

National Carbon Budgets and Net-Zero Targets under Dual Emissions Accounting

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National Carbon Budgets and Net-Zero Targets under Dual Emissions Accounting

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Abstract

Consumption-based and territorial emissions accounting could operate side by side, as has been proposed by a few countries. However, how such dual accounting affects assessments of national mitigation ambition remains unclear. Here, we derive national carbon budgets and implied net-zero emission years under hypothetical net-zero targets that cover both territorial and consumption-based emissions within a dual accounting framework. We apply three effort-sharing approaches for 91 countries plus the European Union. Our results show that the derived national mitigation ambitions are sensitive not only to the effort-sharing approach used but also to the weight given to territorial versus consumption-based emissions when assigning responsibility to individual countries. The impact is strongest for countries with historically large net emissions embodied in trade. Under a dual accounting framework, the weight given to territorial versus consumption-based emissions when assigning responsibility to individual countries cannot be determined empirically and constitutes another inherently normative component.

A growing number of countries are setting long-term net-zero emissions targets, based on the established territorial emission accounting used within international reporting¹. Territorial emission accounting attributes emissions to the countries where they occur and benefits from being consistent with a country's political and economic borders as well as low statistical uncertainty given that emissions are monitored close to their source². Meanwhile, it has been criticized for omitting responsibilities for emissions occurring in other countries during the production and transportation of imported goods and services³. Consumption-based emission accounting instead attributes emissions to countries' end-use of goods and services. Shifting to consumption-based accounting may, however, introduce new blind spots in countries' responsibility for reducing the carbon intensity of exports³, risk reducing the effectiveness of climate change mitigation policy⁴, and not fulfil the transparency frameworks' requirements stipulated in the Paris Agreement⁵. In addition, consumption-based accounting typically has higher uncertainty than territorial⁶, and it is unclear whether such a shift would have an overall beneficial effect on mitigating climate change⁷.

An alternative is to implement the two accounting systems alongside each other at the national level^{3,5}. So far, France has adopted such a complementary consumption-based target as part of its national low-carbon strategy^{8,9}, and a proposal has been put forth in Sweden¹⁰. Other countries are monitoring consumption-based emissions and considering policy interventions (e.g., Denmark¹¹ and the United Kingdom (UK)¹²). Such a dual accounting framework addresses critiques of territorial emission targets, but adds complexity to climate policies. This duality also needs to be reflected in the assessment of national mitigation ambitions in the context of the Paris Agreement's equity principle¹³ "common but differentiated responsibilities and respective capabilities, in the light of different national circumstances".

A large body of literature has proposed different effort-sharing approaches for allocating the global carbon budget using territorial accounting^{14–16}, but less focus has been given to effort-sharing from a consumption-based perspective. Consumption-based accounting has been used by Fanning and Hickel¹⁷, and Hickel¹⁸ to assess countries' historic responsibility in relation to a carbon budget estimated based on equal emissions per capita. However, a dual accounting framework introduces a risk of double-counting emissions in assessing a country's responsibility for mitigating climate change since emissions embodied in the trade of one country's imports (i.e., consumption-based emissions) are also accounted for by another country's exports (i.e., territorial emissions). The theoretical implications of sharing the responsibility for environmental impacts between producers and consumers have been discussed for several decades, such as the dilemma of double-counting of environmental responsibilities^{2,19,20}, justice arguments for

burden-sharing^{7,21}, and how to operationalize burden-sharing^{2,20,22–24}. To the authors' knowledge, no study has yet explored the implications of a dual accounting framework and complementary mitigation targets on global effort sharing.

This paper aims to address how a dual accounting framework affects equity assessments of national mitigation ambitions. In this study, we estimate individual countries' required mitigation targets and national carbon budgets while varying the weight given to territorial versus consumption-based emissions when assigning responsibility to individual countries. We focus on the hypothetical case of countries adopting a net-zero emission year target that encompasses both territorial and consumption-based emissions, inspired by the recent Swedish policy proposal¹⁰, and present results for 91 countries plus the EU and its member states.

Our analysis is the first to systematically consider how a dual accounting framework affects assessments of the mitigation ambitions of countries with complementary consumption-based targets. The results are expected to be useful for analysts who assess countries' mitigation ambitions and provide support for policy-making processes.

Results

National carbon budgets and net-zero emission years across the weighting spectrum

We highlight results for five jurisdictions – China, the EU, South Africa, Sweden, and the United States. For each, we show how shifting the weight given to territorial versus consumption-based emissions in assigning responsibility affects national carbon budgets (Figure 1) and implied net-zero emission years under a linear emissions-reduction pathway (Figure 2). The effect of the shift in weighting on national carbon budgets and implied net-zero emission years depends on the jurisdiction's historical emission trends (Figure 3), which reflect whether the jurisdiction is a net exporter or net importer of emissions embodied in trade.

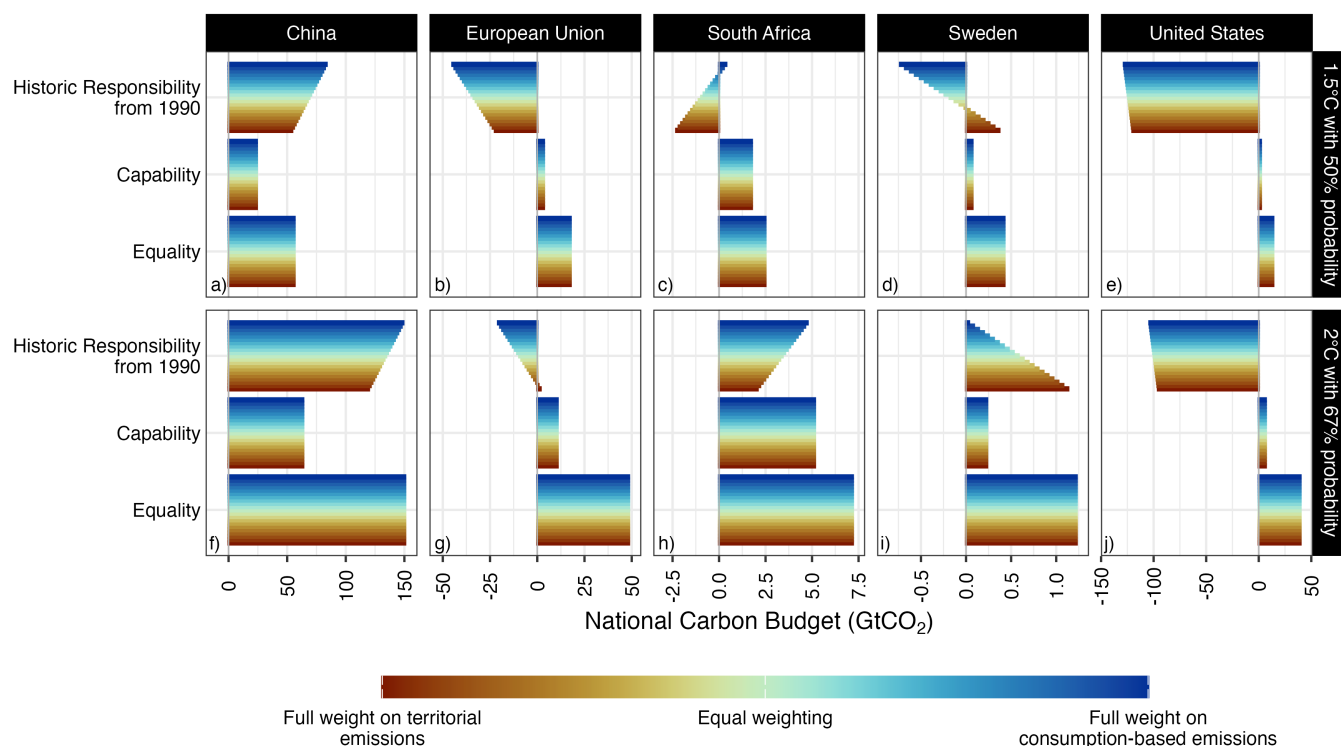


Figure 1. **National carbon budget estimates for different effort-sharing approaches under the dual accounting framework.** National carbon budgets (x-axis) for different effort-sharing approaches (y-axis: historic responsibility from 1990 – cumulative equal emissions per capita; capability – economic and population developments; equality – annual equal emissions per capita) and for the weight given to territorial versus consumption-based emissions when assigning responsibility to individual jurisdictions (color scale). Results are provided for the five jurisdictions, **a,f** – China, **b,g** – the European Union, **c,h** – South Africa, **d,i** – Sweden, and **e,j** – United States, and for two global temperature goals, **a,b,c,d,e** – 1.5°C with 50% probability, and **f,g,h,i,j** – 2.0°C with 67% probability.

