Policy guidance and pitfalls aligning IPCC scenarios to national land emissions inventories

Matthew J. Gidden[1,2*†], Thomas Gasser[1†], Giacomo Grassi[3], Niklas Forsell[1], Iris Janssens[1,4], William F. Lamb[5,6], Jan Minx[5,6], Zebedee Nicholls[1,7,8], Jan Steinhauser[1], Keywan Riahi[1]

[1] International Institute for Applied Systems Analysis, Laxenburg, Austria
[2] Climate Analytics, Berlin, Germany
[3] Joint Research Centre, European Commission, Ispra, Italy
[4] Department of Computer Science, IDLab, University of Antwerp – imec, Antwerp, Belgium
[5] Mercator Research Institute on Global Commons and Climate Change, Berlin, German
[6] Priestley International Centre of Climate, School of Earth and Environment, University of Leeds, Leeds, UK
[7] Melbourne Climate Future’s Doctoral Academy, School of Geography, Earth and Atmospheric Sciences, University of Melbourne, Parkville, Australia
[8] Climate Resource, Northcote, Australia
[*] Corresponding author. Email: gidden@iiasa.ac.at
[†] These authors contributed equally to this manuscript

Taking stock of global progress towards achieving the Paris Agreement requires measuring aggregate national action against modelled mitigation pathways. Because of differences in how land-based carbon removals are defined, scientific sources report higher global carbon emissions than national emissions inventories, a gap which will evolve in the future. We establish a first estimate aligning IPCC-assessed pathways with inventories using a climate model to explicitly include indirect carbon removal dynamics on land area reported as managed for by countries. After alignment, we find that key global mitigation benchmarks can appear more ambitious when considering this extra land sink, though changes vary amongst world regions and temperature outcomes. Our results highlight the need to enhance communication between scientific and policy communities to enable more robust alignment in the future.

Global mitigation pathways play a critical role in informing climate policies and targets that are in line with international climate goals (1). 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. However, measuring mitigation in land-based systems poses a particular challenge due to the complex interaction of natural and human-driven carbon emissions and removals which have resulted in misalignment between modeled pathways and bottom-up measurement frameworks underpinning National Greenhouse Gas Inventories (NGHGIs) (2). Understanding and identifying solutions to minimize these discrepancies and developing appropriate translation mechanisms is crucial to supporting the Global Stocktake (3), the UNFCCC mechanism by which collective progress towards the mitigation, adaptation, and finance goals of the Paris Agreement is measured.

NGHGIs submitted by countries to the UNFCCC report land-based CO2 emissions and removals differently than bookkeeping models used in traditional carbon budget assessments (4). IAM pathways, which are calibrated to bookkeeping models, mainly include direct human-induced emissions and removals, while NGHGIs generally include a wider definition of managed land area as well as the indirect removals on that land, e.g., as induced by the CO2 fertilization effect. As a result, the reported net anthropogenic CO2 flux from land diverges between models and national inventories by ~5.5 GtCO2yr-1 (2005-2015 average) (2). Best estimates of present-day anthropogenic fluxes indicate that the land sector is a net source of emissions (4), whereas NGHGIs collectively report it as a net sink (5), resulting in fundamentally different perspectives of the role of land-based removals at present and in the future when viewed in isolation.

A combination of rapid near-term gross emissions reductions and active carbon removal from the atmosphere in the medium-term are needed to reach net-zero and eventually net-negative emissions to limit warming in line with the Paris Agreement temperature goal. In modeled pathways consistent with 1.5°C, hundreds of gigatonnes of CO2 are removed over the course of this century, with ultimate levels dependent on the strength of near-term mitigation action (6). In addition to Carbon Dioxide Removal (CDR) methods such as bioenergy with CO2 capture and storage (BECCS) and direct air CO2 capture and storage (DACCS), models envision significant removals across scenarios from land-use, land-use change and forestry (LULUCF). However, due to inconsistent definitions and model reporting methodologies, an assessment by the IPCC of required land-use removals consistent with global climate targets was not feasible (6).

In the run up to COP26, nations increasingly made long-term net-zero commitments, which for the first time brought the Paris Agreement long-term temperature goal within reach (7). Together with subsequent NDC updates, national targets, if implemented in full and on time, would reduce the likelihood of exceeding 3°C to nearly zero (8) and provide a 50-50 chance of limiting warming to 2°C (9). As COP27 approaches and nations bring forward potentially more ambitious near and long-term climate goals, clearer guidance around the role of the land sector in overall mitigation becomes increasingly important. Here, we reanalyze the IPCC AR6 database with consistent land-based CDR reporting allowing translation between national inventories and targets to facilitate a like-for-like comparison and enhance communication between scientists and policy makers in the first Global Stocktake so that action can align with ambition.

Aligning Global Pathways with National Inventories

Scenario pathways assessed by the IPCC in AR6 lack key reported information that is needed to align their LULUCF projections with NGHGIs. We use a reduced complexity climate model with explicit treatment of the land-use sector, OSCAR (10), one of the models used by the Global Carbon Project (4), to reanalyze thousands of global pathways and fill information gaps to enable such an alignment. A full description of the calculation approach is provided in the SM.

Across both 1.5°C and 2°C scenarios (Fig.s 1A, S1, S2, definitions in SM), NGHGI-aligned projections showcase a strong increase of the LULUCF sink until around mid-century. However, the ‘alignment gap’ (Fig. 1B) decreases over this period, as aligned and non-aligned trajectories converge by 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 CO2-fertilization effect as well as background climate warming reducing the overall effectiveness of the land sink, which in turn affect the indirect removals considered by NGHGIs. These dynamics lead to land-based emissions reversing their downward trend in most NGHGI-adjusted scenarios by mid-century, and result in the LULUCF sector becoming a net-source of emissions by 2100 in some deep mitigation scenarios (Fig. S1).

Modeled 1.5°C and 2°C pathways see a marked increase by 2030 in CDR from the LULUCF sector compared to 2020 levels, resulting in around 50% more direct removals of CO2 by 2030 in 1.5°C pathways, and combined direct and indirect removals overall sequestering approximately twice as much carbon in 1.5°C pathways compared to 2°C pathways (Fig. 1C). Over time, though, the reduced effectiveness of indirect LULUCF removals counterbalances gains from direct removals (11), maintaining overall yearly direct and indirect removals at around 10-12 Gt CO2 (Fig. S3), with 1.5°C pathways sequestering around 20% more carbon than 2°C pathways by mid-century. Taken together with BECCS, DACCS, and other CDR represented by models, 3.9 [2.3-5.2] Gt CO2yr-1 (interquartile range) and 1.9 [1.3-4.4] CO2yr-1 additional CDR is deployed between 2020 and 2030 in 1.5°C and 2°C pathways, respectively, of which ~85-90% is derived from land-based sequestration.

While deep mitigation scenarios show a significant and continued dependence on land-based removals over the whole century, LULUCF removals based on pathways aligned to NGHGIs would peak by mid-century, declining thereafter (Fig. S3). Thus, while the addition of a larger “managed land” sink may reduce reported levels of present-day national emissions in some cases, continued reliance on these land areas may pose future challenges. For example, the future effort needed to achieve or maintain climate-neutral, economy-wide emissions could be underestimated as these indirect sinks lose efficacy and eventually become net sources of emissions.

