Uncompensated claims to fair emission space risk putting Paris Agreement goals out of reach

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Abstract

Addressing questions of equitable contributions to emission reductions is important to facilitate ambitious global action on climate change within the ambit of the Paris Agreement. Several large developing regions with low historical contributions to global warming have a strong moral claim to a large proportion of the remaining carbon budget. However, this claim needs to be assessed in a context where the remaining carbon budget consistent with the Long-Term Temperature Goal (LTTG) of the Paris Agreement is rapidly diminishing. Here we assess the potential tension between the moral claim to the remaining carbon space by large developing regions with low per capita emissions, and the collective obligation to achieve the goals of the Paris Agreement. Based on scenarios underlying the IPCC's 6th Assessment Report, we construct a suite of scenarios that combine the following elements: (i) two quantifications of a moral claim to the remaining carbon space by South Asia, and Africa, (ii) a "highest possible emission reduction" effort by developed regions, and (iii) a corresponding range for other developing regions. We find that even the best effort by developed regions cannot compensate for a unilateral claim to the remaining carbon space by South Asia and Africa. This would put the LTTG firmly out of reach unless other developing regions cede their moral claim to emissions space and, like developed regions, pursue highest possible emission reductions. Furthermore, regions such as Latin America would need to provide large-scale negative emissions with potential risks and negative side effects. Our findings raise important questions of perspectives on equity in the context of the Paris Agreement including on the critical importance of climate finance. A failure to provide adequate levels of financial support to compensate large developing regions to emit less than their moral claim will put the Paris Agreement at risk.

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Abstract

Addressing questions of equitable contributions to emission reductions is important to facilitate ambitious global action on climate change within the ambit of the Paris Agreement. Several large developing regions with low historical contributions to global warming have a strong moral claim to a large proportion of the remaining carbon budget. However, this claim needs to be assessed in a context where the remaining carbon budget consistent with the Long-Term Temperature Goal (LTTG) of the Paris Agreement is rapidly diminishing. Here we assess the potential tension between the moral claim to the remaining carbon space by large developing regions with low per capita emissions, and the collective obligation to achieve the goals of the Paris Agreement. Based on scenarios underlying the IPCC's 6th Assessment Report, we construct a suite of scenarios that combine the following elements: (i) two quantifications of a moral claim to the remaining carbon space by South Asia, and Africa, (ii) a "highest possible emission reduction" effort by developed regions, and (iii) a corresponding range for other developing regions. We find that even the best effort by developed regions cannot compensate for a unilateral claim to the remaining carbon space by South Asia and Africa. This would put the LTTG firmly out of reach unless other developing regions cede their moral claim to emissions space and, like developed regions, pursue highest possible emission reductions. Furthermore, regions such as Latin America would need to provide large-scale negative emissions with potential risks and negative side effects. Our findings raise important questions of perspectives on equity in the context of the Paris Agreement including on the critical importance of climate finance. A failure to provide adequate levels of financial support to compensate large developing regions to emit less than their moral claim will put the Paris Agreement at risk.

Keywords: Paris Agreement, Equity, Highest Possible Ambition, Emission Scenarios

Introduction

The 2015 Paris Agreement contains a global objective to hold warming "well below 2°C and to pursue efforts to limit warming to 1.5°C" (UNFCCC, 2015). The scientific community has modelled a large number of mitigation scenarios that demonstrate different pathways to achieve this objective, many of which are developed using Integrated Assessment Models (IAMs) (Keppo *et al.*, 2021). Pathways modelled using IAMs form a large proportion of the low carbon emission scenarios assessed by the Working Group III (WGIII) of the Intergovernmental Panel on Climate Change (IPCC) in its Sixth Assessment Report (AR6) (IPCC, 2022b). Given the prominent role these pathways play at the science-policy interface, it is unsurprising that a number of critiques and proposals for improvement have been raised (McCollum *et al.*, 2020; Keyßer and Lenzen, 2021; Peng *et al.*, 2021; Schultes *et al.*, 2021). Such critiques and the blind spots they highlight in the design of scenarios can be consequential, precisely because they map out the solution space for policymakers (Keppo *et al.*, 2021; van Beek *et al.*, 2022). This raises profound questions around perspectives that are currently excluded from the existing suite of scenarios, limiting the perceived solution space seen by policymakers (Beck and Oomen, 2021).

One such perspective that is largely missing in the existing suite of IAM scenarios is equity of regional emission reductions as highlighted by the IPCC, which notes the following about the scenarios assessed in AR6: "[m]ost do not make explicit assumptions about global equity, environmental justice or intra-regional income distribution." (IPCC, 2022b). This absence is concerning because equity is a central theme of international efforts to tackle climate change (and an important pillar of the Paris Agreement). In simple terms, using an equity lens to evaluate contributions to addressing climate change helps to account for one of the key moral dilemmas of climate change – that developed countries have contributed the most to causing the problem, but action to meet global climate targets will also require emission reductions from developing countries, some of which have contributed very little to causing the problem (Gardiner, 2010; Dooley *et al.*, 2021).

Some contributions to the literature have tried to bridge the gap between cost-optimisation (e.g., Rogelj *et al.*, (2018), Riahi *et al.*, (2021)) and equitable mitigation assessments (e.g., Winker, Letete and Marquard, (2013), Meinshausen *et al.*, (2015), Rajamani *et al.*, (2021)), and there are broadly two approaches suggested. The first approach is to *interpret* the gap (in emission terms) using the analytical separation between efficiency (cost optimality), and equity, assuming seamless international financial transfers to facilitate mitigation (Leimbach and Giannousakis, 2019). The second approach is to *design and implement* scenarios with regionally differentiated carbon prices (Bauer *et al.*, 2020). The first approach is potentially difficult to apply directly to the current international climate policy context – international climate finance is continually highlighted as a failed promise, and is proving to be an ongoing challenge in international climate negotiations (Roberts *et al.*, 2021; Pauw *et al.*, 2022). The second approach, which we term "heterogenous scenario construction" lends itself well to answer research questions that assume regionally differentiated mitigation actions – however, differentiation need not necessarily occur due to differences in the assumed regional carbon prices, as applied in Bauer *et al.*, (2020). Other examples of such an approach are papers that aim to evaluate the warming outcomes of current country-level emission reduction pledges, to track progress towards the collective achievement of the Paris Agreement's long-term temperature goal (LTTG) (Geiges *et al.*, 2020; Höhne *et al.*, 2021; Meinshausen *et al.*, 2022).

Here, we apply such a heterogenous scenario construction approach, by performing a reanalysis of the IPCC AR6 WG III scenarios (Byers *et al.*, 2022), to assess the potential tension between the moral claim to the remaining carbon budget (RCB) for 1.5°C by large developing regions, and the collective obligation to achieve the long-term temperature goal of the Paris Agreement. More specifically, we aim to answer the following research question: is the global achievement of the 1.5°C goal of the Paris Agreement still possible if South Asia and Africa (R10INDIA+, and R10AFRICA respectively – see Supplementary Information for the regional definitions) emit as much as they could claim to be morally entitled to, in the absence of adequate international transfers to compensate them for this moral claim? This research question is informed by the calls by some developing countries from those regions to “operationalise equity” including through an “equitable distribution of the carbon space” (LMDC Group, 2022).