The remaining carbon budgets for capability and equality are unaffected by the shift in weighting, as these are forward-looking approaches and independent of the emissions accounting framework. However, for the historic responsibility approach, past emissions matter. For the historic responsibility approach and both temperature goals, the EU and Sweden get a tighter carbon budget by 22.5 GtCO₂ and 1.1 GtCO₂, respectively, when shifting the weighting toward consumption-based emissions (Figure 1b, d). This happens as both jurisdictions have higher historic consumption-based emissions than territorial emissions (Figure 3b, d). For the EU and under the 1.5°C global warming limit (with a 50% probability of remaining below the threshold), the carbon budget is negative under both emissions accounting frameworks, but for Sweden, the shift in weighting results in a shift from a positive to a negative budget. China and South Africa represent an opposite case with higher territorial emissions than consumption-based emissions historically (Figure 3a, c). Here, shifting the weighting toward consumption-based emissions enlarges the remaining carbon budget by 29.4 GtCO₂ and 2.7 GtCO₂, respectively (Figure 1a, c).

Under the 1.5°C temperature goal, shifting the weighting toward consumption-based emissions advances the implied net-zero emission year for all effort-sharing approaches that generate a positive carbon budget by up to 1-4 years and 2-9 years for the EU and Sweden, respectively, depending on the effort-sharing approach (Figure 2b, d). Meanwhile, shifting the weighting toward consumption-based emissions pushes the implied net-zero emission years back for all effort-sharing approaches that generate a positive carbon budget by up to 0-6 years and 3-4 years for China and South Africa, respectively, depending on the effort-sharing approach (Figure 2a, c). Notably, both the US and the EU carry negative carbon budgets under the historic responsibility approach at 1.5°C, precluding a finite net-zero year under either full territorial or full consumption-based weighting. This also applies to Sweden when shifting the weighting towards consumption-based emissions. Conversely, South Africa's budget turns negative when shifting the weighting towards territorial emissions.

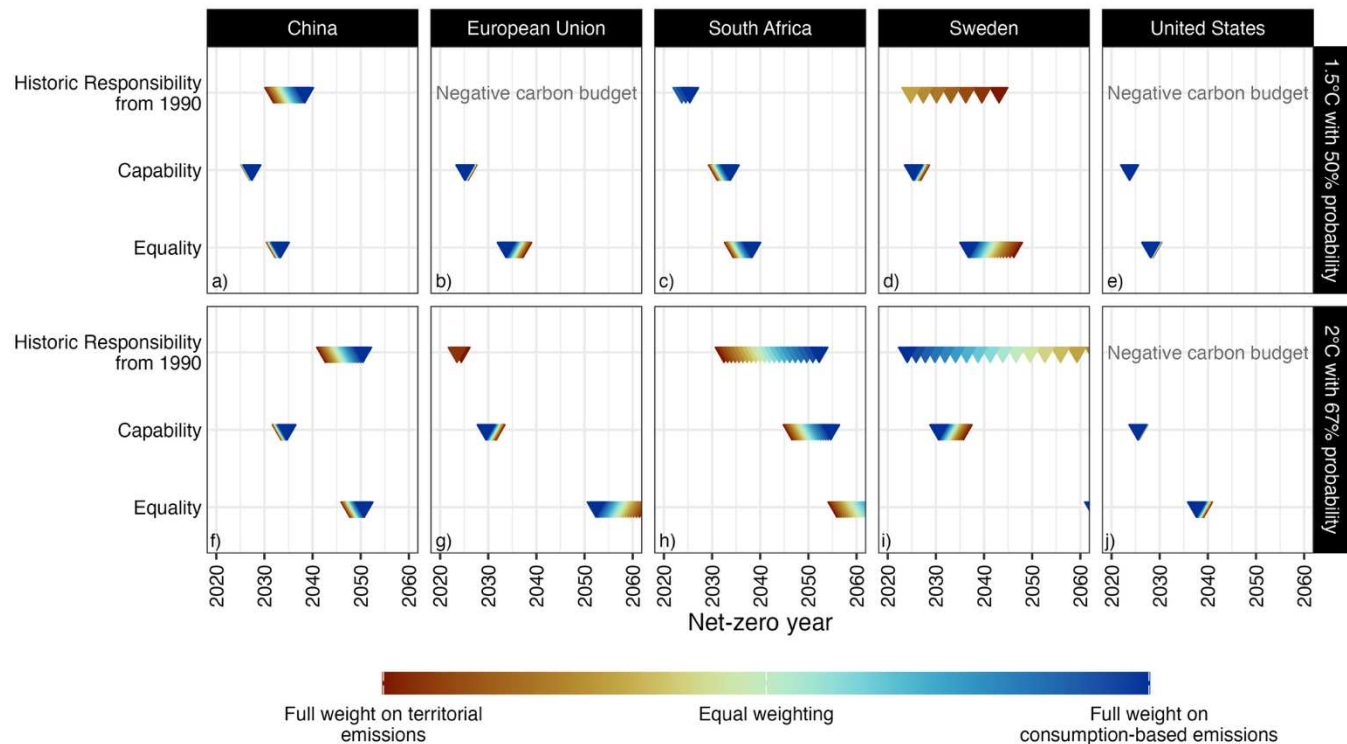


Figure 2. Implied net-zero emission year under a linear emissions reduction pathway for different effort-sharing approaches under the dual accounting framework. Implied net-zero emission year (x-axis) for different effort-sharing approaches (y-axis: historic responsibility from 1990 – cumulative equal emissions per capita; capability – economic and population developments; equality – annual equal emissions per capita) and the weight given to territorial versus consumption-based emissions when assigning responsibility to individual jurisdictions (color scale). Results are provided for the five jurisdictions, **a,f** – China, **b,g** – the European Union, **c,h** – South Africa, **d,i** – Sweden, and **e,j** – United States, and for two global temperature goals, **a,b,c,d,e** – 1.5°C with 50% probability, and **f,g,h,i,j** – 2.0°C with 67% probability.

These patterns still hold qualitatively under the 2.0°C warming limit (with a 67% probability of remaining below the threshold), but the larger global carbon budget amplifies both the

absolute implied net-zero years and the range in the results when shifting across the territorial-consumption-based spectrum. These effects are particularly clear for jurisdictions with large differences in emission trends between the two accounting frameworks (e.g., Sweden and South Africa, Figure 2h, i). While the absolute difference in carbon budgets remains the same regardless of temperature goal, the shift in implied net-zero emission year is brought forward by 61 years under the historic responsibility approach for Sweden and pushed back by 20 years for South Africa when shifting the weighting toward consumption-based emissions. The US shows comparatively small differences between accounting frameworks (Figure 3e), resulting in modest shifts in the implied net-zero emission year of up to 2 years, even under the 2.0°C temperature goal.

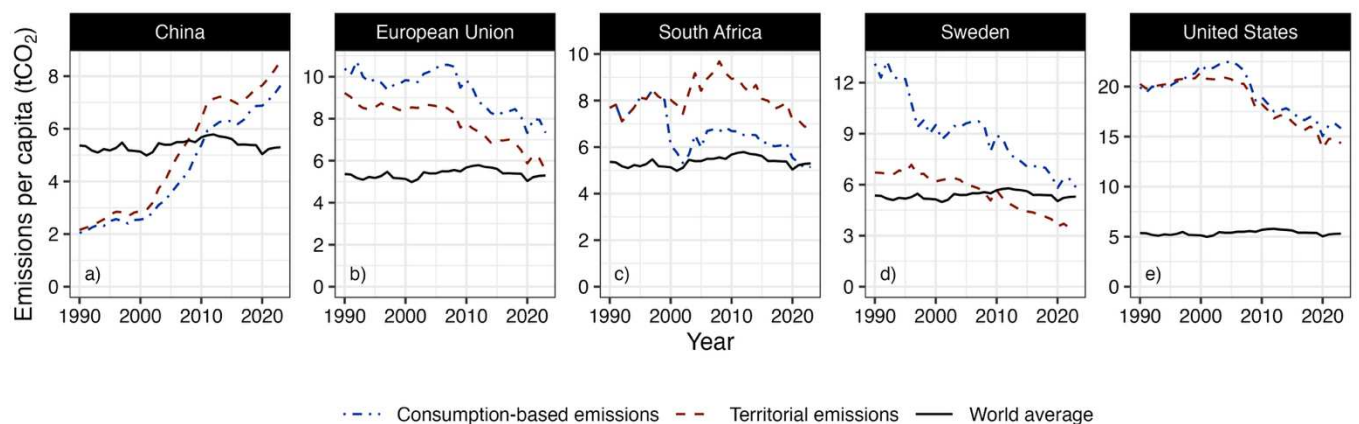


Figure 3. **Historic per-capita emission trends compared to world average.** a China, b European Union, c South Africa, d Sweden, and e United States. Time series (x-axis) are provided for the period 1990-2021 and depending on the accounting framework (line type). A time series for global average emissions per capita (solid line) is provided in each panel for comparison.