Global and Regional Ambition Implications

The downward adjustment of global pathways to match national inventories in combination with changing dynamics of indirect LULUCF removals results in revised emissions benchmarks derived from mitigation pathways (Table S1). We find that after adjustment, net-zero timings are brought forward by around 5 years for both CO2 and GHGs across temperature categories, for instance to ~2045 in the case of net-zero CO2 for 1.5°C. Similarly, 2030 CO2 emission reductions enhance by around 9-10%, from ~50% to ~60% for 1.5°C. While the perceived rate of reductions relative to pathways unaligned to NGHGIs is strongly revised upward in the near term, the change in calculated total carbon budget until net-zero sees only a modest drop, around 2-3% across climate targets, due to countervailing effects.

Although key emissions benchmarks are made ‘more ambitious’ when the land sink is enhanced by the NGHGI adjustment, these revised milestones do not imply that the amount of global effort to achieve key climate outcomes has increased. Multiple dynamics interact that affect the above mitigation outcomes, including the change in historical emission baseline, the enhanced land sink compared to what was reported by IAMs, and declining sequestration in that additional sink. But despite these counterbalancing effects, the same global transition pathways underlie the assessment. As such, this analysis reinforces the need to preserve existing land-based sinks as a key component to an all-of-the-above approach to achieving ambitious climate goals.

This revision is critical, however, to compare compiled national targets with benchmarks provided by IAMs. Historically, NDCs have been assessed against the definition of LULUCF emissions utilized by modeling teams or excluding LULUCF emissions entirely due to definitional issues (12). Comparing our results to one of the most recent aggregate NDC estimates (13) adjusted for base year differences between models and inventories (Fig. 2, see SM), we find that the gap between unconditional NDCs and a median 2°C outcome is around 12.7 Gt CO2-equivalent, about 15% larger than the median estimate reported by (13). However, our assessment of the gap between unconditional NDCs and a median 1.5°C outcome is 25.4 CO2-equivalent when accounting for the indirect land-use sink, around 8% smaller than (13). Thus, under the NGHGIs reporting framework, estimates of needed progress in anthropogenic emissions reductions could be masked by natural sink enhancement in the near term.

Realignment of global pathways to NGHGIs also results in new distributions of perceived effort or ambition needed at the regional level (Fig. 2B), as ~60% of the NGHGI adjustment falls in Non-Annex I countries (5). From a global perspective, there is no change in perceived effort for 1.5°C pathways - that is, the change in decadal emission reductions between both approaches is small (Fig. S4). Regionally, though, developed countries see a modest increase in perceived effort, whereas most developing regions see a modest decrease in perceived effort. In 2°C pathways, the NGHGI adjustment results in stronger 2020-2030 emissions reductions globally compared to the unadjusted pathways. This strengthening most directly affects perceived emissions reductions in regions with large forested area such as Latin America and Russia, while also increasing the perceived effort required by the OECD and Asia. The African region sees on average marginally lower effort required. While we can observe general trends across scenarios, the uncertainty of the results is large and spans both positive and negative effects across many regions.

Balancing Practicalities with Policy Guidance

Here, we provide a full reanalysis of AR6 LULUCF emissions consistent with NGHGIs following Grassi et al. (2021)’s ‘Rosetta Stone’ approach. It is important to stress that these adjustments are estimates from a single model and purely a reallocation of indirect induced fluxes 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 5 years 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 being reached 5 years earlier. This ‘new’ net-zero year also marks a different climatological milestone from the balance of direct sources and sinks of CO2. However, because the best available climate science regarding net-zero emissions levels pertains to direct human-induced climate change, benchmarks pertaining solely to direct processes will likely remain the most scientifically and politically relevant. Nevertheless, confusion will remain between national inventories, targets, and modeled results as long as definitions of land-based removals remain muddied.

The most straightforward solution is for both the policy and scientific communities to mutually make steps towards reconciling terms, definitions, and values of anthropogenic land use CO2 fluxes. Nations can enhance the transparency of their targets by first explicitly including LULUCF levels in their NDCs and long-term targets where not already included (16% of parties do not (12)), explicitly defining the nature of their deforestation pledges (14), and further noting what fraction of their climate target arises from LULUCF. IAM teams, being understandably more flexible than nations, have already begun relaying their individual assumptions for the NGHGI correction as part of their standard output by reporting their alignment outcomes directly from their land-use subcomponents (15), and future IPCC assessments can use such outcomes to vet scenarios. However, it is critical that such changes be made as part of a community effort, also including the climate modeling community, to ensure that existing models can interoperate without double counting emissions reductions due to realignment to NGHGIs.

Science and policy processes are marching forward together. Following COP26, active movement is underway to implement an enhanced transparency framework for national inventories and pledges by 2024. 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 one translation tool for use in the near term, while simultaneously highlighting the potential pitfalls of the dependence on natural sinks in target setting. Ultimately, though, the clear climate guidance from global pathways remains the same: drastic emissions reductions are needed this decade, and net-zero carbon emissions are needed by mid-century to achieve the 1.5°C goal of the Paris Agreement.

Materials and 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 (6). Of those, 1202 were eventually vetted: deemed to have provided enough detail to allow a climate analysis using the IPCC's climate assessment architecture (16). Those scenarios were then divided into different scenario categories based on their peak and end-of-century temperature probabilities.

In this manuscript we focus on two categories of scenarios: "C1" and "C3". "C1" scenarios can be considered consistent with the Paris Agreement's 1.5 °C long-term temperature goal as outlined in its Article 2 (17), although arguments have been made that further delineation should be made into scenarios that do and do not achieve net-zero CO2 emissions in order to better reflect its Article 4 (18). We additionally highlight outcomes from 2 °C, or "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 eschew so-called "high overshoot" or "C2" scenarios, due to their mixing peak-warming characteristics with 2C scenarios, while still drawing down emissions substantially by the end of the century. Such pathways are nominally similar in mitigation and impact assessment with C3 scenarios until at least midcentury (19).

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 Table S2 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 Table S3) given that nearly all models with full global variable coverage also provide detail at the R5 regional level for C1 and C3 scenarios.

To understand how well our scenario subset containing R5 land-cover variables corresponds statistically to the full database sample of C1 and C3 scenarios, we perform a Kolmogorov-Smirnov (K-S) test over key mitigation variables of interest including: GHG and CO2 2030 emission reductions, median peak warming, median warming in 2100, year of median warming, cumulative net CO2 emissions throughout the century, cumulative net CO2 until net-zero, and cumulative net negative CO2 after net-zero (Figure S5). For all metrics, 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 Figure S6. These results indicate that the subset of ~75-80% of all C1 and C3 scenarios we chose to perform subsequent 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: the same version used for the 2021 Global Carbon Budget (GCB) (4), albeit with a key structural change that enables using the land cover information provided in the IPCC WGIII database. In its standard structure (10), OSCAR requires input land cover change data expressed as a transition matrix that describes how much area of a given biome is changed into another biome (in each region and at each time step). In the alternative structure used here (dubbed “lite” in the model’s code), input land cover change data can be prescribed as two vectors of land cover gain and land cover loss (i.e. positive and negative land cover changes, respectively) instead of a transition matrix. Internally, when the matrix information is actually needed by the model, it is created assuming that the area increase of a given biome occurs over 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. When run with historical data, both setups produce virtually identical estimates of bookkeeping emissions (see Figure S7).

We then run a historical simulation (starting in 1750 and ending in 2020) using the same experimental setup as for the 2021 GCB (4, 10), with the updated input data used by Gasser et al. (14). 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 net land-to-atmosphere carbon flux over 1850-2020, and the NGHGI-compatible emissions averaged over 2000-2020. The former is a constraint of 15 ± 45 GtC (4). The latter is a constraint of -0.45 ± 0.77 GtC yr-1, using Grassi et al. (5) as central estimate and combining uncertainties in ELUC and SLAND from the GCB. (All physical uncertainties are 1 standard deviation.) All the values reported in the main text are obtained via a weighted average of the Monte Carlo ensemble, using these two constraints for the weighting (10).