Methods

The focus on R10INDIA+ and R10AFRICA stems from the fact that these are the two world regions with the lowest historic per-capita emissions and thus, arguably, the largest moral claims to carbon space (depending on the equity principle applied). To answer the research question, we need to make two key assumptions to inform the design of long-term emission scenarios. First, we need to assess how much of the RCB for 1.5°C these two regions have a moral claim to. Second, we need to make assumptions around the emission reductions that occur in the other world regions. Combining these two groups of emission pathways yields a global emission pathway that can be compared to the RCB assessed by the IPCC. We first present the two approaches we use to operationalise the moral claim – an equal cumulative per capita emission approach, and a capability-based approach. We choose these two approaches to reflect notions of “responsibility” and “respective capabilities”, which are present in the Paris Agreement (see, for e.g., Article 2(2)).

Equal cumulative per capita emissions – historical responsibility and equality

This approach aims to represent notions of historical responsibility and equality (Höhne, den Elzen and Escalante, 2014). Following van den Berg *et al.,* (2020), we first calculate a “carbon debt” for each region – this is defined as the CO_2 emissions per region, which exceeds a counterfactual equal per capita emission pathway (Equation 1).

$$Debt_r = \sum_{t=t_{start}}^{t_{end}} \frac{pop_{r,t}}{POP_t} * E_t - e_{r,t} \quad (1)$$

for $Debt_r$, the historical carbon debt for region r, t_{start} and t_{end}, the time period (historical) for the assessment, $pop_{r,t}$, the population of region r in timestep t, POP_t, the global population in timestep t, E_t, the global emissions in timestep t, $e_{r,t}$, the actual regional emissions in timestep t.

A key decision while calculating the carbon debt is the starting year of the analysis, which is not only a matter of scientific judgement (e.g., data availability and quality), but also an ethical choice (Dooley *et al.*, 2021). We choose a starting year of 1990 to calculate the carbon debt – our argumentation for selecting this year is that 1990 was the year when the IPCC started providing science-based guidance to policymakers on climate change (Nauels *et al.*, 2019; Beusch *et al.*, 2022). For historical CO_2 emissions (fossil fuel and industrial, as well as land use emissions), we use the dataset published by Minx *et al.,* (2021). For population estimates, we use the population projections from the World Development Indicators database (World Bank, 2022). To evaluate the implications of choosing a much earlier starting date (1850) , we calculate the carbon debt using the PRIMAP-hist dataset (Gütschow *et al.*, 2016; Gütschow, Günther and Pflüger, 2021), which extends back to 1850 (albeit, without land use, land use change, and forestry emissions), and a composite population dataset from Our World in Data (Our World in Data, 2022). We then proceed to calculate the regional fair shares of the remaining carbon budget b_r (Equation 2), assuming that future population projections follow the middle of the road Shared Socio-Economic Pathway (SSP2) (KC and Lutz, 2017).

$$b_r = \sum_{t=2020}^{t_{peak}} \frac{pop_{r,t}}{POP_t} * B + Debt_r \quad (2)$$

where t_{peak} is the year of peak warming and B the global carbon budget. For the RCB (*B* in Equation 2), we use a value of 500 Gt CO_2 (from 2020), which the IPCC AR6 WGI assesses as providing a 50% chance of keeping warming below 1.5°C (Canadell *et al.*, 2021).

Capability using GDP per capita as a proxy

A different approach to equitable allocations is to use a “capability to contribute” metric. Here, we use the GDP per capita of each region in 2015 as a proxy to allocate the remaining carbon budget (Equation 3) – this proxy (GDP/capita) has been used in other studies in the literature as a metric to operationalise the notion of capability (Robiou du Pont and Meinshausen, 2018).

$$b_r = \left[\frac{pop_{r,2015}/gdp_{r,2015}}{POP_{2015}/GDP_{2015}}\right] * B \ (3)$$

where $pop_{r,2015}$ is the regional population in 2015, $gdp_{r,2015}$ the regional GDP in 2015, POP_{2015} the global population in 2015 and GDP_{2015} the global GDP in 2015. We use the GDP/capita estimate for 2015 from the IMAGE SSP2-baseline scenario reported in the AR6 scenario database (Dellink *et al.*, 2017; KC and Lutz, 2017; van Vuuren *et al.*, 2021).

Translating equitable carbon budgets into emission pathways

Now that we have derived equitable carbon budgets for R10INDIA+ and R10AFRICA, we need to translate these budgets into emission pathways. There are multiple emission pathways that can potentially correspond to a cumulative emissions constraint (Raupach *et al.*, 2014). Here, we employ a simple two-stage process. First, we set a 2030 waypoint at the median of the 2030 CO_2 emissions across pathways assessed in AR6 WG III that pass through emission levels consistent with the nationally determined contributions (NDCs) (Byers *et al.*, 2022; IPCC, 2022a; Riahi *et al.*, 2022). We interpolate linearly between the last historical year and the 2030 waypoint. Second, we proceed to identify a post-2030 rate of reduction per region that would result in the achievement of the regional carbon budgets identified above.

Constructing synthetic emission scenarios at the global level

After constructing the equitable emission pathways, we now need to determine the emission reduction pathways in other regions. In this paper, we choose to operationalise the notion of “highest possible ambition” (see, for example, Article 4(3) of the Paris Agreement). In order to do so, we perform a re-analysis of the pathways assessed by AR6 WG III, at the R10 region level. We first filter for modelling frameworks that report more than 3 pathways in the C1 climate category of pathways – this is the lowest warming category available in the AR6 WGIII database. We group the R10 regions (except R10INDIA+, and R10AFRICA) into two groups – developed regions (R10NORTH_AM, R10PAC_OECD, R10EUROPE, R10REF_ECON), and developing regions (R10CHINA+, R10REST_ASIA, R10MIDDLE_EAST, R10LATIN_AM). The metric we choose to select scenarios is the cumulative CO_2 emissions until the regional year of net zero CO_2 emissions.

For developed regions, we select regional scenarios for each modelling framework, which have the lowest cumulative CO_2 emissions across the C1 category of AR6 WG III pathways to represent the highest possible ambition. For developing regions, we choose two pathways per region: (a) a maximum case, with the highest cumulative CO_2 emissions across the C1 and C3 category of AR6 pathways, and (b) a minimum case with the lowest cumulative CO_2 emissions across the C1 and C3 category of AR6 pathways. For reference, the C1 category of pathways limit warming to 1.5°C (>50%) with no or limited overshoot, and the C3 category of pathways limit warming to 2°C (>67%) (IPCC, 2022b). The reason we select regional scenarios per modelling framework is because there are significant differences between each modelling framework (Harmsen *et al.*, 2021). Since we apply a cumulative CO_2 emission metric, calculated up to the regional net zero year, to select the emission pathways per region, this means that a given region (both developed, and developing) can contribute with net-negative CO_2 emissions if the regional year of net zero CO_2 occurs before the global year of net zero CO_2 of the synthetic scenario.

