR options, models deploy 2.8 [1.1-3.4] Gt CO_2 yr^{-1} (interquartile range) and 1.2 [0.9-3.1] Gt CO_2 yr^{-1} additional CDR between 2020 and 2030 in 1.5°C and 2°C pathways, respectively. By 2030, 85-100% of total carbon removals are derived from land-based sinks compared to accounting for nearly 100% at present (Fig. 4B). By 2100, land-based removals account for about 20% [0%-65%] of total net annual carbon removals.

While deep mitigation scenarios of the IPCC show a significant and continued dependence on land-management-based removals over the whole century, LULUCF removals of the same pathways aligned to NGHGIs would peak by mid-century and decline thereafter. Over time, the reduced effectiveness of indirect LULUCF removals counterbalances gains from direct removals[30] (Supplementary Figure 4), maintaining overall direct and indirect removals at around

6-7 Gt CO_2 yr^{-1} by mid-century, with 1.5°C pathways cumulatively sequestering around 20% more carbon from direct removals but 20% less from indirect removals compared to 2°C pathways over that period (Supplementary Figure 5). We find that considering the changing dynamics of indirect carbon removals included in NGHGIs can dramatically change the estimated carbon removals on land over time. While 1.5°C scenarios display a growth in total assessed net land removal by 2030 (Fig. 4C), current policy scenarios aligned with NGHGIs approximately double removals compared to 1.5°C and 2°C scenarios by midcentury, owing to the increasing strength of indirect removals (through, e.g., strong carbon fertilization) (Fig. 4D). Thus, while the addition of a larger “managed land” sink may reduce reported levels of present-day national emissions in some cases, maintaining the strength of the carbon sink on these land areas may pose a fundamental challenge in the long term. In other words, the future effort needed to achieve or maintain net-zero economy-wide emissions would be underestimated using present-day NGHGI accounting methods as the indirect contribution to land sinks lose efficacy and eventually become a net source of emissions.

Balancing Practicalities with Policy Guidance

Here, we reanalyze LULUCF emissions consistent with NGHGIs for all IPCC-assessed scenarios which provide sufficient information to do so. It is important to stress that the adjustments were derived by estimates from a single model and arise from a reallocation of indirect carbon fluxes caused by environmental changes to anthropogenic emissions. Our results do not change any climate outcome or mitigation benchmark produced by the IPCC, but rather provide a translational lens to view those outcomes from the perspective of national emissions reporting frameworks. For example, the fact that we find net-zero timings on average advance by up to 5 years compared to the original benchmarks does not imply that 5 years have been lost in the race to net-zero, but rather that following the reporting conventions for natural sinks used by parties to the UNFCCC results in net-zero needing to be reached 5 years earlier to match modelled benchmarks. This ‘new’ net-zero year, however, occurs prior to the climatological milestone of balancing of direct sources and sinks of CO_2 under the accounting framework of integrated models that results in climate stabilisation. Understanding and addressing how these different frameworks can be mutually interpreted is a fundamental challenge for evaluating progress towards the Paris Agreement, given the reality that carbon removals from anthropogenic and natural land-based processes cannot be estimated separately by NGHGIs , which are typically based on direct observations.

The policy and scientific communities can take steps to meet this challenge by reconciling terms, definitions, and estimates of land-based CO_2 fluxes in three concrete ways. First, targets can be formulated separately for gross CO_2 emission reductions without LULUCF, net land-based removals, engineered carbon removals, and non-CO_2 GHG reductions, allowing for nations to clearly define their expected contributions and to measure progress in each domain separately. While most targets are intentionally vague to allow parties to develop bespoke, flexible mitigation approaches based on their respective capabilities and national circumstances, providing additional clarity is critical to enable translation between modelled pathways and aggregate national targets. Second, nations can clarify the nature of their deforestation pledges, since direct and indirect carbon fluxes vary greatly in different forest types[31]. Third, modelling teams can provide their individual assumptions for the NGHGI correction and estimation of national land-use targets as part of their standard output. Future IPCC assessments can use such outcomes to vet scenarios by, e.g., establishing an acceptable range for present-day direct and indirect contributions to LULUCF emissions or evaluating the land-use component of emissions in policy pathways. Indeed, some teams have begun reporting their alignment outcomes directly from their land-use subcomponents[32]. It is critical that such changes be made as part of a community effort to avoid double counting emissions reductions due to realignment to NGHGIs.