To run the final scenario simulations over 2014-2100, OSCAR needs two types of input data: CO2 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 (20) that enables clear separation of both direct and indirect effects. (Only the direct effect is reported annually in the GCB.)

Atmospheric CO2 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 (21), 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 H2O start at historical level in 2014 (22) and follow the same relative annual change as the reported 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 zero. Finally, we apply a linear transition over 2014-2020 between observed and projected CO2 and climate, so that these variables are 100% observed in 2014 and 100% projected in 2020. We note that observed and projected CO2 are virtually indistinguishable over that period, but observed and projected climate change do differ by up to a few tenth of degrees.

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. 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, we add to both gain and loss vectors an equal and constant amount equal to the historical reciprocal transitions over 2008-2020.

Finally, 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 Grassi et al. (23), 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 Grassi et al. (23) 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. The latter value is deduced from the work of Potapov et al. (24) 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 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 (14).

The reanalyzed bookkeeping net emissions (i.e. direct effect) show an average deviation of -11 Gt CO2 for C1 scenarios and -16 Gt CO2 for C3 scenarios from the reported emissions in the database, accumulated over the course of the century. This implies that the climate outcomes of these scenarios would differ only marginally 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 5.1 Gt CO2 gap between aligned and unaligned historical LULUCF emissions over 2005-2015, very close to the 5.5 Gt CO2 identified by Grassi et al. (23). This difference could arise from many sources, among which input data and aggregation effects within OSCAR, but given the uncertainties associated with both direct and indirect processes (4), these two values remain comparable.

Comparing Adjusted Pathways with NDC Estimates

We use the latest available estimate of aggregate NDCs from den Elzen et al. (13) 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 den Elzen et al. (13), 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 order 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.

References

1. L. van Beek, J. Oomen, M. Hajer, P. Pelzer, D. van Vuuren, Navigating the political: An analysis of political calibration of integrated assessment modelling in light of the 1.5 °C goal. Environmental Science & Policy. 133, 193–202 (2022).

2. G. Grassi, Critical adjustment of land mitigation pathways for assessing countries' climate progress. Nature Climate Change. 11, 14 (2021).

3. "Synthesis report for the technical assessment component of the first global stocktake" (UNFCCC, 2022), pp. 11–12, paragraph 32.

4. P. Friedlingstein, M. W. Jones, M. O'Sullivan, R. M. Andrew, D. C. E. Bakker, J. Hauck, C. Le Quéré, G. P. Peters, W. Peters, J. Pongratz, S. Sitch, J. G. Canadell, P. Ciais, R. B. Jackson, S. R. Alin, P. Anthoni, N. R. Bates, M. Becker, N. Bellouin, L. Bopp, T. T. T. Chau, F. Chevallier, L. P. Chini, M. Cronin, K. I. Currie, B. Decharme, L. M. Djeutchouang, X. Dou, W. Evans, R. A. Feely, L. Feng, T. Gasser, D. Gilfillan, T. Gkritzalis, G. Grassi, L. Gregor, N. Gruber, Ö. Gürses, I. Harris, R. A. Houghton, G. C. Hurtt, Y. Iida, T. Ilyina, I. T. Luijkx, A. Jain, S. D. Jones, E. Kato, D. Kennedy, K. Klein Goldewijk, J. Knauer, J. I. Korsbakken, A. Körtzinger, P. Landschützer, S. K. Lauvset, N. Lefèvre, S. Lienert, J. Liu, G. Marland, P. C. McGuire, J. R. Melton, D. R. Munro, J. E. M. S. Nabel, S.-I. Nakaoka, Y. Niwa, T. Ono, D. Pierrot, B. Poulter, G. Rehder, L. Resplandy, E. Robertson, C. Rödenbeck, T. M. Rosan, J. Schwinger, C. Schwingshackl, R. Séférian, A. J. Sutton, C. Sweeney, T. Tanhua, P. P. Tans, H. Tian, B. Tilbrook, F. Tubiello, G. R. van der Werf, N. Vuichard, C. Wada, R. Wanninkhof, A. J. Watson, D. Willis, A. J. Wiltshire, W. Yuan, C. Yue, X. Yue, S. Zaehle, J. Zeng, Global Carbon Budget 2021. Earth Syst. Sci. Data. 14, 1917–2005 (2022).

5. G. Grassi, G. Conchedda, S. Federici, R. Abad Viñas, A. Korosuo, J. Melo, S. Rossi, M. Sandker, Z. Somogyi, F. N. Tubiello, "Carbon fluxes from land 2000–2020: bringing clarity on countries' reporting" (preprint, Biogeosciences and biodiversity, 2022), , doi:10.5194/essd-2022-104.

6. K. Riahi, R. Schaeffer, J. Arango, K. Calvin, C. Guivarch, T. Hasegawa, K. Jiang, E. Kriegler, R. Matthews, G. P. Peters, A. Rao, S. Robertson, A. M. Sebbit, J. Steinberger, M. Tavoni, D. P. Van Vuuren, "Mitigation pathways compatible with long-term goals." in IPCC, 2022: Climate Change 2022: Mitigation of Climate Change. Contribution of Working Group III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change, P. R. Shukla, J. Skea, R. Slade, A. A. Khourdajie, R. van Diemen, D. McCollum, M. Pathak, S. Some, P. Vyas, R. Fradera, M. Belkacemi, A. Hasija, G. Lisboa, S. Luz, J. Malley, Eds. (Cambridge University Press, Cambridge, UK and New York, NY, USA, 2022).

7. N. Höhne, M. J. Gidden, M. den Elzen, F. Hans, C. Fyson, A. Geiges, M. L. Jeffery, S. Gonzales-Zuñiga, S. Mooldijk, W. Hare, J. Rogelj, Wave of net zero emission targets opens window to meeting the Paris Agreement. Nat. Clim. Chang. 11, 820–822 (2021).

8. Y. Ou, G. Iyer, L. Clarke, J. Edmonds, A. A. Fawcett, N. Hultman, J. R. McFarland, M. Binsted, R. Cui, C. Fyson, A. Geiges, S. Gonzales-Zuñiga, M. J. Gidden, N. Höhne, L. Jeffery, T. Kuramochi, J. Lewis, M. Meinshausen, Z. Nicholls, P. Patel, S. Ragnauth, J. Rogelj, S. Waldhoff, S. Yu, H. McJeon, Can updated climate pledges limit warming well below 2°C? Science. 374, 693–695 (2021).

9. M. Meinshausen, J. Lewis, C. McGlade, J. Gütschow, Z. Nicholls, R. Burdon, L. Cozzi, B. Hackmann, Realization of Paris Agreement pledges may limit warming just below 2 °C. Nature. 604, 304–309 (2022).

10. T. Gasser, L. Crepin, Y. Quilcaille, R. A. Houghton, P. Ciais, M. Obersteiner, Historical CO<sub>2</sub> emissions from land use and land cover change and their uncertainty. Biogeosciences. 17, 4075–4101 (2020).