Comparing net-zero emission years across all jurisdictions

For all jurisdictions, we show how the implied net-zero emission year (up until 2100) shifts when moving from full weight on territorial emissions to full weight on consumption-based emissions. For emissions embodied in trade, this is equivalent to shifting full responsibility from the exporting countries to the importing countries. Emissions occurring within a country to produce goods and services used domestically remain unaffected by the weighting. Results are, hence, compared to the embodied emissions balance, the relative difference between the jurisdiction's consumption-based and territorial emissions, in Figure 4 and compared to economic development according to the World Bank's classification²⁵ in Figure 5. If a jurisdiction's result is on the identity line, the implied net-zero emission year is equal regardless of how weight is shifted between territorial and consumption-based emissions. We also show how jurisdictions transition outside the

range of these graphs, i.e., towards negative carbon budgets or implied net-zero emission years beyond 2100 (Figure 6).

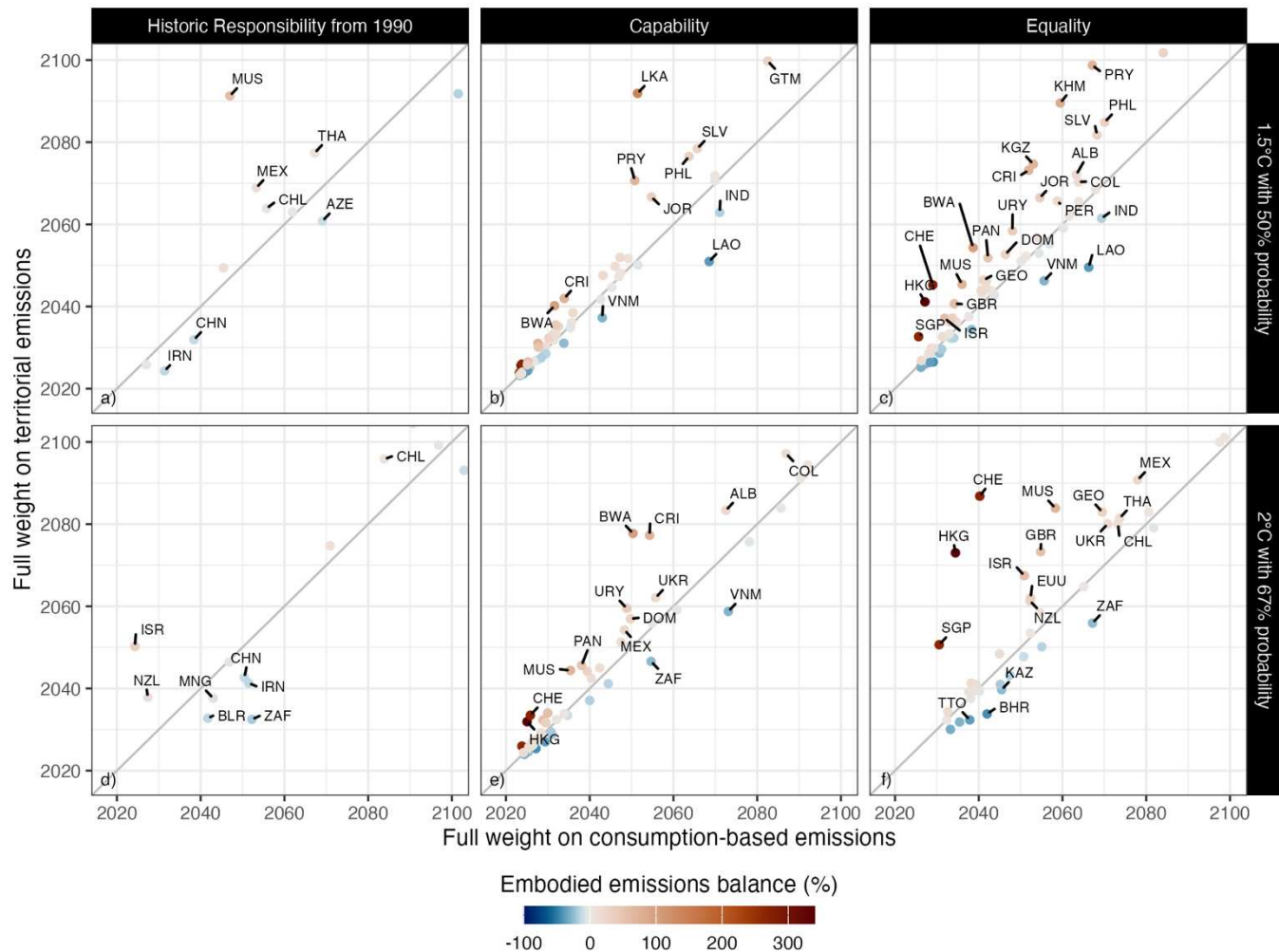


Figure 4. Implied net-zero emission years compared to embodied emissions balance. Implied net-zero emission year for the 91 countries and the European Union when full weight is given to territorial (y-axis) or consumption-based (x-axis) emissions in assigning responsibility to individual jurisdictions, for the effort-sharing approaches, **a,d** – historic responsibility from 1990 (cumulative equal emissions per capita), **b,e** – capability (economic and population developments), **c,f** – equality (annual equal emissions per capita), for two global temperature goals, **a,b,c** – 1.5°C with 50% probability, and **d,e,f** – 2.0°C with 67% probability, depending on the jurisdiction’s embodied emission balance, i.e. relative difference between consumption-based and territorial emissions (color). The embodied emission balance represents the country’s relative difference between accounting systems for the last year for capability and equality, while representing the cumulative balance since 1990 for historic responsibility, due to the approaches methodological differences. Jurisdictions that move more than five years when shifting the weighting are highlighted with their ISO-code.

As indicated in the five-jurisdiction analysis (Figure 1 and Figure 2), the direction of shift is strongly influenced by each jurisdiction’s embodied emissions balance. Figure 4 shows that a positive embodied emissions balance, where consumption-based emissions are larger than territorial emissions, generally results in an earlier implied net-zero emission year when shifting the weighting toward consumption-based emissions, and vice versa.

The effect is less pronounced for jurisdictions with initially small carbon budgets relative to their annual emissions, resulting in near-term implied net-zero emission years, such as Switzerland for capability compared to equality. Results for EU member states are available in Extended Data Figure 2.