For each modelling framework, we assume that the AR6 WGIII pathway ensemble is comprehensive, and complementary, in terms of regional decarbonisation efforts, so that a recombination of different regional decarbonisation pathways is possible for the purpose of constructing "synthetic emission scenarios". We construct four such synthetic emission scenarios (scenario labels: ecpc_minc1_maxc3, ecpc_minc1_minc1, cap_minc1_maxc3, and cap_minc1_minc1) to answer our research question. These scenarios combine the two equity schemes, as well as the two sets of emission pathways for the developing regions, chosen to represent the range of "highest possible ambition" outcomes. Each scenario is labelled using the following scheme that consists of three parts, with each part separated by an underscore. The first part indicates the equity scheme underlying the pathways for R10INDIA+ and R10AFRICA (ecpc - equal cumulative per capita, and cap - capability). The second part indicates the assumption underlying the pathway selection for developed regions (in this case, the minimum cumulative emissions across the C1 pathways, or, minc1). By design, this is the same across all the four scenarios. The final part indicates the assumption underlying the pathway selection for developing regions, which varies between the minimum across the C1 pathways (minc1) for each region, and the maximum across the C1 pathways (maxc3) for each region.

Formal assessment of the warming implications of the pathways

The primary point of reference we use to assess the consistency of the scenarios with the LTTG of the Paris Agreement is the 1.5°C RCB. However, a more complete assessment of the scenarios is necessary to compare the warming outcomes of the scenarios to criteria that have been suggested to operationalise the two textually linked elements of the LTTG ("hold warming well below 2°C" and "pursue efforts to limit warming to 1.5°C") (Schleussner *et al.*, 2022). This requires assumptions to be made about the non-CO_2 emission trajectories, and the use of an appropriately calibrated simple climate model to capture uncertainty in the response of the climate system to emissions (Brecha *et al.*, 2022; Kikstra *et al.*, 2022). In this paper, we first infer the methane (CH_4) and nitrous oxide (N_2O) emissions using a quantile-based infilling method (Lamboll *et al.*, 2020), and then proceed to use the sequence of harmonisation, infilling, and climate assessment steps applied in AR6 WG III (Kikstra *et al.*, 2022), with one key difference. We use the FaIR simple climate model (Smith *et al.*, 2018) with the solar cycle forcing estimates removed from 2016, so that we only assess the anthropogenic warming contribution of these emission pathways (Rogelj, Schleussner and Hare, 2017).

Results

Focusing on the remaining carbon budget

Determining whether the fair share of emission space should be based on the RCB, or the total carbon budget (the RCB plus historical cumulative CO_2 emissions from a pre-industrial reference) is an open question. When we apply the equal cumulative per capita emission scheme (Equation 1) to historical CO_2 emissions between 1850 and 2019 (excluding LULUCF emissions – see Methods), we calculate that R10INDIA+ and R10AFRICA have together emitted around 430 Gt CO_2 less than a counterfactual equal per capita emission pathway for the two regions (Figure S1a and Figure S1b). If the two regions were to lay claim to this 430 Gt CO_2, even without considering their claim to the 1.5°C RCB, this would leave around 70 Gt CO_2 for all other regions to emit to remain within a no-overshoot 1.5°C RCB, or around 220 Gt CO_2 for a low overshoot 1.5°C RCB. If, in addition, the two regions were to claim their fair share of the RCB (Equation 2), then we cannot generate any synthetic scenarios that would stay within the 1.5°C RCB. Since such an allocation puts the climate objectives of the Paris Agreement out of reach, we focus on the application of equity schemes to the 1.5°C RCB (Equation 2 and 3), to investigate whether the climate objectives of the Paris Agreement can be attained (and, under what conditions). When we apply Equation 2 (the equal cumulative per capita emission allocation) to the 1.5°C RCB, we derive an emission allocation of 276 GtCO_2 for R10INDIA+ and 174 Gt CO_2 for R10AFRICA. When we apply Equation 3 (the capability-based allocation) to the 1.5°C RCB, we derive an emission allocation of 111 GtCO_2 for R10INDIA+ and 116 Gt CO_2 for R10AFRICA.