11. M. Jiang, B. E. Medlyn, J. E. Drake, R. A. Duursma, I. C. Anderson, C. V. M. Barton, M. M. Boer, Y. Carrillo, L. Castañeda-Gómez, L. Collins, K. Y. Crous, M. G. De Kauwe, B. M. dos Santos, K. M. Emmerson, S. L. Facey, A. N. Gherlenda, T. E. Gimeno, S. Hasegawa, S. N. Johnson, A. Kännaste, C. A. Macdonald, K. Mahmud, B. D. Moore, L. Nazaries, E. H. J. Neilson, U. N. Nielsen, Ü. Niinemets, N. J. Noh, R. Ochoa-Hueso, V. S. Pathare, E. Pendall, J. Pihlblad, J. Piñeiro, J. R. Powell, S. A. Power, P. B. Reich, A. A. Renchon, M. Riegler, R. Rinnan, P. D. Rymer, R. L. Salomón, B. K. Singh, B. Smith, M. G. Tjoelker, J. K. M. Walker, A. Wujeska-Klause, J. Yang, S. Zaehle, D. S. Ellsworth, The fate of carbon in a mature forest under carbon dioxide enrichment. Nature. 580, 227–231 (2020).

12. Nationally determined contributions under the Paris Agreement, Revised synthesis report by the secretariat (2021).

13. M. G. J. den Elzen, I. Dafnomilis, N. Forsell, P. Fragkos, K. Fragkiadakis, N. Höhne, T. Kuramochi, L. Nascimento, M. Roelfsema, H. van Soest, F. Sperling, Updated nationally determined contributions collectively raise ambition levels but need strengthening further to keep Paris goals within reach. Mitigation and Adaptation Strategies for Global Change. 27, 33 (2022).

14. T. Gasser, P. Ciais, S. L. Lewis, How the Glasgow Declaration on Forests can help keep alive the 1.5 °C target. Proc. Natl. Acad. Sci. U.S.A. 119, e2200519119 (2022).

15. M. Gusti, A. L. D. Augustynczik, F. Di Fulvio, P. Lauri, N. Forsell, "Bridging the Gap between the Estimates of Forest Management Emissions from the National GHG

Inventories and Integrated Assessment Models via Model–Data Fusion" in The 2nd International Electronic Conference on Forests - Sustainable Forests: Ecology, Management, Products and Trade (MDPI, 2021; https://www.mdpi.com/2673-4931/13/1/23), p. 23.

16. J. S. Kikstra et al., The IPCC Sixth Assessment Report WGIII climate assessment of mitigation pathways: from emissions to global temperatures. EGUsphere 2022, 1-55 (2022).

17. M. J. Mace, Mitigation Commitments Under the Paris Agreement and the Way Forward. Climate Law 6, 21-39 (2016).

18. C.-F. Schleussner, G. Ganti, J. Rogelj, M. J. Gidden, An emission pathway classification reflecting the Paris Agreement climate objectives. Communications Earth & Environment 3, 135 (2022).

19. C.-F. Schleussner et al., Science and policy characteristics of the Paris Agreement temperature goal. Nature Climate Change 6, 827-835 (2016).

20. T. Gasser, P. Ciais, A theoretical framework for the net land-to-atmosphere CO2 flux and its implications in the definition of "emissions from land-use change". Earth Syst. Dynam. 4, 171-186 (2013).

21. T. Gasser et al., The compact Earth system model OSCAR v2.2: description and first results. Geosci. Model Dev. 10, 271-319 (2017).

22. C. Smith et al., in Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change, V. Masson-Delmotte et al., Eds. (2021), chap. 7.SM.

23. G. Grassi et al., Critical adjustment of land mitigation pathways for assessing countries’ climate progress. Nature Climate Change 11, 425-434 (2021).

24. P. Potapov et al., The last frontiers of wilderness: Tracking loss of intact forest landscapes from 2000 to 2013. Science Advances 3, e1600821 (2017).

Acknowledgments. The authors thank and acknowledge the helpful comments by Dr. Maria Sanz on an initial draft 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).

Author contributions. Conceptualization: MJG, TG, KR. Methodology: MJG, TG, GG, IJ, ZN. Investigation: MJG, TG. 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, as well as the source code of the analysis, will be made publicly available upon acceptance of the paper.