Science and policy processes continue to co-evolve, informing one another. It is clear that a full reconciliation of the conceptual discrepancies outlined here will take time. However, the first iteration of the Global Stocktake will be completed by 2023, necessitating earlier compatibility between national targets and benchmarks estimated by global models. Our results provide estimates and a line of evidence which can be directly used by the Global Stocktake to meaningfully compare aggregated national targets and mitigation benchmarks. No matter the reporting conventions used, the near-term action that is needed to meet the Paris Agreement is clear: emissions must peak as soon as possible and reduce significantly this decade. Our study helps to ensure this message is not lost in the translation between different concepts of anthropogenic land carbon fluxes.

Methods

Selection of AR6 Scenarios. As part of its 6th Assessment Report, IPCC WGIII authors analyzed over 2200 scenarios for potential inclusion in its mitigation pathway assessment [33]. Of those, 1202 were eventually vetted: deemed to have provided enough detail to allow a climate analysis using the IPCC's climate assessment architecture[34]. Those scenarios were then divided into different scenario categories based on their peak and end-of-century temperature probabilities[35].

In this manuscript, we focus on three categories of scenarios: C1, C2, and C3 as defined in the IPCC's AR6[33]. "C1" scenarios are as likely as not to limit warming to 1.5 °C and have been interpreted as consistent with the Paris Agreement's 1.5 °C long-term temperature goal as outlined in its Article 2[36], although arguments have been made that further delineation should be made into scenarios that do and do not achieve net-zero CO_2 emissions in order to better reflect its Article 4[37]. We assess outcomes from 2°C "C3" scenarios given their historic policy relevance, their capability to show progress towards 1.5°C, and their use in examining climate impacts beyond what is envisioned by the Paris Agreement. We also highlight mitigation outcomes of C2 scenarios, also called 'high overshoot' scenarios, which are as likely as not to limit warming to 1.5°C in 2100 but are likely to exceed 1.5°C in the interim period. Such pathways are nominally similar in mitigation and impact assessment with C3 scenarios until at least midcentury[37].

For the purposes of this analysis, we require that scenarios have been vetted by the IPCC climate analysis framework and provide a minimum set of land-cover variables, notably: "Land Cover|Cropland", "Land Cover|Forestry", and "Land Cover|Pasture". We analyze the presence of each of these variables and their combination in Supplementary Table 2 at the global, IPCC 5-

region (R5), and IPCC 10-region (R10) levels. Balancing concerns of greater regional detail and greater scenario coverage, we perform our analysis based on the R5 regions (see Supplementary Table 3) given that nearly all models with full global variable coverage also provide detail at the R5 regional level for C1-C3 scenarios.

To understand how well our scenario subset containing R5 land-cover variables corresponds statistically to the full database sample of C1-C3 scenarios, we perform a Kolmogorov-Smirnov (K-S) test over key mitigation variables of interest including: GHG and CO_2 2030 emission reductions, median peak warming, median warming in 2100, year of median warming, cumulative net CO_2 emissions throughout the century, cumulative net CO_2 until net-zero, and cumulative net negative CO_2 after net-zero (Supplementary Figure 6). For all variables, the K-S test is not able to determine whether the R5 subset comes from a different distribution than the full database sample, whereas it is able to determine the non-R5 subset is different for peak warming and cumulative net CO2 emissions, both of which are shown in Supplementary Figure 7. These results indicate that the subset of ~75-80% of all C1- C3 scenarios we chose to perform our analysis will result in sufficiently similar macro mitigation outcomes to represent such outcomes from the original distribution of scenarios.

Reanalysis with OSCAR. We use OSCAR v3.2: a version structurally similar to the one used for the 2021 Global Carbon Budget (GCB)[38], albeit used here with a regional aggregation that matches the R5 IPCC regions. We first run a historical simulation (starting in 1750 and ending in 2020) using the same experimental setup as for the 2021 GCB[5,38], with the updated input data used in ref[31]. This historical simulation is used to initialize the model in 2014 for the scenario simulations, but also to constrain the Monte Carlo ensemble (n=1200) using two values (instead of one in the GCB): the cumulative land carbon sink in the absence of land cover change over

1960-2020, and the NGHGI-compatible emissions averaged over 2000-2020. The former is a constraint of 135 ± 25 GtC[38]. The latter is a constraint of -0.45 ± 0.77 GtC yr^{-1}, using ref[2] as central estimate and combining uncertainties in ELUC and SLAND from the GCB. (All physical uncertainties in this section are 1 standard deviation.) All the values reported in the main text and figures are obtained via weighted average and standard deviation of the Monte Carlo ensemble, using these two constraints for the weighting[5].