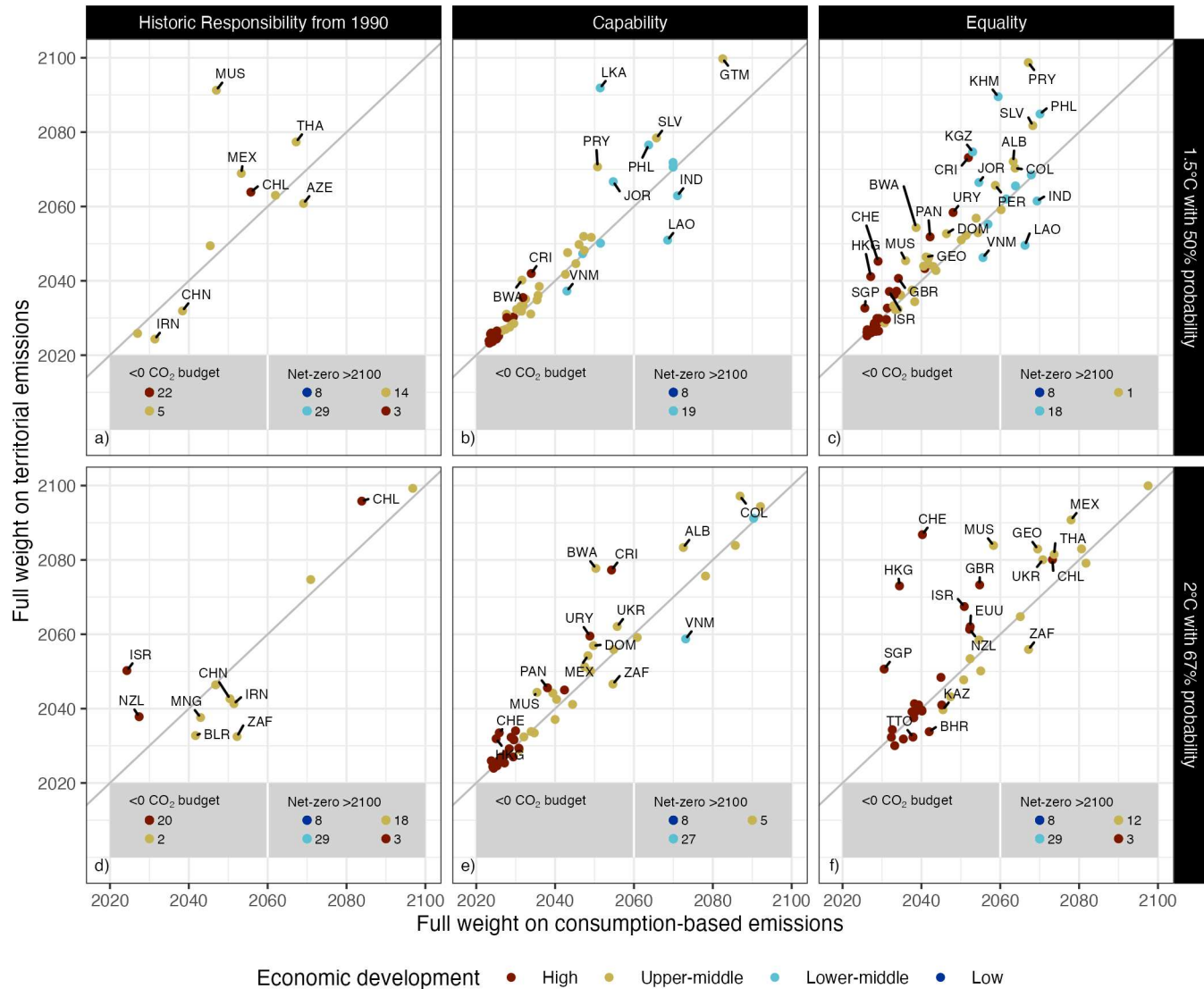


Figure 5. Implied net-zero emission years compared to economic development level. Implied net-zero emission year for the 91 countries and the European Union when full weight is given to territorial (y-axis) or consumption-based (x-axis) emissions in assigning responsibility to individual jurisdictions, for the effort-sharing approaches, **a,d** – historic responsibility from 1990 (cumulative equal emissions per capita), **b,e** – capability (economic and population developments), **c,f** – equality (annual equal emissions per capita), for two global temperature goals, **a,b,c** – 1.5°C with 50% probability, and **d,e,f** – 2.0°C with 67% probability, depending on the jurisdiction’s level of economic development (color). Jurisdictions that move more than five years when shifting the weighting are highlighted with their ISO-code.

The strongest shifts (>20 years) towards earlier implied net-zero emission years when shifting the weighting toward consumption-based emissions are observed among high- or

upper-middle-income jurisdictions as well as for three lower-middle-income jurisdictions under the 1.5°C temperature goal (Figure 5): Sri Lanka (40 years earlier under capability), Cambodia (30 years earlier under equality), and Kyrgyz Republic (22 years earlier under equality). The strongest shifts towards later implied net-zero emission years (>20 years) for high- and upper-middle-income jurisdictions are observed for Mauritius (44 years later under historic responsibility from 1990), Paraguay (32 years later under equality), and Costa Rica (21 years later under equality). For the 2°C temperature goal, the strongest shifts (>20 years) towards earlier implied net-zero emission years when shifting the weighting toward consumption-based emissions include Costa Rica (23 years earlier under capability) and Singapore (20 years earlier under capability), while net-zero is pushed back for South Africa (20 years later under historic responsibility from 1990).

Since only a subset of jurisdictions have implied net-zero emission years during the period 2024-2100 (shown in Figure 4 and Figure 5), we here consider differences in the number of jurisdictions with negative budgets and implied net-zero emission years after 2100, and how this is affected by shifting the weighting toward consumption-based emissions (Figure 6). Implied net-zero emission years occur after 2100 for low-income jurisdictions under all effort-sharing approaches and both temperature goals, and for lower-middle-income jurisdictions under historic responsibility except for one country and the 1.5°C temperature goal. The implied net-zero emission years for lower-middle-income jurisdictions mainly occur after 2100 for capability (19 and 27 for the 1.5°C and 2.0°C temperature goals, respectively, with two jurisdictions getting earlier net-zero emission years when shifting the weighting) and for equality (17 and 29 for the 1.5°C and 2.0°C temperature goals with an additional two and one jurisdictions when shifting the weighting, respectively). Even though lower-middle- and low-income jurisdictions generally have an implied net-zero year after 2100 – due to their currently low emission levels as compared to their assigned carbon budgets for the different effort-sharing approaches – the effects of shifting the weighting toward consumption-based emissions are prevalent also within these income categories. Given that most of these jurisdictions have larger consumption-based emissions than territorial (i.e., a positive embodied emission balance in Extended Data Figure 1), the shift in weighting results in an earlier implied net-zero emission year also for jurisdictions in the Net-zero after 2100 category, except for Burkina Faso, Lao PDR, Honduras, Viet Nam, India, Tunisia, Indonesia, and Jamaica, whose implied net-zero years are all pushed back by more than five years. Upper-middle-income jurisdictions are mixed between categories under all approaches. Meanwhile, negative budgets only arise under historic responsibility – since equality and capability budgets are always non-negative – and are concentrated among high-income jurisdictions (20 and 16 for the 1.5°C and 2.0°C temperature goals with an additional two and four jurisdictions when shifting the weighting, respectively). Few high-

income jurisdictions have implied net-zero emission years beyond 2100: one for historic responsibility (1.5°C temperature goal) and one for equality (2.0°C temperature goal), both with two additional when shifting the weighting, as well as three for historic responsibility (2.0°C temperature goal).

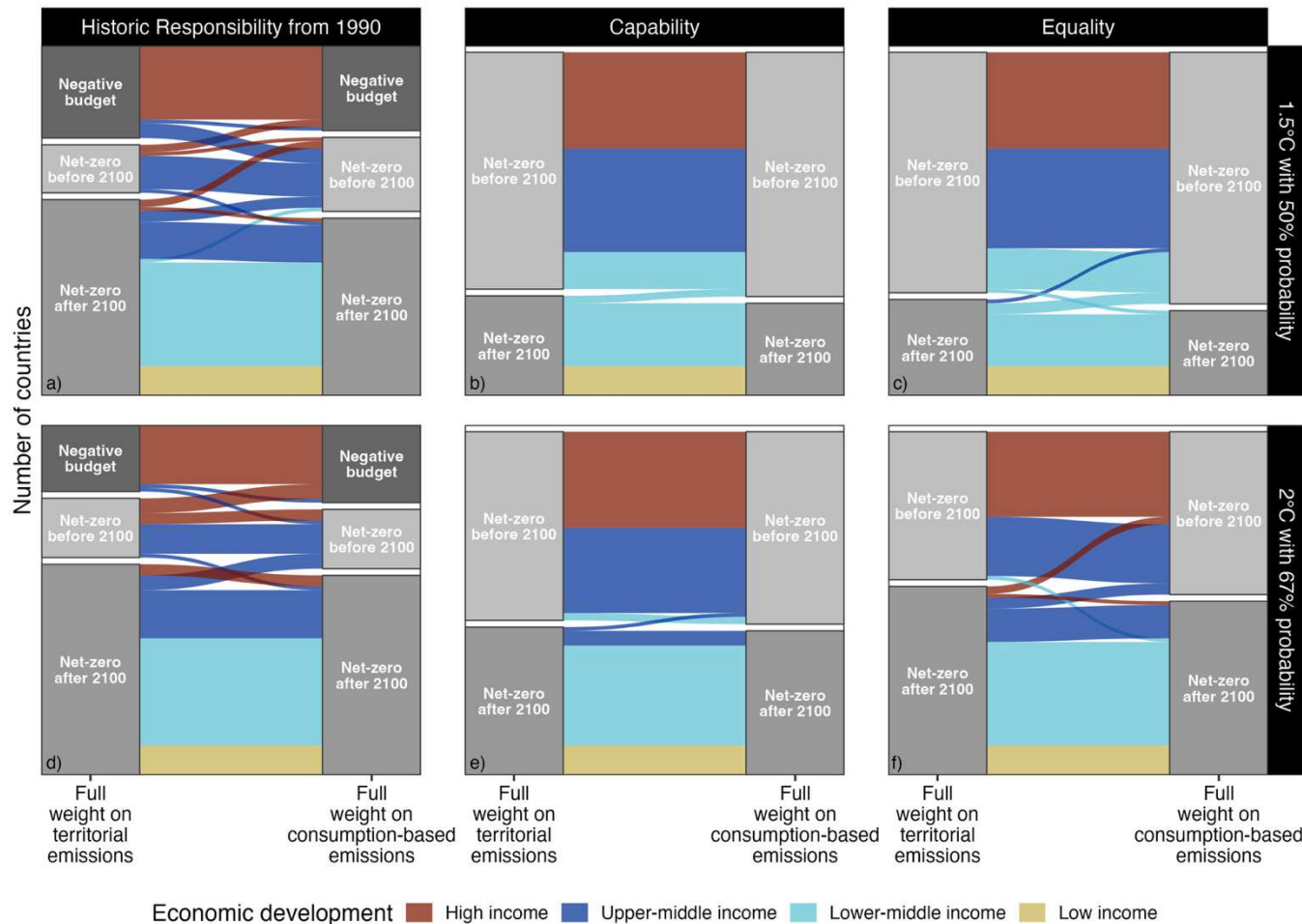


Figure 6. **Number of jurisdictions with negative budget, net-zero before 2100, and net-zero after 2100.** Sankey diagrams showing the number of jurisdictions that transition to or from the groups: negative budget, net-zero before 2100 and net-zero after 2100 when shifting the weight from territorial to consumption-based emissions when assigning responsibility to individual jurisdictions, for the effort-sharing approaches, **a,d** – historic responsibility from 1990 (cumulative equal emissions per capita), **b,e** – capability (economic and population developments), **c,f** – equality (annual equal emissions per capita), for two global temperature goals, **a,b,c** – 1.5°C with 50% probability, and **d,e,f** – 2.0°C with 67% probability, depending on the jurisdiction’s level of economic development (color).