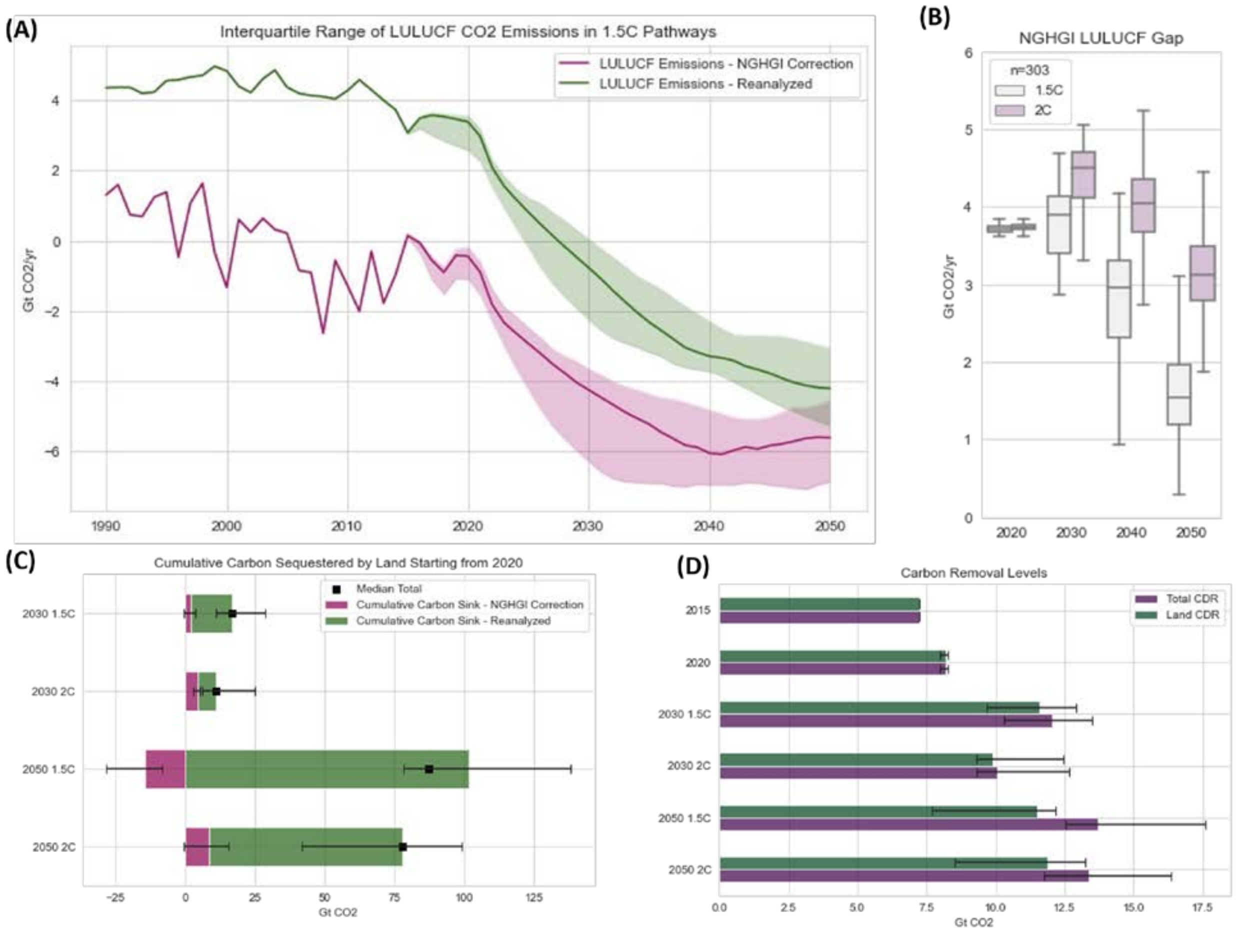
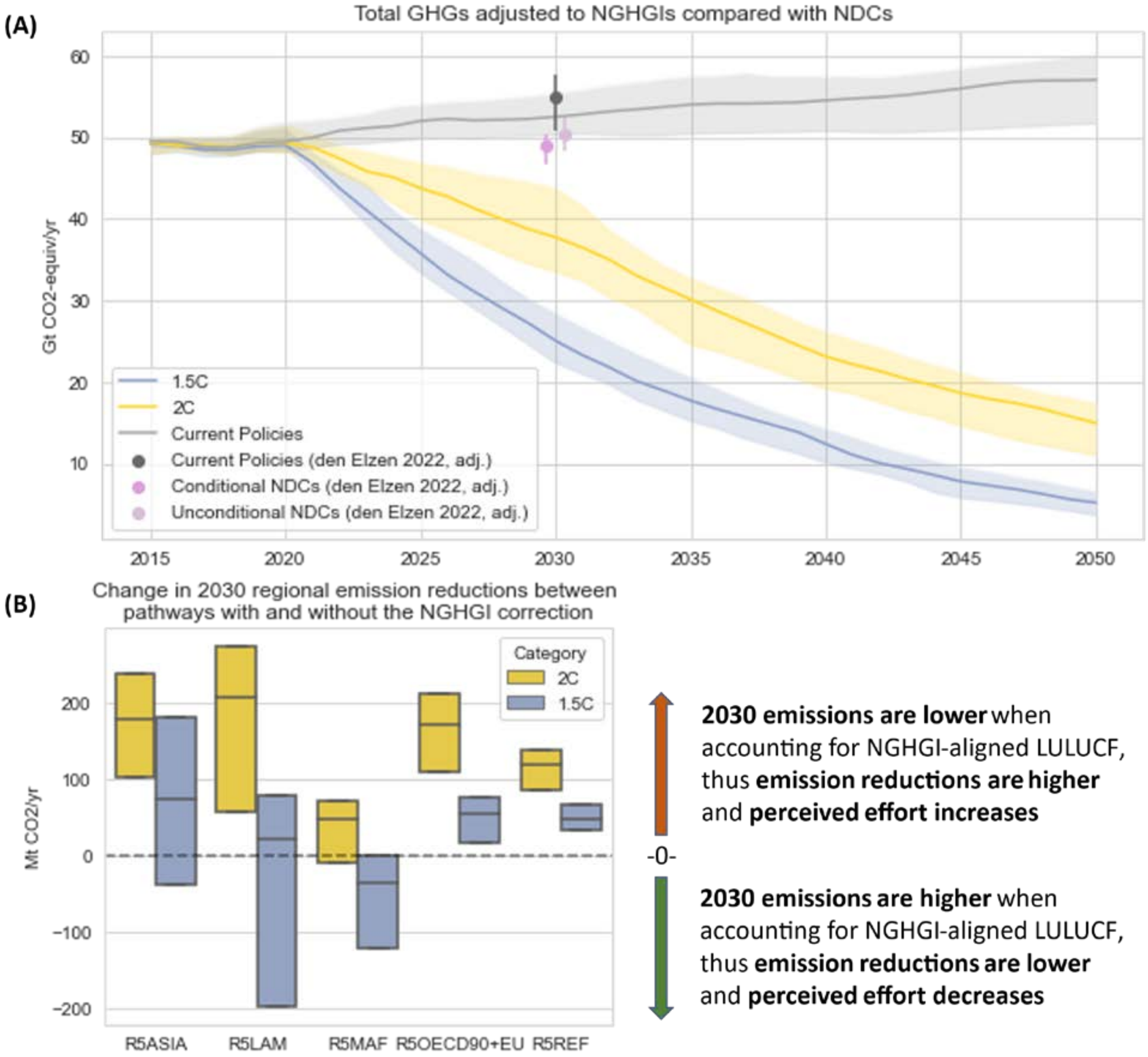


Fig. 1. Land use emissions and carbon dioxide removal characteristics of reanalyzed IPCC pathways. Land use emissions pathways before and after adjustment to match NGHGIs for 1.5°C pathways bounded by the scenario interquartile (25th-75th) range and highlighting the median of trajectories (A). The difference (gap) between reanalyzed and NGHGI-adjusted pathways (B). Total accumulated sequestered carbon in land sinks between 2020 and the provided time point by managed and natural sinks (C). CDR levels by time point and pathway temperature classification for land use and in total, comprising land use, BECCS, and DACCS (D).



2030 emissions are lower when accounting for NGHGI-aligned LULUCF, thus **emission reductions are higher** and **perceived effort increases**

2030 emissions are higher when accounting for NGHGI-aligned LULUCF, thus **emission reductions are lower** and **perceived effort decreases**

Fig. 2. Global and regional greenhouse gas outcomes. NGHGI-adjusted global GHG pathways (interquartile range shown and median highlighted) compared against current estimates of 2030 aggregated national climate target levels from den Elzen et al. (2022) (A). The interquartile range of the change in perceived effort between reanalyzed pathways (anthropogenic only) and adjusted pathways (including natural sinks from NGHGIs) (B).

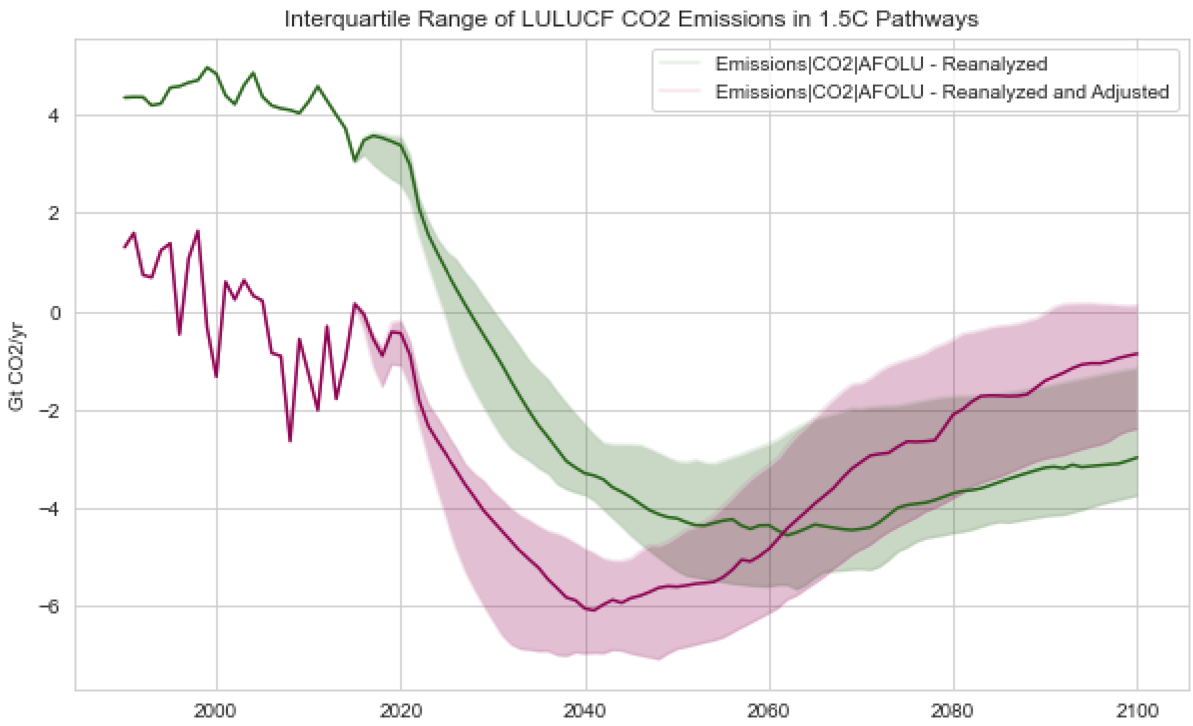


Fig. S1. Emissions trajectories for LULUCF CO2 reanalyzed with OSCAR, from direct sources (green) and including indirect sources (purple) for 1.5 °C pathways.