To run the final scenario simulations over 2014-2100, OSCAR needs two types of input data: CO_2 and local climate projections, and land use and land cover change projections. The former mostly affect the land carbon sink (i.e. the indirect effect), while the latter mostly affect the bookkeeping emissions (i.e. the direct effect). OSCAR follows a theoretical framework[39] that enables clear separation of both direct and indirect effects. (Only the direct effect is reported annually in the GCB.)

Atmospheric CO_2 time series are taken directly from the database, as the median outcome estimated by the MAGICC simple climate model. However, local climate temperature and precipitation changes are not directly available. These are therefore computed using the internal equations of OSCAR[40], and time series of global temperature change and species-based effective radiative forcing (ERF) from the database (same source). Missing components of global ERF were treated as follows. BC on snow and stratospheric H_2O start at historical level in 2014[41] and follow the same relative annual change as the scenario's ERF from BC and CH4, respectively. Contrails are assumed constant after 2014. Solar forcing is assumed to follow the same pathway common to all SSPs. Volcanic aerosols are assumed to be constant and equal to the average of the historical period (i.e. to have a zero ERF). Finally, we apply a linear transition over 2014-2020 between observed and projected CO_2 and climate, so that these variables are 100%

observed in 2014 and 100% projected in 2020. We note that observed and projected CO_2 are virtually indistinguishable over that period but observed and projected regional climate change do differ by up to a few tenth of degrees. We further note that, because only median atmospheric CO2, ERF, and global temperature are used as input, we do not sample and report the full physical uncertainty of the Earth system, but only the biogeochemical uncertainty from the terrestrial carbon cycle in response to these median outcomes.

Land use and land cover change input data for OSCAR encompasses three variables: the land cover change per se, wood harvest data (expressed in carbon amount taken from woody areas without changing the land cover) and shifting cultivation (a traditional activity consisting in cycles of cutting forest for agriculture, then abandoning to recover soil fertility, then returning). Wood harvest and shifting cultivation information are not provided in the database, and so we use proxy variables to extrapolate historical 2014 values. Wood harvest is scaled using the "Forestry Production|Roundwood" variable, and shifting cultivation is using "Primary Energy|Biomass|Traditional" as a proxy of a region's development level. When scenarios did not report these proxy variables, we assumed a constant wood harvest or shifting cultivation in the future, because these are second-order effects on the global bookkeeping emissions.

Land cover change is split between gains and losses that are deduced directly as the year-to-year difference (gain if positive, loss if negative) in the following land cover variables of the database: "Land Cover|Forest", "Land Cover|Cropland", "Land Cover|Pasture" and "Land Cover|Built-up Area" (built-up area is assumed constant if not available). Land cover change in the remaining biome of OSCAR (non-forested natural land) is deduced afterwards to maintain constant land area. To build the transitions matrix required as input by OSCAR, it is then assumed that the area increase of a given biome occurs at the expense of all the biomes that see an area decrease (within the same region and at the same time step), in proportion to the biomes' share of total area decrease. By construction, this approach only provides net land cover transitions because it is impossible to have gain and loss in the same year, in a given region. Therefore, and because our historical data accounts for gross transitions but scenarios do not, we add to this net transitions matrix a constant amount of reciprocal transitions equal to their average historical value over 2008-2020 to obtain a gross transitions matrix. Finally, the three land use and land cover change input variables follow the same linear transition over 2014-2020 as the CO_2 and climate forcings.