Assessing cumulative CO_2 emissions to regional and global net zero years

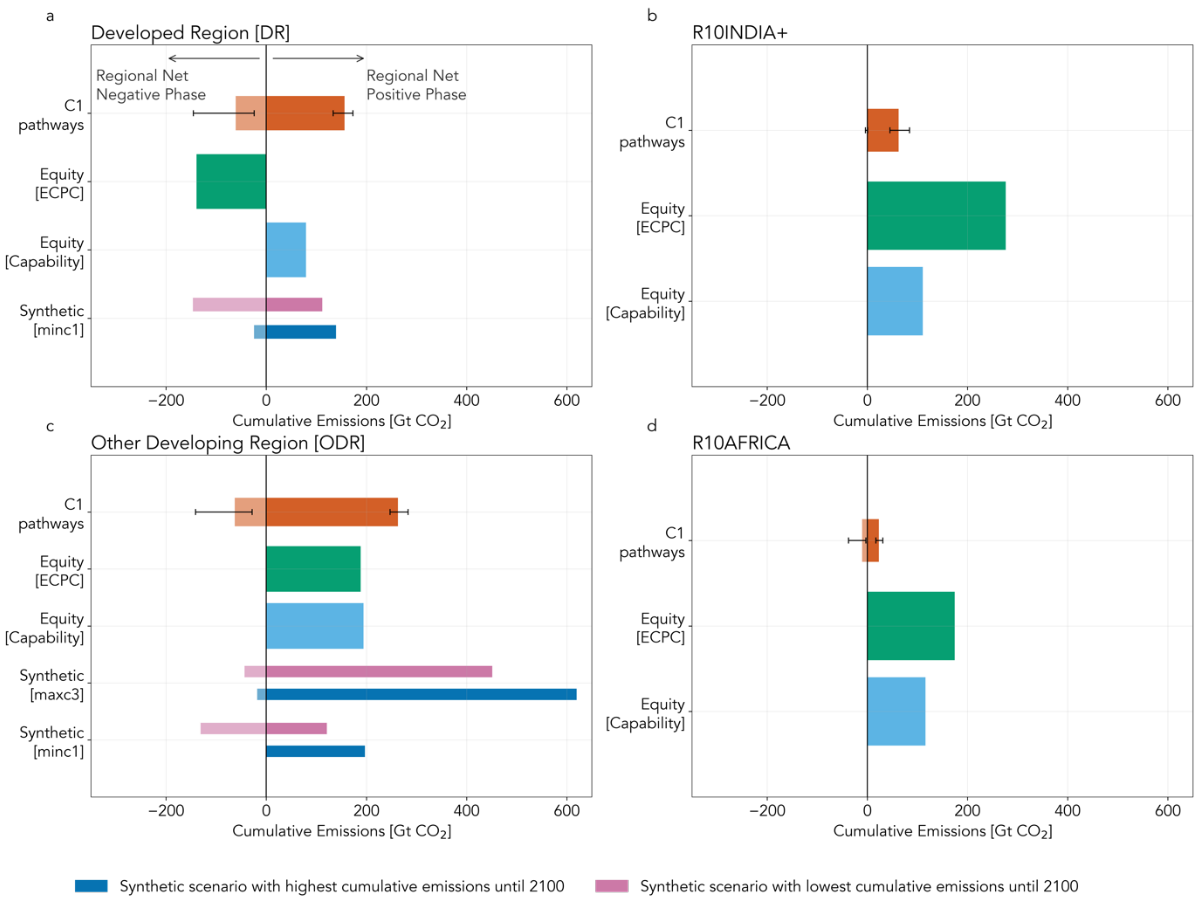

Figure 1: Cumulative emissions until the regional year of net zero CO_2. We compare the typical emissions across the C1 pathways (median, interquartile range indicated by the error bars) from the

AR6 scenario database with the computed equitable emission allocations, and the emission allocations across the synthetic emission pathways (a) For the Developed Region [DR] (R10NORTH_AM, R10PAC_OECD, R10EUROPE), (b) R10INDIA+, (c) for the Other Developing Region [ODR], which excludes R10INDIA+ and R10AFRICA, and (d) R10AFRICA. The C1 pathways limit warming to 1.5°C (<50%) with no or limited overshoot.

Given the lack of explicit equity assumptions in the mitigation pathways assessed in AR6, it is unsurprising that the typical emission allocation across the C1 pathways for R10INDIA+ (Figure 1b) and R10AFRICA (Figure 1d) are much lower than the emission allocations that would be consistent with the two equity schemes. We aggregate the emissions across the developed regions into a composite Developed Region [DR], and the corresponding emissions across the developing regions into a composite Other Developing Region [ODR] to present the results. For the DR (Figure 1a), the synthetic scenarios have net positive CO_2 emissions that range between 80 – 153 Gt CO_2, compared to a median of 156 Gt CO_2 across the C1 pathways in the AR6 WG III scenario database. In the net-negative CO_2 phase, cumulative emissions span -146 to -23 Gt CO_2, compared to a median of -61 Gt CO_2 across the C1 pathways. We already observe that even the "highest possible ambition" by the DR cannot make up for the increased emissions by R10INDIA+ and R10AFRICA (Figure 1b and Figure 1d), indicating the importance of the ODR (and its constituent regions) in determining whether the Paris Agreement's LTTG can be kept in reach.

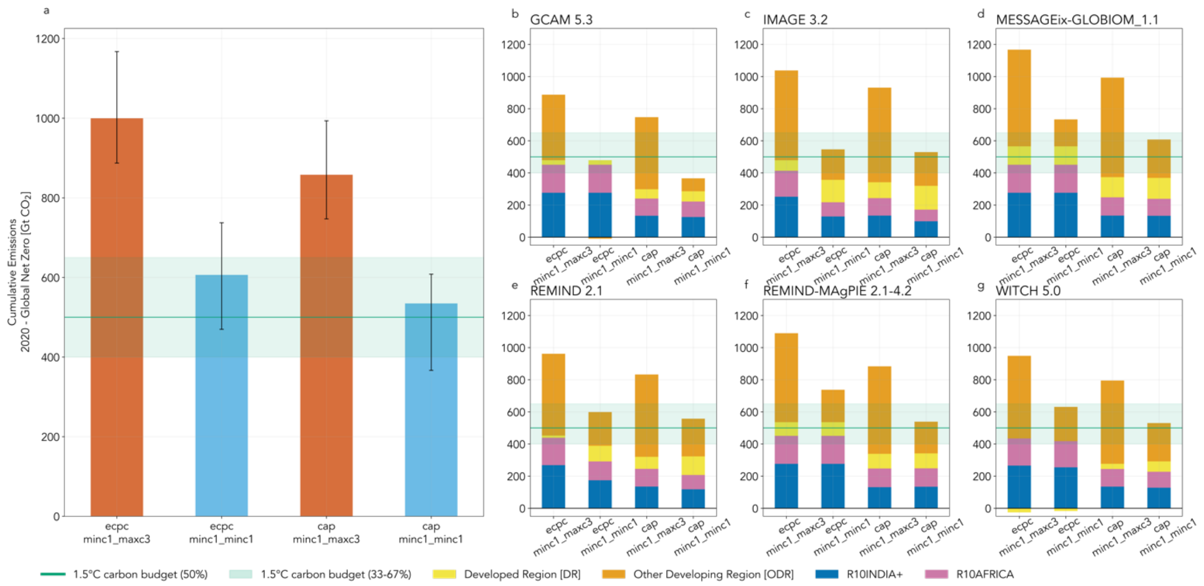

Figure 2: Comparing cumulative emissions until global net zero CO_2 with the remaining carbon budget for 1.5°C. (a) Across the four sets of scenarios, where the error bar shows the range of outcome across the individual synthetic scenarios, (b-h) Across each synthetic scenario for a single modelling framework. The modelling framework is indicated in the top-left corner of each panel. The

horizontal line and the shaded region indicate the median, and the 33rd – 67th percentile of the remaining carbon budget for 1.5°C assessed by the IPCC (Canadell *et al.*, 2021).

None of the synthetic scenarios constructed using the maximum cumulative emissions across the C1 and C3 categories for the developing regions (ecpc_minc1_maxc3, and cap_minc1_maxc3) keep cumulative emissions until net zero CO_2 within a low overshoot 1.5°C carbon budget. This finding holds irrespective of the quantification of the moral claim for R10INDIA+ and R10AFRICA, with the remaining low overshoot 1.5°C carbon budget exceeded by 237-517 Gt CO_2 for the ECPC case, and 97-343 Gt CO_2 for the CAP case (Figure 2a). The quantification of the moral claim becomes important when we assess the scenarios where the developing regions instead follow the lowest cumulative emission trajectories across the C1 and C3 categories (ecpc_minc1_minc1, and cap_minc1_minc1).

For this subset of scenarios, all scenarios constructed using the capability-based equity approach (cap_minc1_minc1) keep cumulative emissions until global net zero CO_2 within the low overshoot 1.5°C remaining carbon budget (Figure 2a). We also note that many of the scenarios in this subset (Figure 2b, 2c, 2f, 2g) have cumulative CO_2 emissions that are close to a remaining carbon budget associated with limiting peak warming to 1.5°C (>50%). However, in the ECPC case (ecpc_minc1_minc1), two out of six scenarios have cumulative CO_2 emissions that exceed the low overshoot 1.5°C RCB (these scenarios are constructed using the scenarios reported by MESSAGEix-GLOBIOM 1.1 – Figure 2d, and REMIND-MAgPIE 2.1-4.2 – Figure 2f). The reason these two synthetic scenarios demonstrate this behaviour is because they do not achieve net zero CO_2 emissions globally, to compensate for the increased emissions in R10INDIA+ and R10AFRICA. This is an issue which we explore in further detail in the following section.