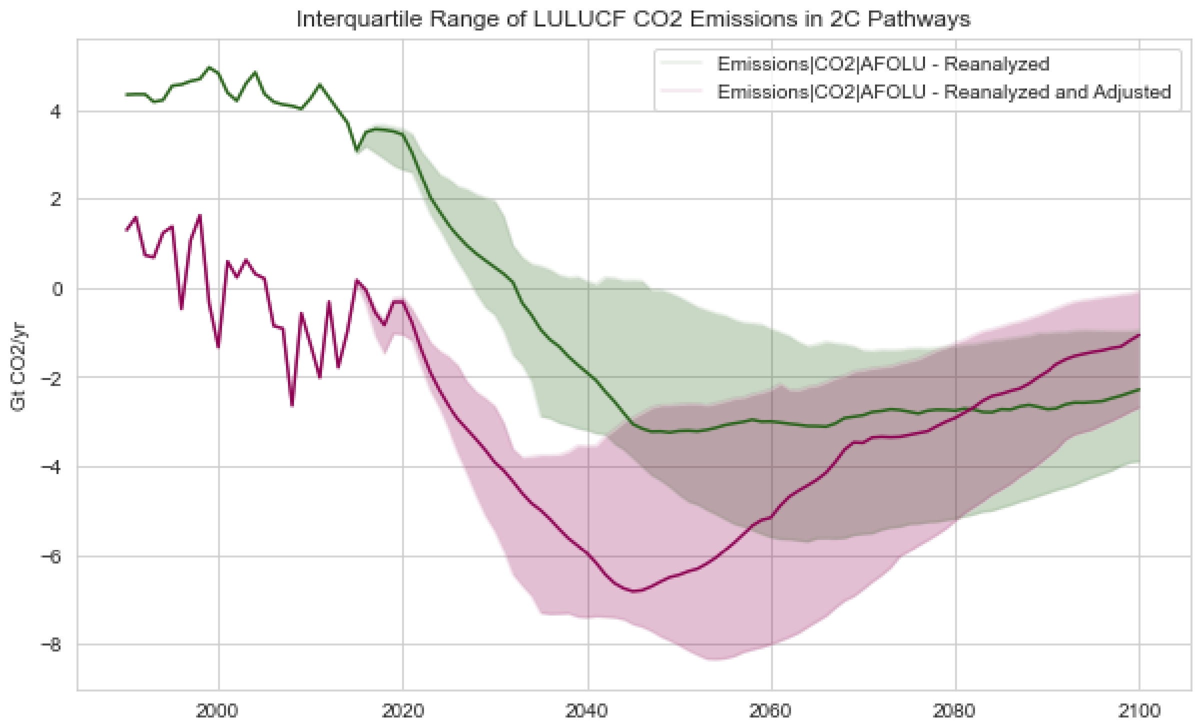


Fig. S2. Emissions trajectories for LULUCF CO2 reanalyzed with OSCAR, from direct sources (green) and including indirect sources (purple) for 2 °C pathways.

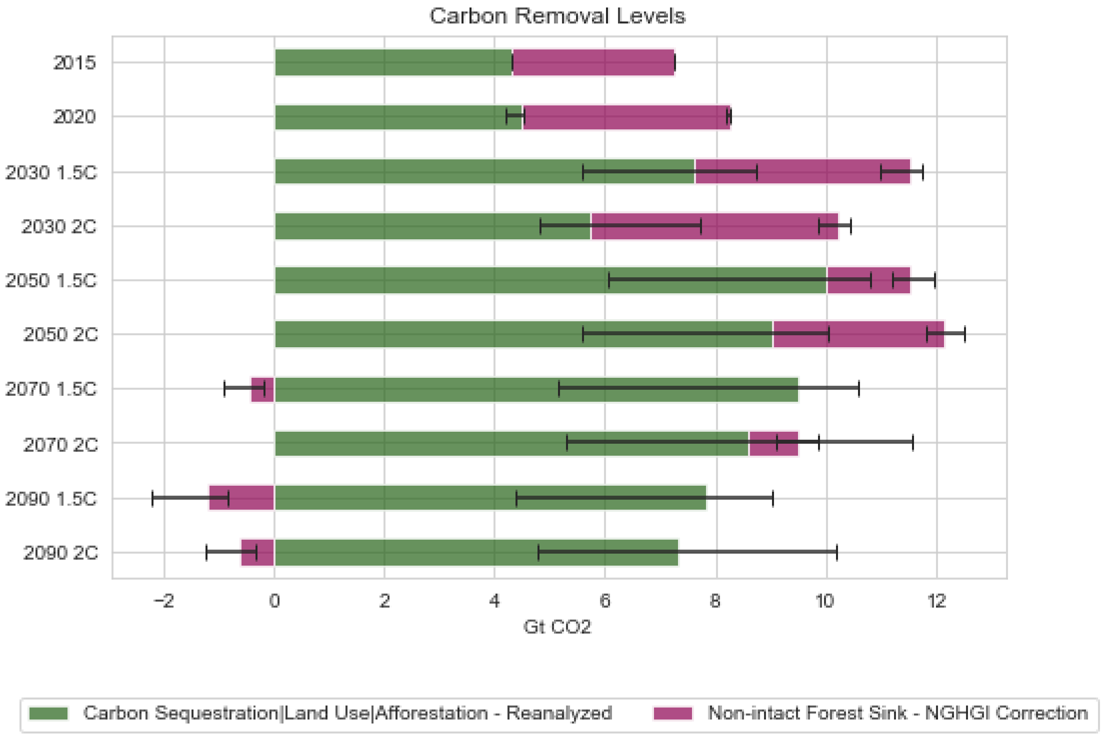


Fig. S3. Gross carbon removal levels from LULUCF (reanalyzed with OSCAR) by direct effects (green) and indirect effects (purple) across 1.5 °C and 2 °C pathways. Interquartile ranges of each estimate are shown by error bars.