We extract two key variables (and their subcomponents) from these scenario simulations: the bookkeeping emissions (ELUC in the GCB) and the land carbon sink (SLAND in the GCB). Following the approach by ref[4], the adjustment flux required to move from bookkeeping emissions to NGHGI-compatibles ones is calculated as the part of the land carbon sink that occurs in forests that are managed. Therefore, we obtain the adjustment flux by multiplying the value of SLAND simulated for forests by the fraction of (officially) managed forests. We set this fraction to the one estimated by ref[4] for 2015, which also allows us to deduce the area of managed and unmanaged (i.e. intact) forest in our base year. We then estimate how the area of intact forest evolves in each scenario, assuming that forest gains are always managed forest (i.e. they do not change intact forest area), and that half of forest losses are losses of intact forest with the other half being losses of managed forest. This fraction is deduced from ref[42] that estimated that ~92 Mha of intact forest disappeared between 2000-2013, while the FAO FRA 2020 reports ~170 Mha of gross deforestation over the same period. We acknowledge, however, that applying a global and constant value for this fraction is a coarse approximation that should be refined in future work, possibly using information from the scenario database itself. This assumption also implies that, as long as there is a background gross deforestation (as is the case here, given the added reciprocal transitions), countries will report more and more managed forest area. This is not necessarily inconsistent with the Glasgow declaration on forest made at COP26, as its implications in terms of pristine forest conservation are unclear[31]. The subcomponent of the bookkeeping emissions are extracted following the land categories defined by ref[2], and we consider that the net flux happening within the Forest land category, excluding shifting cultivation, is the direct contribution to land CDR. The indirect contribution to land CDR is exactly the adjustment flux described above.

The reanalyzed bookkeeping net emissions (i.e., direct effect) exhibit an average deviation of -87 Gt CO_2 for C1 scenarios and -63 Gt CO_2 for C3 scenarios from the reported emissions in the database, accumulated over the course of the century. Using the best-guess transient climate response to cumulative emissions estimated by the IPCC[43], this implies that the global temperature outcomes of these scenarios would differ by about -0.04 °C and -0.03 °C, respectively, from what was reported in the IPCC report, if our estimates of bookkeeping emissions were used instead of those reported by IAM teams.

In addition, after reallocating the indirect effect in managed forest (to align with the NGHGIs), we observe a 4.4 ± 1.0 Gt CO2 yr^{-1} gap between aligned and unaligned historical LULUCF emissions over 2000-2020. This number is at the lower end of the latest 6.4 ± 1.2 Gt CO_2 yr^{-1} provided in the 2022 GCB[3]. Compared to the 6.7 ± 2.5 Gt CO_2 yr^{-1} gap reported by ref [2], and correcting for the absence of organic soils emissions in our simulations with OSCAR (~0.8 Gt CO_2 yr^{-1}), OSCAR can explain ~75% of the observed gap.

Comparing Adjusted Pathways with Current Policy and NDC Estimates. We use the latest available estimate of aggregate NDCs from ref [1] to compare with NGHGI-adjusted global pathways. The 1.5°C and 2°C pathways we use are the same as previously discussed: IPCC C1 and C3 pathways with sufficient land cover detail at the R5 region level. We additionally reanalyze 'Current Policy' pathways from the IPCC AR6 database. These correspond to pathways consistent with current policies as assessed by the IPCC, or "P1b" pathways per the AR6 database metadata indicator "Policy_category_name".

We incorporate an endogenous estimation of the indirect effect with OSCAR, which varies over time based on land-cover pattern changes and changes to carbon cycle dynamics and carbon fertilization. As such, we compare our central estimate of global GHG emissions in 2015, approximately 49.4 Gt CO2-equiv to that of ref[1], 51.2 Gt CO2-equiv, resulting in a difference of 1.8 Gt CO2-equiv. We then apply this offset value (1.8 Gt) to all estimations of 2030 emission levels in ref[1] to provide comparable levels with our pathways. This ensures that NDC targets calculated based on national inventories become comparable with the NGHGI-adjusted modeled pathways.

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Acknowledgments: The authors thank and acknowledge the helpful comments by Dr. Maria Sanz and Dr. Carl-Friedrich Schleussner on an initial draft of the manuscript. The authors would also like to thank the anonymous reviewers whose comments greatly enhanced the quality of the manuscript.

Funding:

The European Union's Horizon Europe research and innovation program RESCUE, grant agreement no. 101056939 (MJG, TG).