Detailed results on the implied net-zero emission year for all jurisdictions are available in Extended Data Figure 3 for the 1.5°C temperature goal and Extended Data Figure 4 for the 2.0°C temperature goal; Extended Data Figure 5 and Extended Data Figure 6 show results for EU member states for the respective temperature goals. Estimated carbon budgets are available in Extended Data Figure 7 for the 1.5°C temperature goal and Extended Data

Figure 8 for the 2.0°C temperature goal; Extended Data Figure 9 and Extended Data Figure 10 show results for EU member states for the respective temperature goals.

Discussion

Our results show a notable difference in both national carbon budgets and implied net-zero emission years for many countries when shifting the weight given to territorial versus consumption-based emissions for assigning responsibility to individual countries. However, unequivocally determining where in this range fair emission attribution lies goes beyond value-neutral scientific reasoning but rather depends on philosophical standpoints. A review of philosophical arguments for how to account for emissions in the context of allocating the carbon budget finds consensus that producers and consumers should be considered jointly responsible since they both benefit from the production of goods and services²¹. Duus-Otterström and Hjorthen⁷ consider both the demand for products and services (emanating from consumers and, by extension, the countries where they reside) and producers' positive response to this demand necessary for giving rise to emitting activities. Meanwhile, Duus-Otterström and Hjorthen⁷ argue that the joint responsibility does not necessarily mean equally divided attribution and that the attribution level rather depends on the specific supply chain (e.g., agency of actors along the supply chain to reduce emissions). Rodrigues et al.²⁰ instead argue that the responsibility is equal for both producers and consumers and that any environmental indicator, therefore, should attribute 50% of the environmental impacts to each. Another alternative is to use current trade patterns to determine the level of attribution between countries. Andrew and Forgie²³ attributed emissions based on each industry sector's value added in the supply chain using data from multi-regional input-output analysis. Csutora and Vetőné Mózner²⁴ suggest using real-world data on imports and exports to determine which country benefited the most from producing versus consuming goods and services. In this case, an attribution to consumers is estimated using the value passed along the supply chains of products and services, whereas producers are attributed emissions corresponding to the value added in proportion to total output for domestic production. While the latter two approaches are grounded in data, that is also their limitation since countries' future carbon budgets then also become intertwined with current trade patterns. Ultimately, we consider the weight given to territorial versus consumption-based emissions when assigning responsibility to individual countries to be another normative assumption needed when assessing national mitigation ambitions, similar to other uncertainties²⁶ (e.g., the carbon budget chosen to represent a given temperature goal, the choice of effort-sharing approach, and assumptions made in the calculation of national carbon budgets).

Many countries may need to delay emission reductions to catch up in terms of economic development, especially the least developed countries, which also currently respond to a small share of global emissions¹. Our approach assumes a linear emission reduction pathway from current emission levels to an implied net-zero emission year, consistent with the country's carbon budget. The approach results in notably late implied net-zero emission years for jurisdictions with low economic development and historic emissions. This indicates room for these jurisdictions to delay the phase-out of carbon dioxide-emitting sources, which could be accounted for by assuming different national emission pathways for developing economies (e.g., as implemented by Anderson et al.²⁷), but that would in itself require additional assumptions. Further, effort-sharing approaches that consider historic responsibility for emissions often result in negative carbon budgets for countries with large historic emissions. Countries with negative carbon budgets are, in our analysis, at a high or upper-middle level of economic development, but could not practically achieve net-negative emissions from day one despite their economic strength. In contrast to the countries with late implied net-zero emission years, the negative carbon budgets indicate a need for reallocating emission space between countries, where economically stronger countries could finance a faster transition towards a low-carbon economy in countries at lower levels of economic development. Hahn et al.²⁸ show that many countries may not use all their territorial emission allowances when comparing countries' estimated carbon budgets to their future claims if their emission reduction targets are achieved. The comparison indicates emission allowances available for transfer, but also that such a reallocation of emission allowances is not enough to meet the 1.5°C temperature goal. In that case, carbon dioxide removal combined with increased ambition levels for domestic mitigation would be required.

We define net-zero emissions as territorial and consumption-based fossil carbon dioxide emissions reaching zero. In practice, adopted territorial net-zero emissions targets often have a more complex design: (i) encompassing additional greenhouse gases, (ii) sometimes including international transport and including all or some of emissions and removals from land-use, land-use change and forestry, (iii) allowing for limited use of carbon dioxide removal and internationally traded mitigation outcomes²⁹. First, our choice of which greenhouse gases to include in the analysis is limited by available data for the large set of countries analyzed. Even if data were available, the differences in logic between fossil carbon dioxide and other greenhouse gases also limit the scope of national carbon budget calculations, since short-lived greenhouse gases do not exhibit the linear relationship between temperature impact and cumulative emissions necessary for using a cumulative budget approach³⁰. Nevertheless, emissions of these gases still need to be drastically reduced for the assumed carbon budget to be consistent with its associated

warming level³¹. Second, national data are lacking on consumption-based emissions and removals in land-use, land-use change, and forestry and international transport; hence, they are allocated to the Rest of World pool, and constitute a limitation of our study. Third, both carbon dioxide removal and internationally traded mitigation outcomes can be treated as domestic mitigation contributions and may be reflected in both accounting frameworks in parallel if they are used to offset the domestic emissions associated with consumption within national borders. However, this requires strict separation from contributions that are intended to offset emissions embodied in trade to avoid double-counting across countries and accounting systems.

Online Methods

Combining territorial and consumption-based emissions

We define an environmental responsibility indicator, E_r (see Equation (1)), and introduce a relative weight factor, α , that determines the weight given to territorial versus consumption-based emissions when assigning responsibility to individual countries.

$$E_r = E_t \cdot (1 - \alpha) + E_c \cdot \alpha, \quad (1)$$

where α ranges from 0 to 1. 0 means that full weight is placed on territorial emissions when assigning responsibility to individual countries, whereas 1 means that full weight is placed on consumption-based emissions when assigning responsibility to individual countries.

This approach is similar to Peters², who show how responsibility can be shared between production-based and consumption-based emission inventories using a weighting factor. Territorial emissions are equivalent to production-based, except that they do not allocate international transport emissions to individual countries². We use territorial emissions nonetheless due to their use in the design of current net-zero emission year targets within the scope of the Paris Agreement.

One can note that emissions occurring within a country to produce goods and services used domestically, E_d , are accounted for in both approaches and, hence, not affected by α (see Equation (2)).

$$E_r = E_d + E_e \cdot (1 - \alpha) + E_i \cdot \alpha, \quad (2)$$

where E_e represents territorial emissions occurring in the country for the production of exported goods and services and E_i represents the embodied emissions in imported goods and services.

Estimating national carbon budgets

The ambition level of national mitigation ambitions is commonly assessed by comparing the future policy-consistent GHG emissions pathway(s) of a country with the country's allocated share of global future GHG emissions, based on that national mitigation ambitions should "reflect equity and the principle of common but differentiated responsibilities and respective capabilities, in the light of different national circumstances"¹³. Estimating a country's share in the global GHG emissions budget ultimately comes down to effort sharing in global climate action. There is a large body of research that tries to quantify the statements around effort sharing in the Paris Agreement (e.g., van den Berg et al.¹⁵, Robiou du Pont et al.¹⁶, and Höhne et al.³²). A critique of these studies is that they claim value-neutrality by showcasing results for a limited number of effort-sharing approaches without excluding ones that rely on grandfathering, which is not consistent with the fairness principles of the Paris Agreement^{26,33}.

Since this study aims to highlight an additional complexity in effort sharing if countries impose emission reduction targets on both consumption-based and territorial emissions, we rely on previous studies on how to allocate the global carbon budget to individual countries. We consider three effort-sharing approaches: (i) historic responsibility – equal cumulative emissions per capita from a given starting year¹⁵, (ii) equality – annual equal emissions per capita¹⁵, and (iii) capability – based on gross domestic product (GDP) and population¹⁶. Due to a lack of data for earlier years, we only consider historic responsibility from 1990 for equal cumulative emissions per capita.