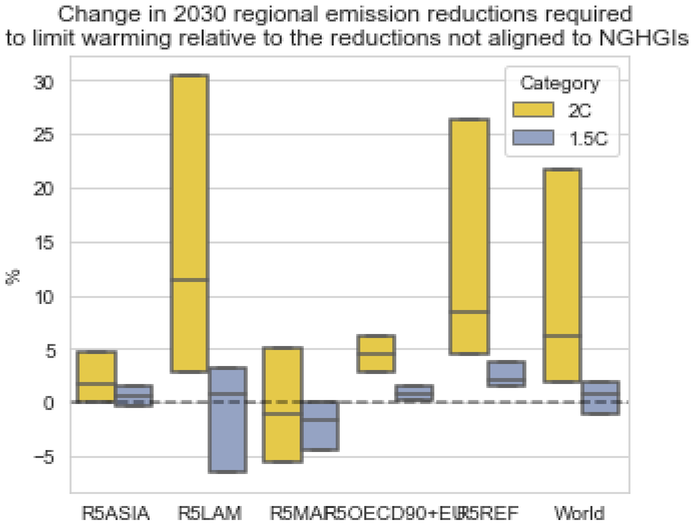
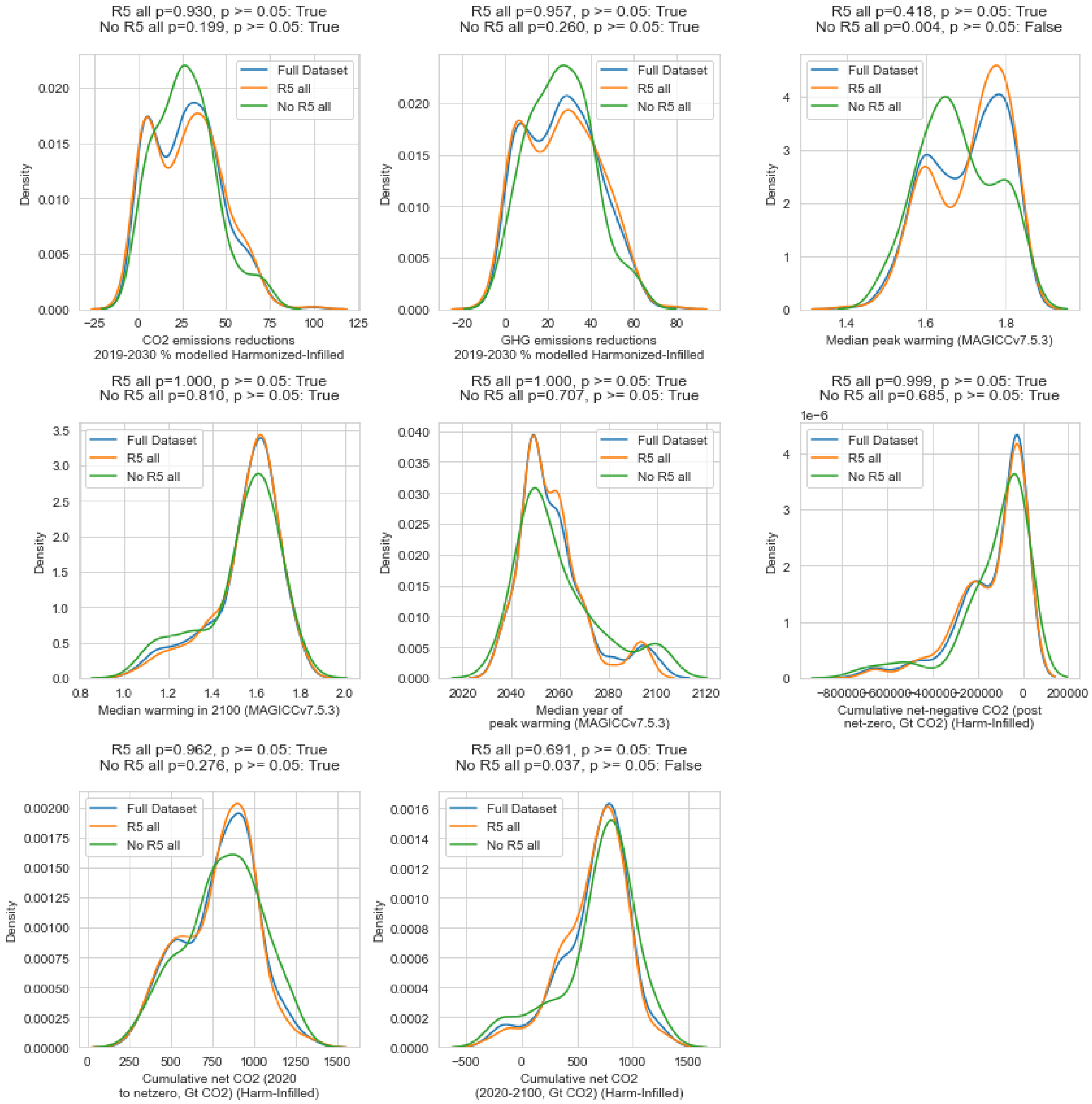


Fig. S4. The relative change in emission reduction gap when considering direct effects versus direct and indirect effects. A positive value means that the gap is larger when considering both (i.e. when aligned to NGHGIs), and a negative value means the gap is smaller.



R5 all p=0.930, p >= 0.05: True
No R5 all p=0.199, p >= 0.05: True

R5 all p=0.957, p >= 0.05: True
No R5 all p=0.260, p >= 0.05: True

R5 all p=0.418, p >= 0.05: True
No R5 all p=0.004, p >= 0.05: False

R5 all p=1.000, p >= 0.05: True
No R5 all p=0.810, p >= 0.05: True

R5 all p=1.000, p >= 0.05: True
No R5 all p=0.707, p >= 0.05: True

R5 all p=0.999, p >= 0.05: True
No R5 all p=0.685, p >= 0.05: True

R5 all p=0.962, p >= 0.05: True
No R5 all p=0.276, p >= 0.05: True

R5 all p=0.691, p >= 0.05: True
No R5 all p=0.037, p >= 0.05: False

Fig. S5. Kolmogorov-Smirnov test results for key mitigation indicators for the full set of C1 and C3 scenarios, those scenarios having all land-cover variables defined at the R5 region level, and those not having all land-cover variables defined at the R5 region level.

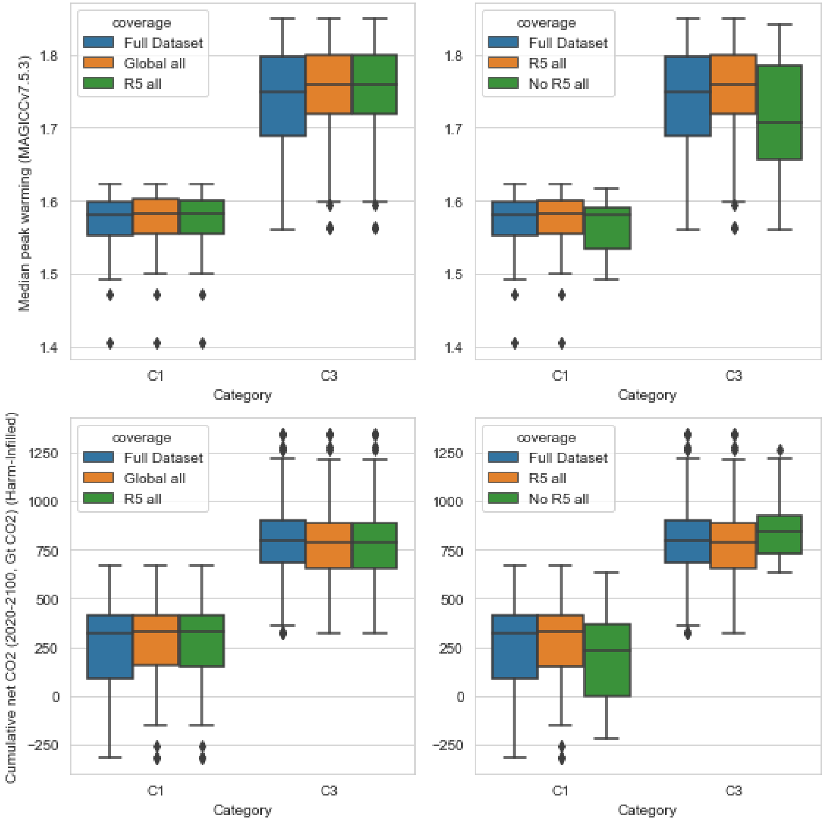


Fig. S6. Key mitigation metrics where scenarios without R5 region coverage cannot replicate the full database outcome. The left column presents the outcome for the full database as well as for scenarios with global values of land-cover variables and R5 values. The right column shows how the distribution changes when considering the population of scenarios without full variable coverage (‘No R5 all’).