The European Union's Horizon 2020 research and innovation program ESM2025 – Earth System Models for the Future, grant agreement no. 101003536 (TG, ZN)

The European Union's ERC-2020-SyG "GENIE" grant, grant ID 951542 (MJG, WFL, JM and KR).

The views expressed are purely those of the writers and may not under any circumstances be regarded as stating an official position of the European Commission

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Software: TG

Visualization: MJG

Writing – original draft: MJG

Writing – review & editing: MJG, TG, GG, NF, IJ, RFL, JM, ZN, JS, KR

Competing interests: The authors declare no competing interests.

Data and materials availability: OSCAR is an open-source model available at https://github.com/tgasser/OSCAR. All data generated and analyzed here is available via the GENIE Scenario Explorer at https://data.ece.iiasa.ac.at/genie. Source code for all analysis files is available at https://github.com/iiasa/gidden_ar6_reanalysis.

Figures

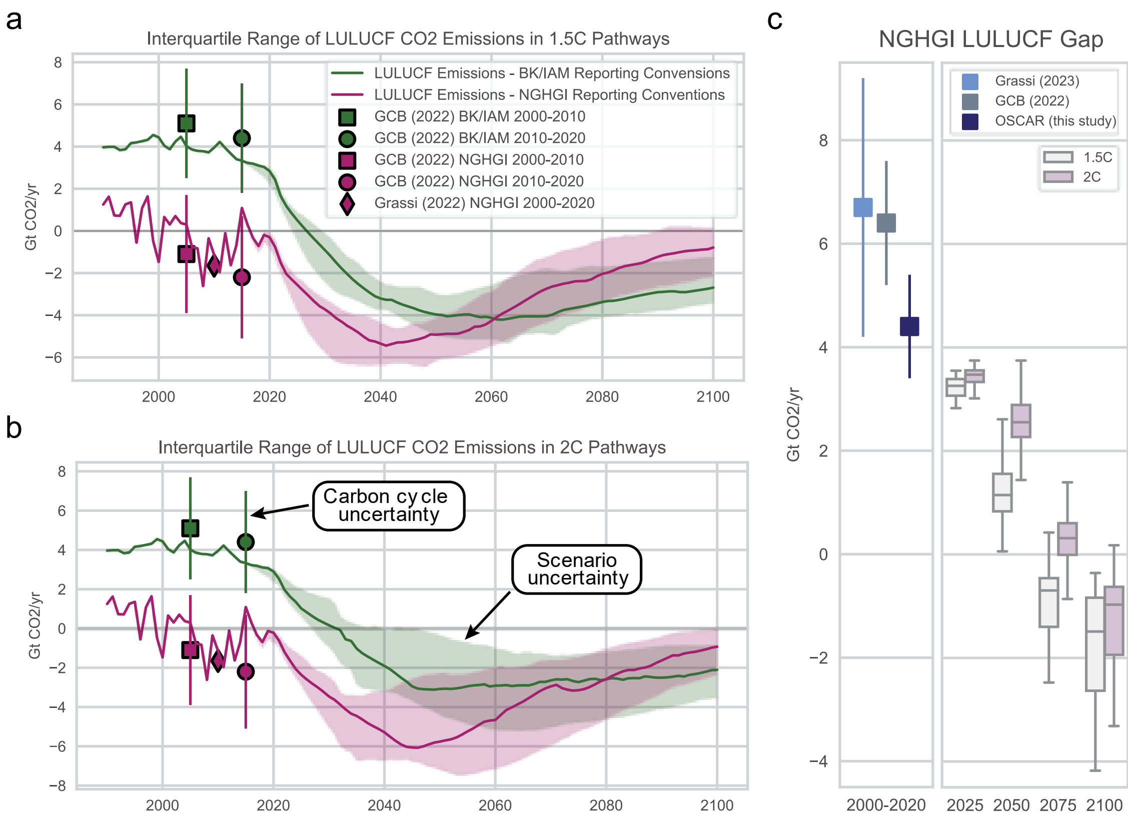

Fig. 1. Land use emissions in reanalyzed IPCC pathways with model-based and NGHGI-based accounting conventions. Land use emissions pathways before and after adjustment to match NGHGIs for 1.5°C and 2°C pathways. We highlight historical estimates with carbon cycle uncertainty (1-σ) and the median of scenario pathways with the scenario interquartile range in shaded plumes (**a, b**). For the most part, IAMs and bookkeeping models only include direct human-induced emissions and removals (green bands). NGHGIs generally include a wider definition of managed land area as well as the indirect removals on that land caused by environmental changes (e.g., the CO_2 fertilization effect). These indirect removals are added to the direct net LULUCF emissions (shown in green) to give a different reported total (shown in purple). Comparing the two conventions results in a difference (gap) between reanalyzed

and NGHGI-adjusted pathways (**c**) which evolves as a function of the strength of land-based climate mitigation.