The effort-sharing approaches are forward-looking in different ways, requiring projected global emission levels, population levels, or economic production (i.e., GDP). We assume that the global emissions pathway is assumed to be linear towards a future net-zero emission year. The net-zero emission year is denoted y_{GNZ} , and calculated using Equation (3), and the global emissions pathway, being $E_{World}(y)$, is estimated using Equation (4).

$$y_{GNZ} = 2024 + \frac{CB_{Global}}{E_{World}(y=2023)} \cdot 2 \quad (3)$$

$$E_{World}(y) = \begin{cases} E_{World}(2023) \cdot \left(1 - \frac{y-2023.5}{y_{GNZ}-2024}\right), & 2024 \leq y \leq y_{GNZ} - 1 \\ \frac{E_{World}(2023)}{2(y_{GNZ}-2024)} \cdot (y_{GNZ} - y)^2, & y < y_{GNZ} < y + 1 \\ 0, & y \geq y_{GNZ} \end{cases} \quad (4)$$

The carbon budget, CB_i , for country, i , is estimated using Equation (5) for equal cumulative emissions per capita (i.e., historic responsibility) from a given starting year, s , to an end year that we assume to be the same as when the global carbon budget is exhausted at year y_{GNZ} .

$$CB_i = (CB_{Global} + \sum_{y=s}^{2023} E_{World}(y)) \cdot \frac{\sum_{y=s}^{y_{GNZ}} P_i(y)}{\sum_{y=s}^{y_{GNZ}} P_{World}(y)} - \sum_{y=s}^{2023} E_{r,i}(y), \quad (5)$$

where CB_{Global} is the global carbon budget, E_{World} are annual global emissions, P_{World} is the global population, and P_i is the population of country, i , all for year y . Finally, $E_{r,i}$ denotes the weighted emissions in year, y , for country, i , computed from territorial and consumption-based emissions using Equation (1).

When using annually equal emissions per capita (i.e., equality) as the effort-sharing approach, the carbon budget for country, i , is estimated based on the annual global emissions pathway, E_{World} , and the population projections for the country, P_i , and globally, P_{World} , as expressed in Equation (6).

$$CB_i = \sum_{y=2024}^{y_{GNZ}} E_{World}(y) \cdot \frac{P_i(y)}{P_{World}(y)} \quad (6)$$

For the capability effort sharing approach, the carbon budget for the country, i , is estimated based on population projections, P_i , for the country as well as the country's economic production, GDP_i , in comparison to all countries in the sample, as expressed in Equation (7). Note that "all countries" treat countries not included in the sample as one single "rest of world" region, which may affect the results, and that European Union member states are included individually.

$$CB_i = \sum_{y=2024}^{y_{GNZ}} E_{World}(y) \cdot \left(\frac{P_i^2 / GDP_i}{\sum_{j=\{all\ countries\}} P_j^2 / GDP_j} \right). \quad (7)$$

Implied net-zero emission year target

In addition to the national carbon budget results, an implied net-zero emission year is estimated since a carbon budget in relation to the environmental responsibility, E_r , is difficult to interpret. The implied net-zero year, Y_r , when a country's emissions based on the environmental responsibility, E_r , should be zero, is estimated by assuming a linear

pathway to the net-zero year. The pathway is anchored at the observed 2023 emission levels for each country and then exhausting the remaining carbon budget from 2024 onward. Annual emissions in 2023 are treated as the emissions level at the start of 2024.

$$Y_r = 2024 + \frac{CB_i}{E_r(2021)} \cdot 2, \quad (8)$$

Note that we use the implied net-zero emission year for each country to showcase the impact of the weighting between territorial and consumption-based emissions. While useful for the points made here, this indicator is only illustrative and many developing countries may require an emission pathway that allows for a potential increase in the short-term and/or stagnation followed by an eventual decline in emissions.

Data sources

This study uses publicly available data to facilitate replication of the results. The global carbon budgets are assumed to be 500 GtCO₂ and 1,150 GtCO₂, representing holding the global temperature increase below 1.5°C with 50% probability and below 2°C with 67% probability, respectively, based on estimates from the IPCC's sixth assessment report³⁴ and adjusted with data from the Global Carbon Project³⁵ to establish the remaining budget from January 2024 onwards.

Territorial and consumption-based emission time series come from the Global Carbon Project³⁵ (i.e., the National Fossil Carbon Emissions dataset). The analysis covers all jurisdictions with available historic territorial and consumption-based emissions for the period 1990-2023 (91 countries plus the EU and its member states). Territorial and consumption-based emissions for these jurisdictions cover 83% and 84% of global emissions (based on the estimates in the Global Carbon Budget dataset from the Global Carbon Project³⁵), respectively. The remaining emissions are pooled as "Rest of world". Note that net emissions from land-use change as well as international shipping and aviation are included in the "Rest of world"-pool for both territorial and consumption-based emissions since the Global Carbon Project lacks national allocation of these emissions.

Historic data on GDP and population are based on the World Bank²⁵ and the United Nations³⁶, respectively. Future projections on GDP and population are based on the second socioeconomic pathway (SSP2)^{37,38} to ensure internal consistency between GDP and population projections.

Data availability

The data used for generating all graphs have been made available for peer review and will be preserved in a Zenodo data repository upon completion of the peer-review process.

Code availability

The code is written in R and available in the GitHub repository, <https://github.com/morfeldt/EffortSharingTerritorialvsConsumptionBased>. The final code used for generating the results for this article will be preserved in a Zenodo data repository upon completion of the peer-review process.

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Author contributions

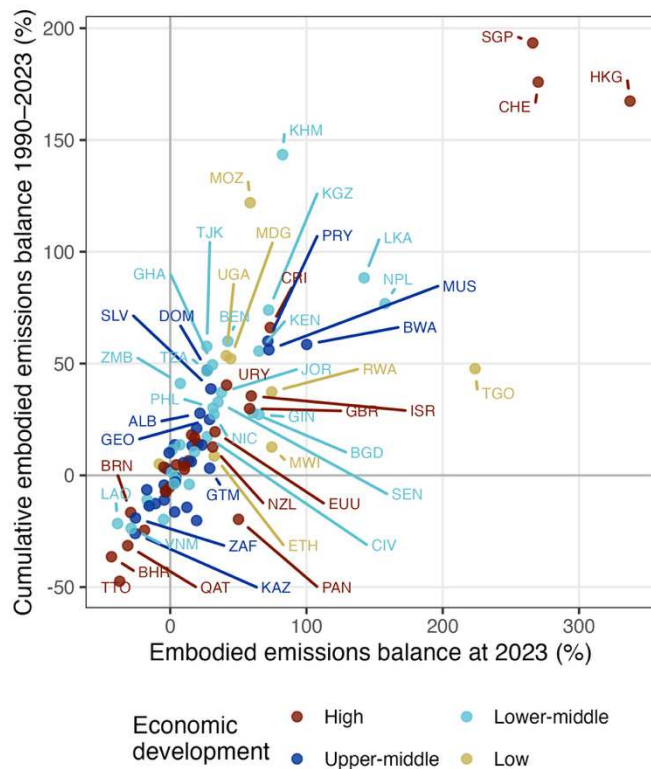
J.M. and D.J.A.J. jointly contributed to conceptualization of the research and writing the article. C.A. contributed to reviewing and editing the article. J.M. performed the computational analysis and visualized the results.