A waterbed effect – regional net zero timings and net negative emissions sensitivity case

In the previous section, we have established that there are two key features of the scenarios that would place future emissions on a 1.5°C low overshoot trajectory. The first, is a scenario design input, which is that the DR minimises its net emissions (Figure 1a). The second is that other regions comprising the ODR in our analysis are also required to minimise net emissions. Across the synthetic scenarios we observe that the latter also results in a convergence between the net zero CO_2 timings between DR, and ODR (Figure 3a-f). Note that we calculate this metric for the aggregate region, and not across the individual sub-regions.

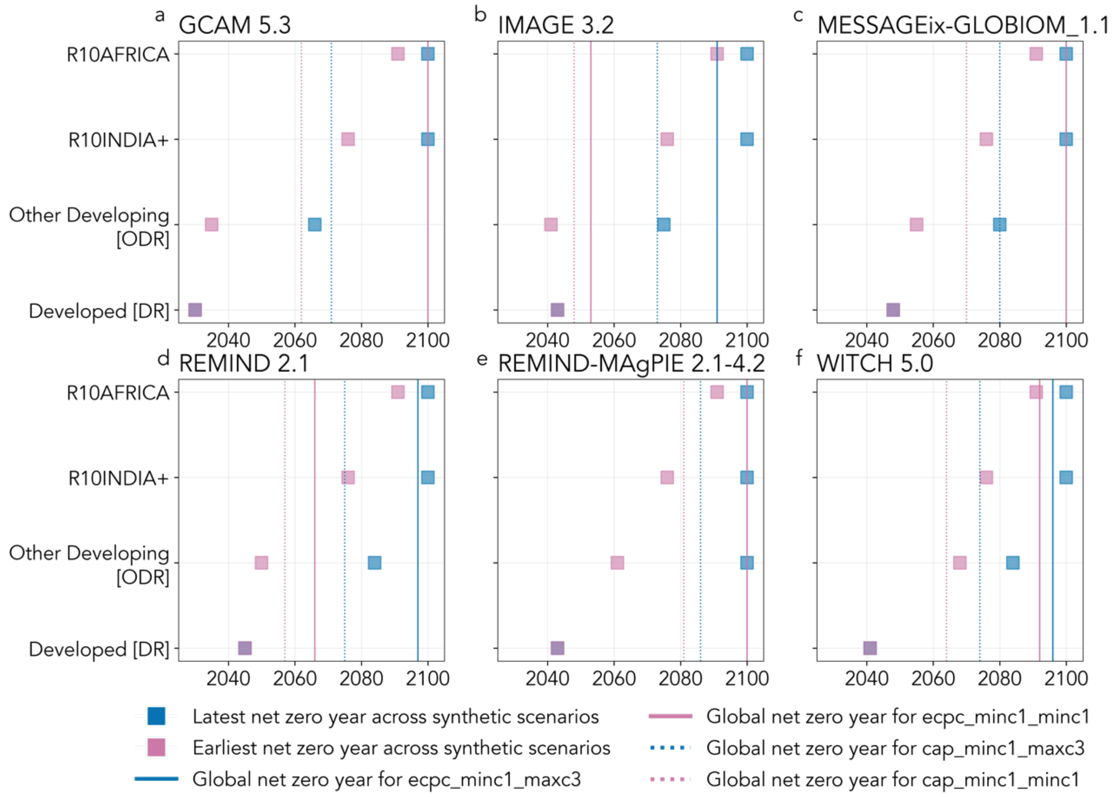

Figure 3: Net zero timings across the synthetic scenarios for key regions. (a-f) Across each synthetic scenario for a single modelling framework. Note that the net zero years for DR are in purple because the latest and earliest net zero years coincide.

Only 5 out of 24 synthetic scenarios have a net zero CO_2 year for the ODR, which is later than the global net zero CO_2 timing (Figure 3). Across the other 19 scenarios, the ODR has global net zero CO_2 timings, which are around 2 decades on average (range: 0-6 decades) ahead of the global net zero CO_2 year. This indicates that, by the time of global net zero CO_2 emissions, the ODR is already contributing negative emissions, which raises further questions around equity and fairness related to negative emissions (Fyson *et al.*, 2020; Pozo *et al.*, 2020). Among the developing regions that constitute the ODR, R10LATIN_AM has negative emissions in the year of global net zero CO_2 across all the synthetic scenarios (Table S3). For R10LATIN_AM, the negative emissions in the year of global net zero CO_2 can span from 3-5% (REMIND-MAgPIE 2.1-4.2) to 59-161% of the 2015 emission levels

(WITCH 5.0) (Table S3). To assess the potential implications of this regional reliance on negative emissions, we construct a set of sensitivity scenarios, where emissions for R10LATIN_AM are flatlined after achieving zero CO_2 emissions. We evaluate the results of the formal assessment of the warming outcomes of the main, and sensitivity scenarios in the following section.

Formal assessment of the warming outcomes of the scenarios

So far, we have restricted our scenario assessment to a 33%, or 50% RCB for 1.5°C - this corresponds to a "low overshoot" or "no overshoot" definition respectively, as adopted by the IPCC. Here, we assess the warming outcomes using the simple climate model FaIR (v1.6.2) in a probabilistic setup, which allows us to map these outcomes to pathway criteria that operationalise the long-term temperature goal of the Paris Agreement (Schleussner *et al.*, 2022). In Table 1, we highlight scenario characteristics which pass the criteria in sky blue, and those which do not, in red.

Table 1: Formal assessment of warming outcomes of the scenarios. We compare the warming outcomes to the thresholds outlined in Schleussner *et al.,* (2022). The cells are colored according to whether they pass the criterion (sky blue) or not (red). For an overview of the criteria applied here, please refer to the Table S4.