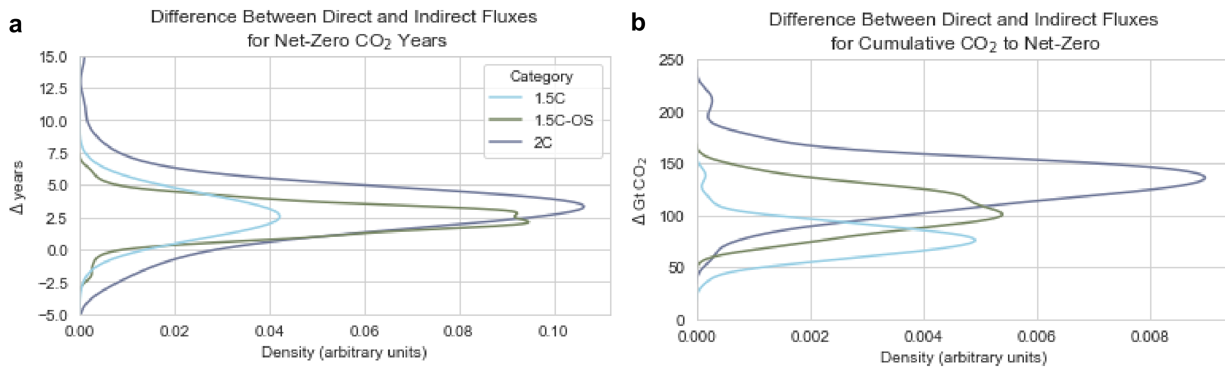

Fig 2. Changes in global mitigation benchmarks across assessed scenarios. Estimates of the change in the net-zero CO2 year (**a**) and cumulative emissions until net-zero CO2 (**b**) are shown for 1.5°C (blue, IPCC category C1), 1.5°C-OS (green, IPCC category C2), and 2°C (purple, IPCC category C3) scenarios. Values are computed for each assessed scenario by replacing the original LULUCF emission trajectory with reassessed trajectories including either direct effects or both direct and indirect effects. The resulting global CO_2 emissions trajectory is then used to recalculate both mitigation benchmarks. This figure then shows the scenario-wise distribution of the difference between the benchmark with only direct effects (corresponding to model-based LULUCF accounting) less the benchmark with direct and indirect effects (corresponding to NGHGI LULUCF accounting). A positive value indicates that the benchmark comes later (for net-zero years) or is higher (for cumulative emissions) in the model-based framework compared to the NGHGI-based framework. A comparison with the original AR6 benchmarks is shown in Supplementary Figure 1.