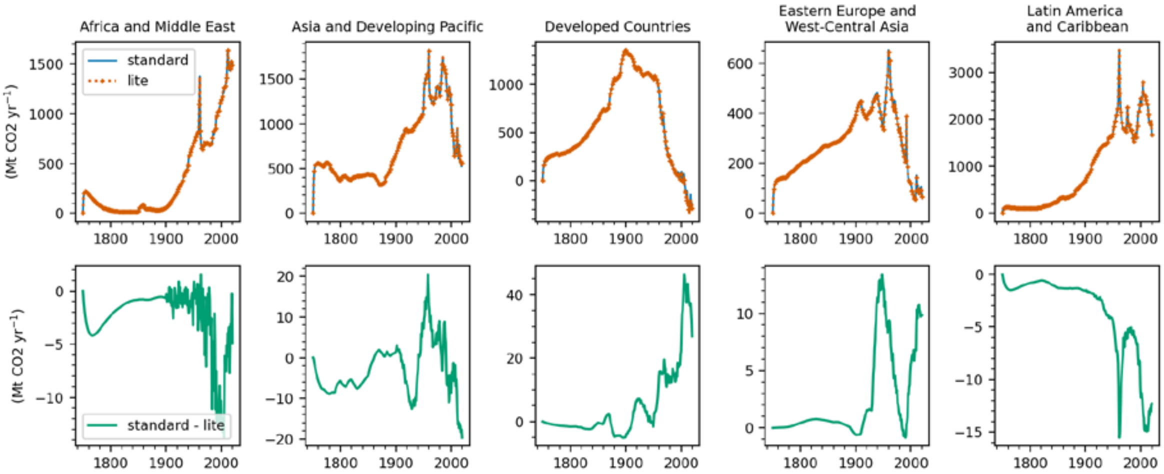


Fig. S7. Comparison of the standard and lite variants of the OSCAR model. The top panels show time series of regional bookkeeping emissions, while the bottom panels show the difference between the two variants. Note that these were averaged over all configurations of the Monte Carlo ensemble before constraining (and therefore do not exactly match the reported constrained values).

	1.5C			2C		
	(a)	(b)	(c)	(a)	(b)	(c)
Carbon Budget from 2020 (Gt CO2)	550 (470-572)	538 (463-564)	525 (461-555)	933 (776-999)	901 (754-989)	898 (745-979)
CO2 Emissions Reductions (2020-2030) (GtCO2 yr^{-1})	47 (41-57)	48 (37-56)	57 (49-62)	21 (6-30)	18 (7-29)	26 (12-36)
Net-zero CO2 Year	2055 (2049-2060)	2051 (2047-2054)	2046 (2043-2049)	2071 (2067-2079)	2068 (2063-2075)	2062 (2056-2069)
Net-zero GHG Year	2070 (2062-2076)	2067 (2059-2077)	2059 (2054-2073)	2082 (2078-2087)	2080 (2074-2085)	2080 (2071-2085)

Table S1. Net mitigation outcomes from scenarios: (a) prior to assessment by OSCAR, (b) with direct effects of LULUCF reanalyzed by OSCAR, and (c) including both direct and indirect effects of LULUCF (i.e. aligned to NGHGIs). All values provided as medians with interquartile ranges in parentheses.

Category	C1	C2	C3	C4	C5	C6	C7	C8
Global Land Cover|Forest	77%	80%	77%	88%	89%	84%	61%	31%
Global Land Cover|Pasture	74%	80%	75%	87%	88%	84%	60%	31%
Global Land Cover|Cropland	74%	80%	75%	87%	88%	84%	60%	31%
Global all	74%	80%	75%	87%	88%	84%	60%	31%
R5 Land Cover|Forest	76%	80%	77%	88%	89%	84%	60%	31%
R5 Land Cover|Pasture	73%	80%	75%	87%	88%	84%	60%	31%
R5 Land Cover|Cropland	73%	80%	75%	87%	88%	84%	60%	31%
R5 all	73%	80%	75%	87%	88%	84%	60%	31%
R10 Land Cover|Forest	59%	63%	56%	57%	66%	56%	30%	17%
R10 Land Cover|Pasture	59%	62%	56%	57%	66%	56%	30%	17%
R10 Land Cover|Cropland	59%	63%	56%	57%	66%	56%	30%	17%
R10 all	59%	62%	56%	57%	66%	56%	30%	17%

Table S2. Fraction of AR6 database scenarios with land-use variables of interest, per scenario category.

Macro Region	Short Name	Country Constitutents
R5ASIA	Asia	China, China Hong Kong SAR, China Macao SAR, Mongolia, Taiwan, Afghanistan, Bangladesh, Bhutan, India, Maldives, Nepal, Pakistan, Sri Lanka, Brunei Darussalam, Cambodia, Democratic People's Republic of Korea, East Timor, Indonesia, Lao People's Democratic Republic, Malaysia, Myanmar, Papua New Guinea, Philippines, Republic of Korea, Singapore, Thailand, Viet Nam
R5LAM	Latin American	Argentina, Bahamas, Barbados, Belize, Bolivia, Brazil, Chile, Colombia, Costa Rica, Cuba, Dominican Republic, Ecuador, El Salvador, Guadeloupe, Guatemala, Guyana, Haiti, Honduras, Jamaica, Martinique, Mexico, Netherlands Antilles, Nicaragua, Panama, Paraguay, Peru, Puerto Rico, Suriname, Trinidad and Tobago, Uruguay, Venezuela
R5MAF	Middle East and Africa	Bahrain, Iran (Islamic Republic of), Iraq, Israel, Jordan, Kuwait, Lebanon, Oman, Qatar, Saudi Arabia, Syrian Arab Republic, United Arab Emirates, Yemen, Algeria, Angola, Benin, Botswana, Burkina Faso, Burundi, Cote d'Ivoire, Cameroon, Cape Verde, Central African Republic, Chad, Comoros, Congo, Democratic Republic of the Congo, Djibouti, Egypt, Equatorial Guinea, Eritrea, Ethiopia, Gabon, Gambia, Ghana, Guinea, Guinea-Bissau, Kenya, Lesotho, Liberia, Libyan Arab Jamahiriya, Madagascar, Malawi, Mali, Mauritania, Mauritius, Morocco, Mozambique, Namibia, Niger, Nigeria, Reunion, Rwanda, Senegal, Sierra Leone, Somalia, South Africa, Sudan, Swaziland, Togo, Tunisia, Uganda, United Republic of Tanzania, Western Sahara, Zambia, Zimbabwe
R5OECD90+EU	OECD90 and EU (and EU candidate)	Albania, Austria, Belgium, Bosnia and Herzegovina, Bulgaria, Croatia, Cyprus, Czech Republic, Denmark, Estonia, Finland, France, Germany, Greece, Hungary, Iceland, Ireland, Italy, Latvia, Lithuania, Luxembourg, Macedonia, Malta, Montenegro, Netherlands, Norway, Poland, Portugal, Spain, Sweden, Switzerland, Turkey, United Kingdom, Canada, United States of America, Australia, Fiji, French Polynesia, Guam, Japan, New Caledonia, New Zealand, Romania, Samoa, Serbia, Slovakia, Slovenia, Solomon Islands, Vanuatu
R5REF	Reforming Ecomonies of the Former Soviet Union	Armenia, Azerbaijan, Belarus, Georgia, Kazakhstan, Kyrgyzstan, Republic of Moldova, Russian Federation, Tajikistan, Turkmenistan, Ukraine, Uzbekistan

Table S3. Definitions of IPCC 5-region macro regions as listed in the IPCC AR6 database.