		Exceedance Probability 1.5C (FaIRv1.6.2)				median warming in 2100 (FaIRv1.6.2)				Exceedance Probability 2.0C (FaIRv1.6.2)			
	scenario	cap_minc1_maxc3	cap_minc1_minc1	ecpc_minc1_maxc3	ecpc_minc1_minc1	cap_minc1_maxc3	cap_minc1_minc1	ecpc_minc1_maxc3	ecpc_minc1_minc1	cap_minc1_maxc3	cap_minc1_minc1	ecpc_minc1_maxc3	ecpc_minc1_minc1
model	case												
GCAM 5.3	baseline	0.64	0.46	0.66	0.47	1.54	1.36	1.61	1.43	0.13	0.05	0.16	0.07
	sensitivity_lam	0.64	0.48	0.67	0.53	1.56	1.39	1.62	1.5	0.13	0.06	0.16	0.09
IMAGE 3.2	baseline	0.73	0.54	0.76	0.57	1.59	1.37	1.68	1.47	0.17	0.06	0.21	0.08
	sensitivity_lam	0.73	0.57	0.81	0.6	1.63	1.44	1.76	1.54	0.18	0.08	0.27	0.11
MESSAGEix-GLOBIOM_1.1	baseline	0.72	0.54	0.75	0.6	1.64	1.46	1.71	1.56	0.18	0.08	0.22	0.12
	sensitivity_lam	0.73	0.53	0.78	0.64	1.67	1.46	1.73	1.6	0.2	0.08	0.24	0.15
REMIND 2.1	baseline	0.66	0.55	0.71	0.55	1.54	1.35	1.64	1.44	0.14	0.06	0.18	0.08
	sensitivity_lam	0.66	0.53	0.71	0.57	1.56	1.4	1.65	1.51	0.14	0.06	0.19	0.1
REMIND-MAgPIE 2.1-4.2	baseline	0.68	0.51	0.79	0.61	1.6	1.45	1.74	1.59	0.16	0.07	0.25	0.14
	sensitivity_lam	0.68	0.52	0.8	0.62	1.61	1.46	1.75	1.59	0.16	0.07	0.26	0.14
WITCH 5.0	baseline	0.65	0.51	0.74	0.6	1.56	1.42	1.69	1.56	0.14	0.07	0.21	0.12
	sensitivity_lam	0.67	0.53	0.78	0.63	1.6	1.47	1.74	1.6	0.16	0.08	0.24	0.15

We generally observe that the formal warming outcomes of the scenarios map well to the 1.5°C RCB assessment that we carry out above, with a few exceptions. The first is that the synthetic scenarios for the ecpc_minc1_maxc3 case constructed using the GCAM 5.3 modelling framework keep peak warming below 1.5°C with at least a 33% chance, while the cumulative CO_2 emissions until net zero CO_2 exceeds the 1.5°C RCB by a wide margin (Figure 2b) – we trace this difference back to the process of infilling the non-CO_2 gases, especially in the 2020-2030 timeframe (Figure S2), reiterating the importance of a formal warming assessment, and associated warming uncertainties. Second, we observe that while many scenarios in the ecpc_minc1_minc1 case keep peak warming below 1.5°C with a greater than 33% chance, they do not bring warming down to 1.5°C in 2100 with at least a 50% chance, or keep warming below 2°C with at least a 90% chance. For both criteria, the sensitivity cases constructed with no negative CO_2 emissions lead to an increase in the peak exceedance probability (around 3% points increase for 1.5°C, and around 2% points increase for 2°C), and median end of century warming (around 0.05°C increase) for the ecpc_minc1_minc1 case. We note that these results, especially those close to the thresholds, are somewhat sensitive to the choice of emulator (FaIR v1.6.2 in this case). Another simple climate model, MAGICC (Nicholls *et al.*, 2020), which was applied for the scenario categorization in AR6 WGIII, exhibits faster near-term warming, and slightly higher peak temperatures than FaIR, especially for scenarios consistent with a 1.5°C RCB (Kikstra *et al.*, 2022). Hence, for some scenarios (e.g., GCAM 5.3 ecpc_minc1_maxc3 in Table 1), we would expect them to breach the thresholds identified by Schleussner *et al.*, (2022), if MAGICC was used for the climate assessment.

Discussion and Conclusion

In the absence of appropriate recognition of equity, and international financial transfers from developed countries, some scholars have suggested a unilateral claim to the remaining carbon space as a last resort (Jayaraman and Kanitkar, 2016). In this paper, we have constructed a set of synthetic emission scenarios to assess the implications of such a moral claim by South Asia and Africa using the scenarios underlying IPCC AR6 WG III. We find that there are mainly two possible outcomes across all scenarios, even when developed regions minimize their ongoing CO_2 emissions – either the Paris Agreement's LTTG is breached, or other developing regions need to minimize their CO_2 emissions as well to compensate for the gap between maximum developed regions emission reductions observed in the AR6 WG III scenarios and the 1.5°C LTTG.

The former case, which is invariant to the specific quantification of the moral claim is in itself an undesirable and highly inequitable outcome, especially for the populations of South Asia and Africa exposed to the impacts of climate change (Schleussner *et al.*, 2018; Saeed, Schleussner and Ashfaq, 2021). The latter case, which requires other developing regions to not only minimize their CO_2 emissions, but also to contribute with negative emissions, risks cascading inequities to other developing regions, as well as raising concerns over potential sustainability concerns associated with large-scale deployment of negative emissions (Fuss *et al.*, 2018). Facilitating such a minimization of emissions in other developing regions would also require appropriate levels of international finance. Looking ahead, based on the scenarios we assess here, we suggest three policy-relevant actions for developed regions. First, we propose that developed regions commit to deploying net-negative CO_2 emissions in proportion to the cumulative net-positive CO_2 emissions that they deploy (Fyson *et al.*, 2020). Second, we suggest that developed regions recognize the importance of equity in discussions of international climate finance. Finally, we reiterate that developed regions should show appropriate haste in facilitating the deployment of international financial transfers at scale to avoid putting the goals of the Paris Agreement out of reach.

Limitations and outlook for further work

In this work, we have used an ethically, and methodologically transparent approach to construct emission scenarios with heterogenous regional objectives. However, as is true for any work that relies on an unstructured ensemble of opportunity, we cannot draw conclusions on whether the regional bounds assessed here are the actual lowest possible regional emissions (Guivarch *et al.*, 2022). The scenarios (per modelling framework) constructed here should be understood to represent a potential scenario that could have been constructed by that modelling framework if: (i) regionally differentiated carbon prices were applied to match a pre-defined regional carbon budget, (ii) regional carbon budgets are applied. Ideally, a structured ensemble of scenarios using an inter-model comparison project would help evaluate further characteristics of such heterogenous scenarios, including a feasibility assessment (Brutschin *et al.*, 2021), and quantification of the magnitude of financial transfers.

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Author contributions

GG, CFS, and MJG initiated the study. GG performed the analysis with input from MJG, CFS, and AN. CJS provided the FaIR parameter set used in this study. GG and CFS wrote the manuscript with input from CJS, AN, MJG, KR, and CF. All authors provided contributions to the final draft of the manuscript.

Data and Code Availability

All input data necessary to run the analysis is openly available, with references included in the paper. Please refer to the README file in the code repository for further instructions.

The code used to conduct the analysis and prepare the figures is available at: https://gitlab.com/climateanalytics/tradeoff_scenarios.

<u>**Supplementary Information**</u>

Uncompensated claims to fair emission space risk putting Paris Agreement goals out of reach

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Region definitions applied in this paper

In this paper, we have used the R10-level scenario information published by the IPCC. In Table S1 below, we provide a brief overview of the regional definitions, using the information published along with the AR6 scenario database (Byers *et al.*, 2022). We also group the scenarios according to the composite regions which are used to present the information in this paper.

Table S1: Regional definitions. We also indicate the composite region definitions applied for Figure 1, Figure 2, and Figure 3 in the main text.