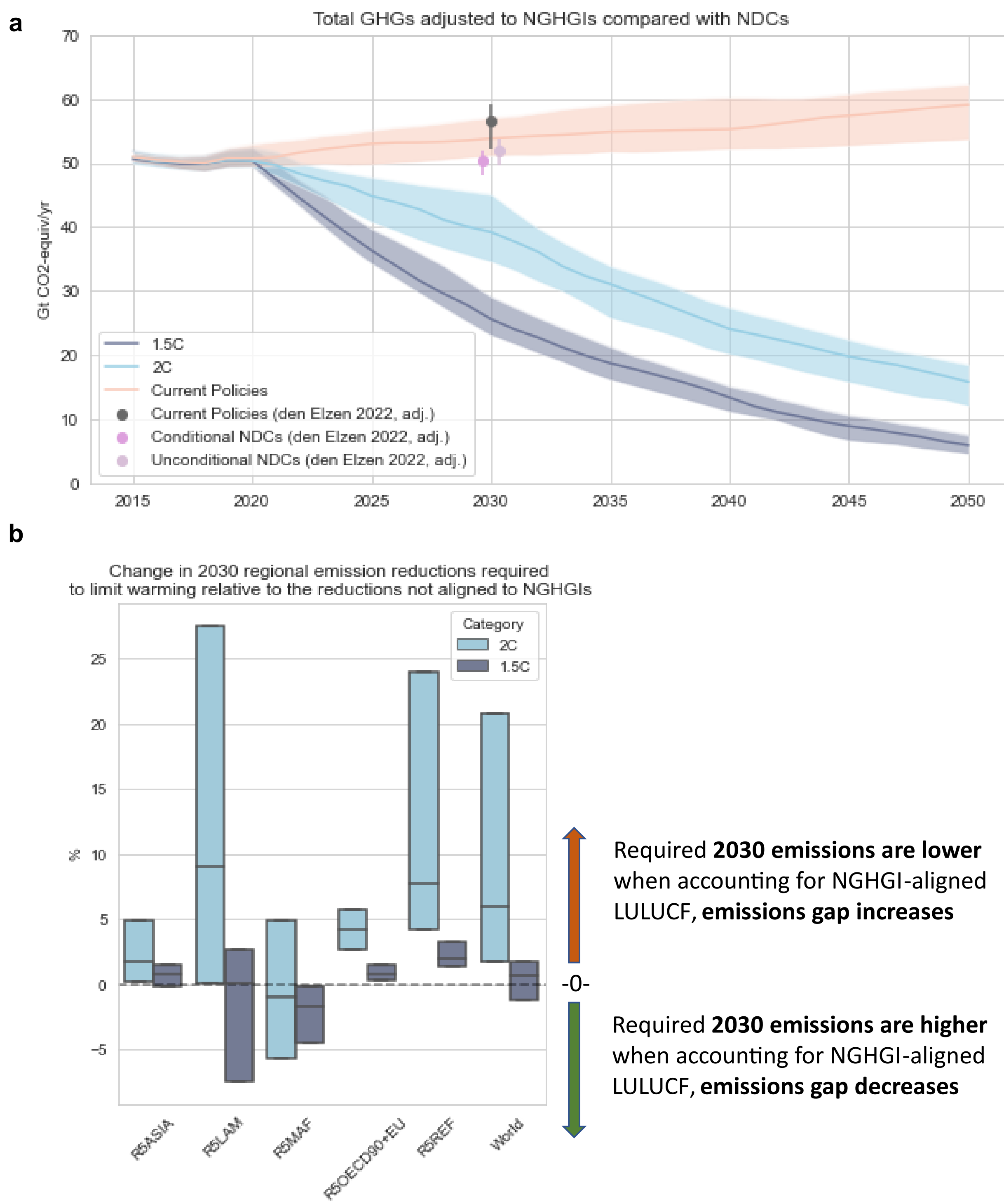

Fig. 3. Global and regional greenhouse gas emissions outcomes. NGHGI-adjusted global GHG pathways (interquartile range shown and median highlighted) plotted together with current estimates of

2030 aggregated national climate target levels and current policy estimates from [1] (**a**). The emission gap between current targets and long-term climate goals change in opposite directions (Supplementary Figure 2) due to evolving dynamics of indirect flux contributions to global CO_2. These changes occur differently across different regions, as shown by the interquartile range of the change in required 2020-2030 emissions reductions between reanalyzed pathways (following IAM conventions) and adjusted pathways (following NGHGI conventions) across IPCC geographical regions (Supplementary Table 3) (**b**).