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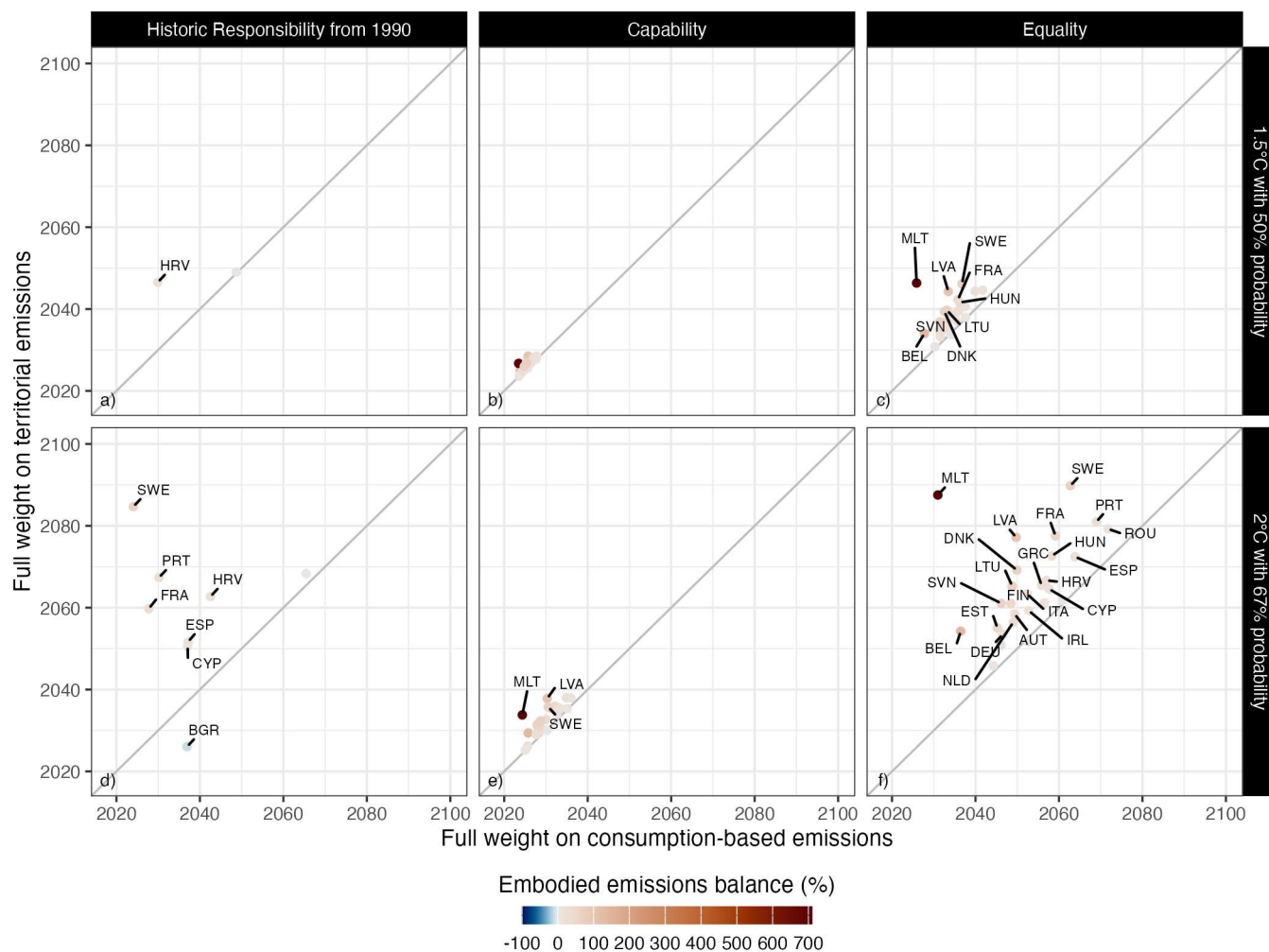
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Competing interests

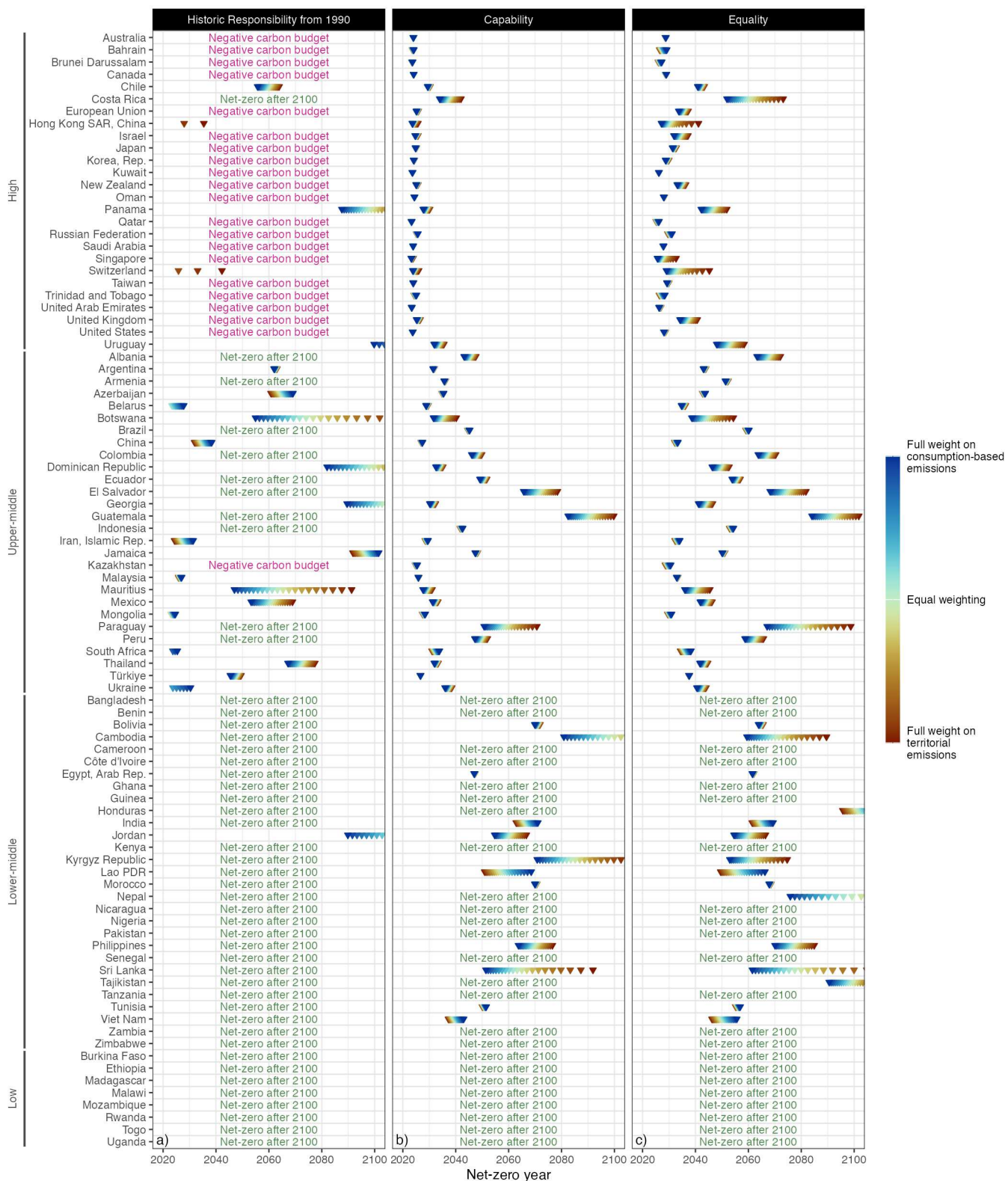
The authors report no competing interests.



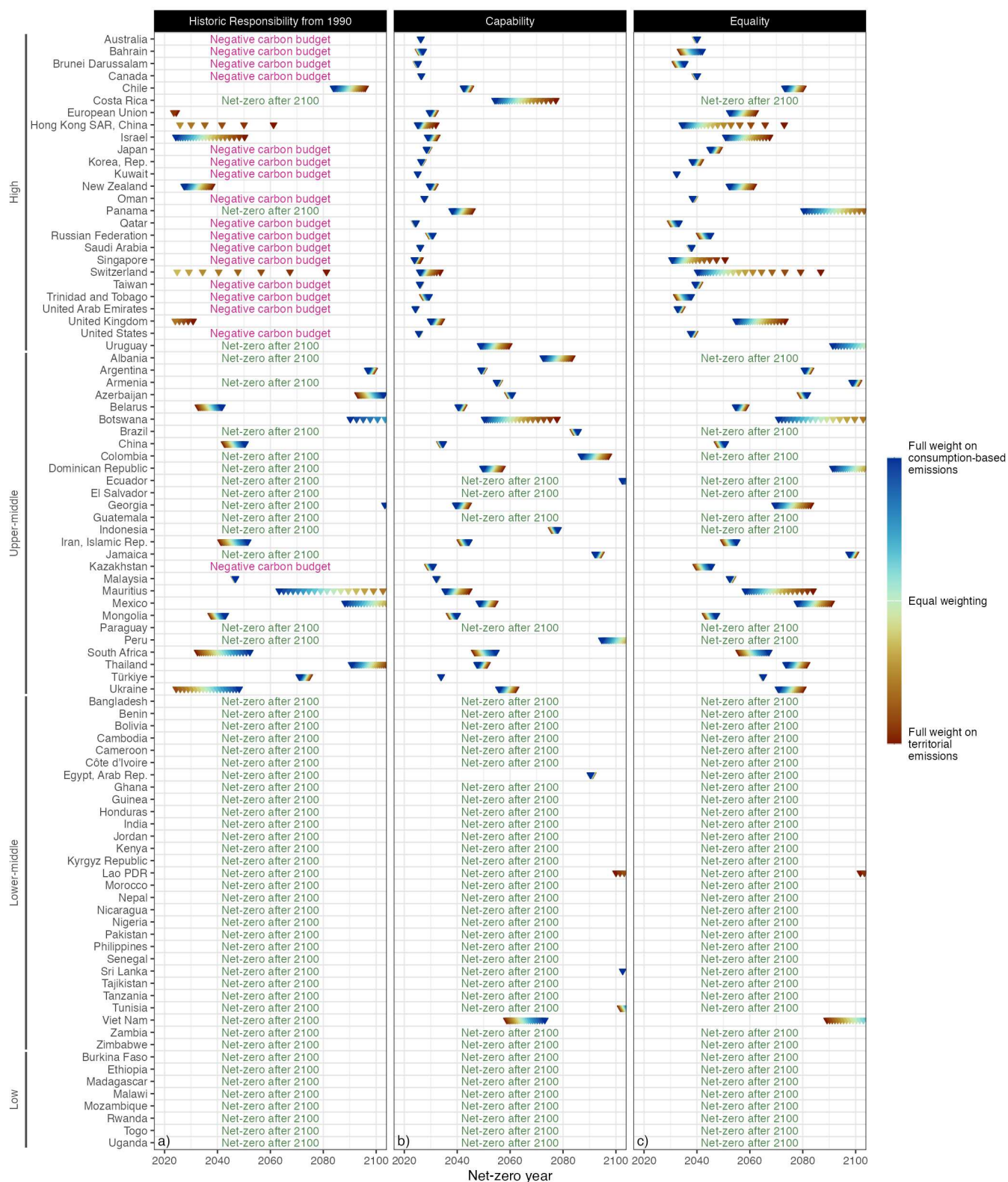
Extended Data Figure 1. **Relative embodied emissions balance in 2023 and cumulative embodied emissions balance.** Consumption-based emissions minus territorial emissions divided by territorial emissions (i.e., relative embodied emissions balance) for the latest year, 2023 (x-axis), compared to cumulatively over the period 1990-2023 (y-axis) for jurisdictions at different levels of economic development (color). Jurisdictions with an absolute embodied emissions balance exceeding 25% are highlighted with their ISO-code.