Region name	Region definition
Composite region from this paper: Developed Region [DR]	
R10NORTH_AM	North America; primarily the United States of America and Canada
R10EUROPE	Eastern and Western Europe (i.e., the EU28)
R10PAC_OECD	Pacific OECD
R10REF_ECON	Reforming Economies of Eastern Europe and the Former Soviet Union; primarily Russia
Composite region from this paper: Other Developing Region [ODR]	
R10CHINA+	Countries of centrally-planned Asia; primarily China
R10REST_ASIA	Other countries of Asia, except R10INDIA+
R10MIDDLE_EAST	Countries of the Middle East; Iran, Iraq, Israel, Saudi Arabia, Qatar, etc.
R10LATIN_AM	Countries of Latin America and the Caribbean
Individual regions assessed	
R10INDIA+	Countries of South Asia; primarily India
R10AFRICA	Countries of Sub-Saharan Africa

Applying the equal cumulative per capita emissions scheme from 1850-2019

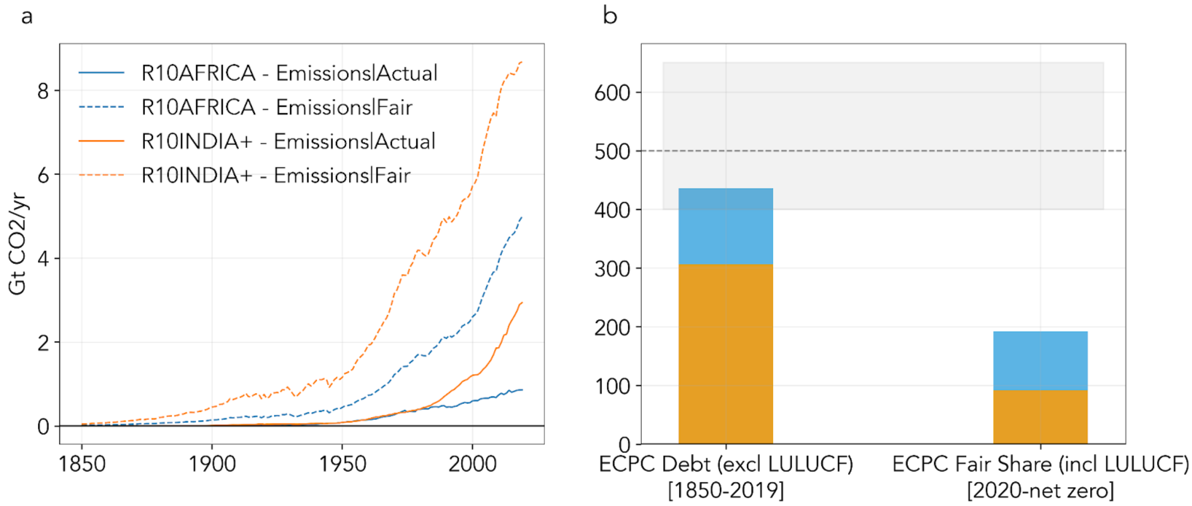

Figure S1: Comparing the equal cumulative per capita approach applied from 1850. (a) Emission pathways (actual versus the equal per capita counter factual), (b) Cumulative emission allowances in proportion to the debt.

Here, we calculate the moral claim for R10INDIA+ and R10AFRICA starting from the year 1850. Given data limitations for CO_2 land use, land use change, and forestry emissions (LULUCF), we restrict our analysis to total CO_2 emissions excluding land use, land use change, and forestry. We draw the emissions from the PRIMAP-Hist dataset, and the population estimates from a composite dataset published by Our World in Data (Gütschow, Günther and Pflüger, 2021; Our World in Data, 2022). We compare this cumulative emission allowance (i.e., moral claim between 1850-2019) and the moral claim to the remaining carbon budget (Figure S1b). This figure accompanies the analysis presented in the section “Focusing on the remaining carbon budget” in the main text.

Regional scenarios selected to construct global synthetic scenarios

In Table S2, we indicate the specific regional scenarios from the AR6 scenario database used to construct the synthetic emission scenarios (per modelling framework). The labels 'min' and 'max' in each cell indicates the scenarios with the minimum and maximum CO_2 emissions until regional net zero CO_2 emissions. Please note that we do not use the 'max' scenarios for developed regions.

Table S2: Regional scenarios per modelling framework underlying synthetic scenarios

	GCAM 5.3	IMAGE 3.2	MESSAGEix-GLOBIOM_1.1	REMIND 2.1	REMIND-MAgPIE 2.1-4.2	WITCH 5.0
R10CHINA+	'min':'R_MAC_30_n0', 'max':'R_MAC_75_n8'	'min':'SSP1_SPA1_19I_RE_LB', 'max':'SSP1_SPA1_26I_LIRE'	'min':'EN_NPi2020_500', 'max':'EN_NPi2020_1200'	'min':'CEMICS_GDPgrowth_1p5', 'max':'LeastTotalCost_CBA_brkSR15_SSP2_P50'	'min':'EN_NPi2020_400', 'max':'EN_INDCi2030_1200'	'min':'EN_NPi2020_450', 'max': 'EN_INDCi2030_1000f'
R10EUROPE	'min': 'R_MAC_30_n0' 'max': 'R_MAC_75_n8'	'min':'SSP1_SPA1_19I_LIRE_LB', 'max':'SSP2_SPA2_26I_D'	'min':'EN_NPi2020_450', 'max':'EN_NPi2020_1200_COV'	'min': 'R2p1_SSP1-PkBudg900', 'max':'LeastTotalCost_LTC_brkSR15_SSP5_P50'	'min':'NGFS2_Net-Zero 2050 - IPD-median', 'max':'EN_NPi2020_1200'	'min': 'EN_NPi2020_450', 'max': 'EN_INDCi2030_1000f_NDCp'
R10LATIN_AM	'min':'R_MAC_30_n0', 'max': 'NGFS2_Below 2°C'	'min':'SSP1_SPA1_19I_LIRE_LB', 'max': 'SSP2_SPA2_26I_D'	'min':'EN_NPi2020_450', 'max': 'EN_INDCi2030_1200_COV_NDCp'	'min': 'R2p1_SSP5-PkBudg900', 'max':'LeastTotalCost_CBA_brkSR15_SSP2_P50'	'min': 'EN_NPi2020_400', 'max': 'EN_INDCi2030_1000_NDCp'	'min':'EN_NPi2020_450', 'max':'EN_INDCi2030_1000f_NDCp'
R10MIDDLE_EAST	'min': 'R_MAC_35_n8', 'max': 'R_MAC_65_n0'	'min':'SSP1_SPA1_19I_RE_LB', 'max':'SSP1_SPA1_26I_LIRE'	'min': 'NGFS2_Delayed Transition', 'max': 'EN_NPi2020_1200'	'min': 'R2p1_SSP5-PkBudg900', 'max': 'LeastTotalCost_CBA_brkSR15_SSP2_P50'	'min':'EN_NPi2020_400', 'max':'EN_NPi2020_1200'	'min': 'CO_Bridge', 'max': 'EN_NPi2020_1000f'
R10NORTH_AM	'min':'R_MAC_30_n0', 'max':'R_MAC_75_n8'	'min': 'SSP2_SPA1_19I_LIRE_LB', 'max':'SSP1_SPA1_26I_D'	'min':'EN_NPi2020_450', 'max':'EN_NPi2020_1200_COV'	'min': 'R2p1_SSP1-PkBudg900', 'max':'CEMICS_GDPgrowth_2C'	'min':'EN_NPi2020_400', 'max':'EN_NPi2020_1200f'	'min':'EN_NPi2020_450', 'max':'EN_INDCi2030_1000f'
R10PAC_OECD	'min':'R_MAC_35_n8', 'max':'R_MAC_65_n0'	'min':'SSP1_SPA1_19I_LIRE_LB', 'max':'SSP1_SPA1_26I_RE'	'min': 'EN_NPi2020_450', 'max':'EN_NPi2020_1200_COV'	'min': 'R2p1_SSP1-PkBudg900', 'max':'CEMICS_GDPgrowth_2C'	'min': 'EN_NPi2020_400', 'max': 'EN_INDCi2030_1200'	'min':'EN_NPi2020_450', 'max':'EN_INDCi2030_1000f_NDCp'
R10REF_ECON	'min':'R_MAC_30_n0', 'max': 'NGFS2_Below 2°C'	'min':'SSP1_SPA1_19I_LIRE_LB', 'max':'SSP2_SPA2_26I_D'	'min':'EN_NPi2020_450', 'max':'EN_NPi2020_1200'	'min':'CEMICS_Linear_1p5', 'max':'LeastTotalCost_CBA_brkSR15_SSP2_P50'	'min':'EN_NPi2020_400', 'max':'EN_INDCi2030_1200'	'min':'EN_NPi2020_450', 'max':'EN_INDCi2030_1000f_NDCp'
R10REST_ASIA	'min': 'R_MAC_35_n8', 'max': 'R_MAC_65_n0'	'min':'SSP1_SPA1_19I_LIRE_LB', 'max':'SSP1_SPA1_26I_LIRE'	'min':'EN_NPi2020_450', 'max':'EN_NPi2020_1200'	'min':'CEMICS_GDPgrowth_1p5', 'max':'LeastTotalCost_CBA_brkSR15_SSP2_P50'	'min':'EN_NPi2020_400', 'max':'EN_NPi2020_1200f'	'min':'EN_NPi2020_450', 'max':'CO_Bridge'