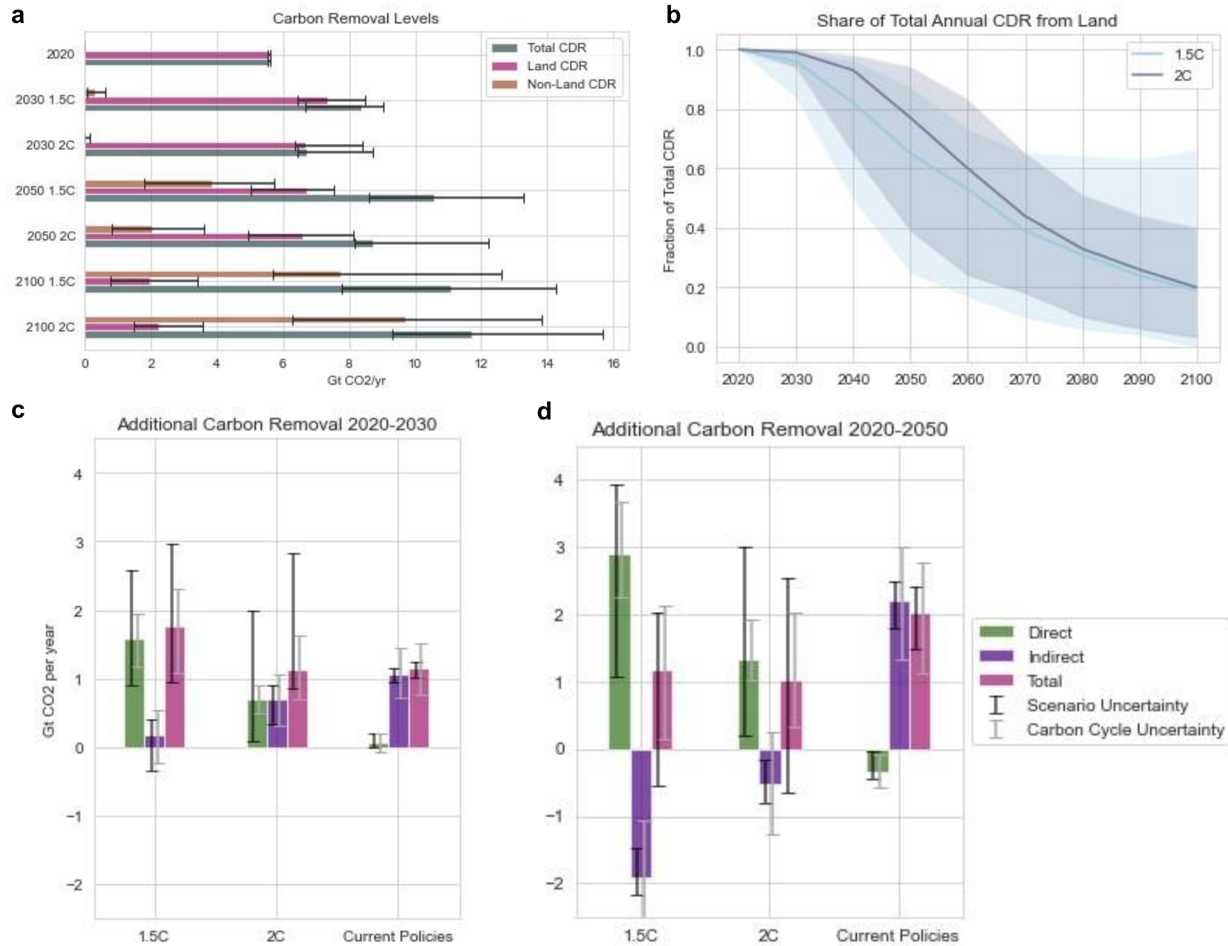

Fig 4. Carbon dioxide removal characteristics in mitigation and current policy pathways. Net land-use carbon removal levels including direct and indirect effects (green bars) are compared with novel CDR (brown bars) and total levels (summing land-use and novel CDR, grey bars) with whiskers denoting the interquartile range of each estimate across 1.5°C and 2°C scenarios (**a**). Here, novel CDR comprises technologies included in IAM pathways assessed in AR6, such as bio-energy with carbon capture and storage (BECCS), direct air capture of CO_2 with storage (DACCS), and Enhanced mineral Weathering. The share of land-based CDR reduces over time across both 1.5° and 2°C pathways (**b**), with the median (solid line) and interquartile range (shaded area) shown for the population of scenarios assessed. However, the contribution to total land-based removals varies across pathways between indirect and direct components. In the near-term, until 2030, 1.5°C pathways see a strong enhancement of additional removals whereas 2C pathways see a similar addition of total removals as current-policy pathways (**c**). By

mid-century, additional removals in current-policy pathways out-pace both 1.5 and 2C pathways, owing to the continued enhancement of indirect removals compared to an overall weakening of this flux in mitigation pathways (**d**). Scenario uncertainty in (**c, d**) is estimated by the interquartile range of scenario-based estimates, whereas the carbon cycle uncertainty is estimated by the interquartile range of the median ensemble of climate runs (see Methods).