Other developing region emissions at global net zero CO_2

In Table S3, we show the regional emission profiles (for the developing regions) in the year of global net zero CO_2, relative to 2015 emission levels.

Table S3: Regional emissions at global net zero CO_2 (relative to 2015 emissions) [%]

	R10LATIN_AM_normalised		R10CHINA+_normalised		R10MIDDLE_EAST_normalised		R10REST_ASIA_normalised	
stat_type	**max**	**min**	**max**	**min**	**max**	**min**	**max**	**min**
model								
GCAM 5.3	-7	-33	-3	-16	25	3	8	-38
IMAGE 3.2	-65	-133	7	-4	58	1	13	-4
MESSAGEix-GLOBIOM_1.1	-42	-86	3	-1	49	1	13	1
REMIND 2.1	-16	-75	-1	-13	47	20	31	-14
REMIND-MAgPIE 2.1-4.2	-3	-5	-1	-4	28	15	19	-2
WITCH 5.0	-59	-161	18	10	71	-7	10	-15

Criteria to assess Paris Agreement consistency of scenarios

Here, we describe the criteria used to assess the Paris Agreement consistency of the synthetic emission scenarios (Table S4), based on the criteria proposed by Schleussner et al.,(2022).

Table S4: Criteria to assess Paris Agreement consistency of scenarios

Criterion	Specification
Crit I: “pursuing efforts to limit warming to 1.5°C”	• Pathways should not ever have a greater than 67% chance of exceeding 1.5°C • Pathways should bring warming to 1.5°C in 2100 with at least a 50% chance in case of overshoot
Crit II: hold warming to “well below 2°C”	• Pathways should keep warming below 2°C with at least a 90% chance throughout the century

Methane emissions compared for the ecpc_minc1_maxc3 case

Figure S2 accompanies the assessment presented in the section “Formal assessment of the warming outcomes of the scenarios” in the main text. Here, Scenario 1 refers to the ecpc_minc1_maxc3 case.

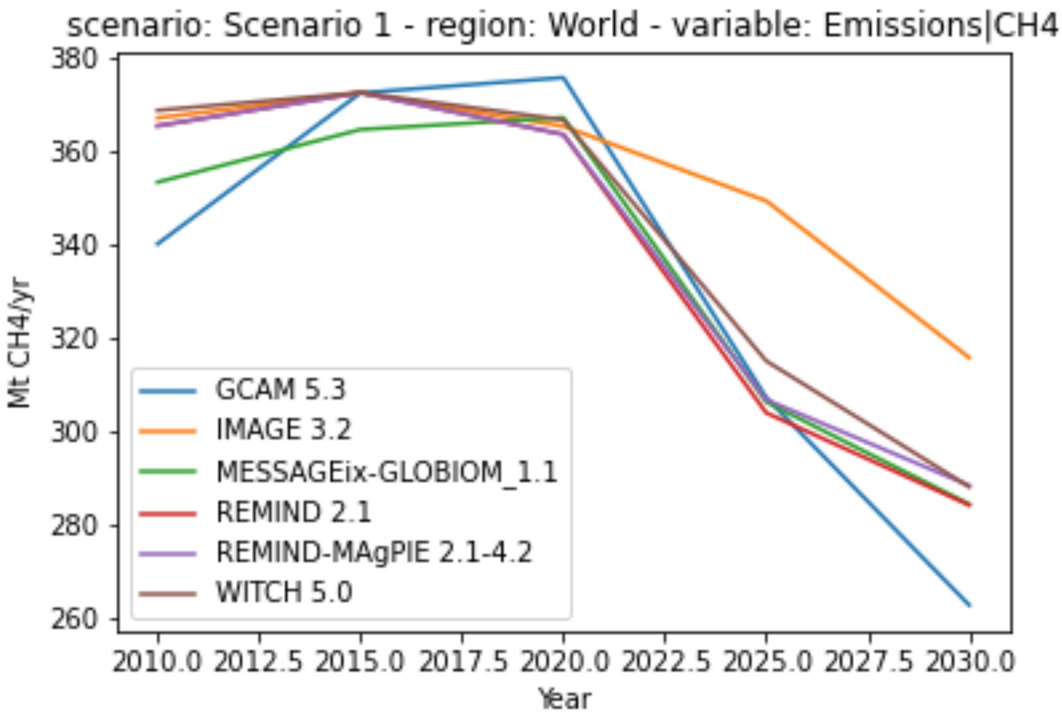

Figure S2: Comparison of infilled CH_4 emissions across the “ecpc_minc1_maxc3” scenarios.

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