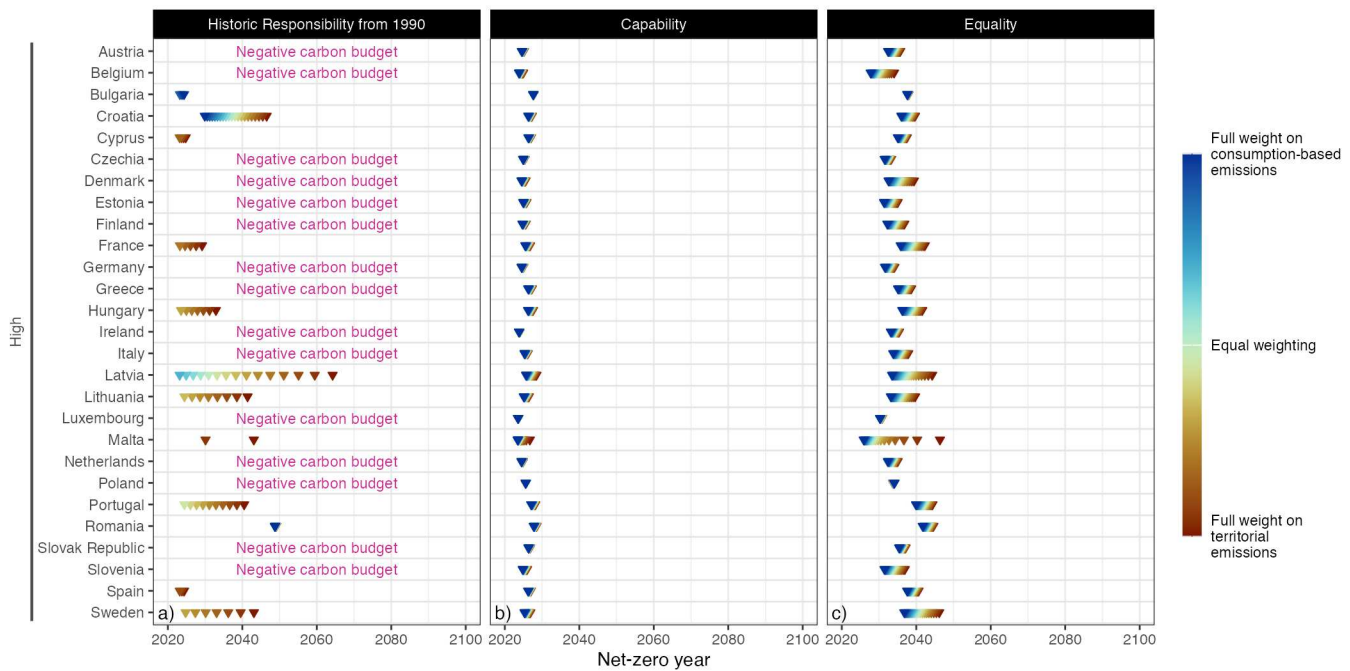
Extended Data Figure 2. **Implied net-zero emission years compared to embodied emissions balance – European Union member states.** Implied net-zero emission year for European Union member states when full weight is given to territorial (y-axis) or consumption-based (x-axis) emissions in assigning responsibility to individual jurisdictions, for the effort-sharing approaches, **a,d** – historic responsibility from 1990 (cumulative equal emissions per capita), **b,e** – capability (economic and population developments), **c,f** – equality (annual equal emissions per capita), for two global temperature goals, **a,b,c** – 1.5°C with 50% probability, and **d,e,f** – 2.0°C with 67% probability, depending on the jurisdiction's embodied emissions balance, i.e. relative difference between consumption-based and territorial emissions (color). The embodied emission balance represents the country's relative difference between accounting systems for the last year for capability and equality, while representing the cumulative balance since 1990 for historic responsibility, due to the approaches' methodological differences. Jurisdictions that move more than five years when shifting the weighting are highlighted with their ISO-code.



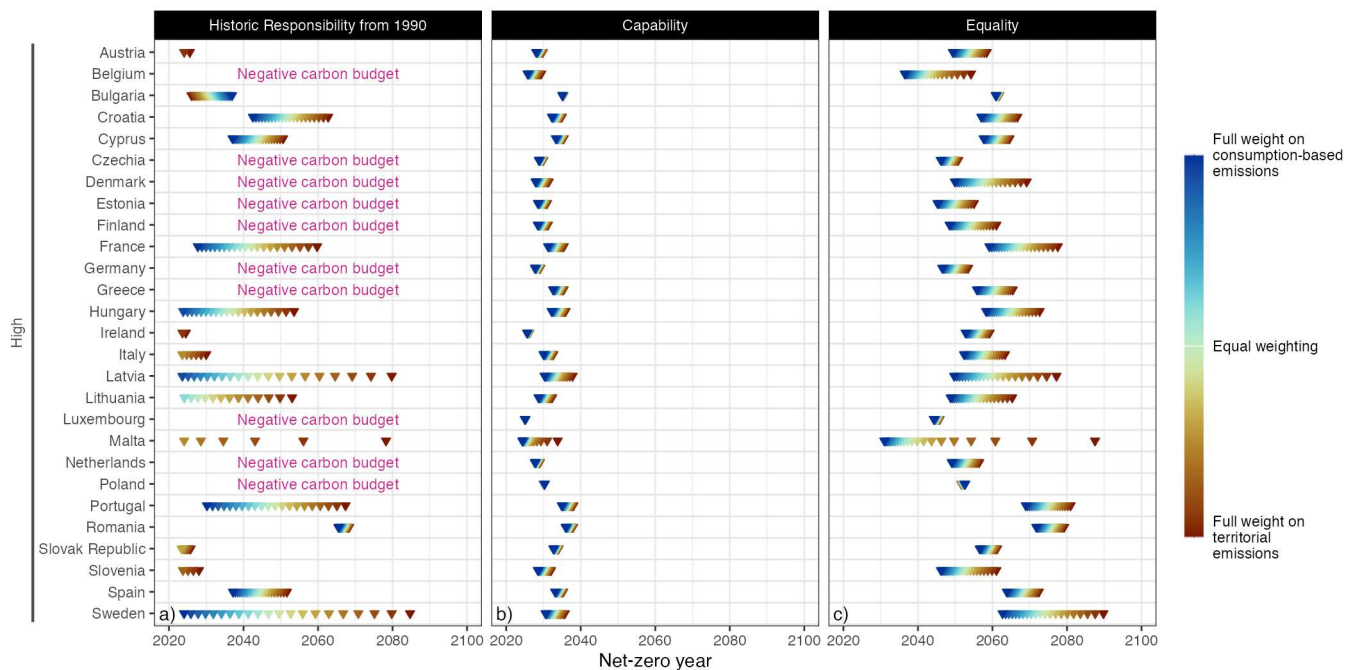
Extended Data Figure 3. **Implied net-zero emission year for different effort-sharing approaches under the dual accounting framework.** Implied net-zero emission year (x-axis) for different effort-sharing approaches, **a** – historic responsibility from 1990 (cumulative equal emissions per capita), **b** – capability (economic and population developments), **c** – equality (annual equal emissions per capita), and the weight given to territorial versus consumption-based emissions when assigning responsibility to individual jurisdictions (color scale). The allocated global carbon budget aims to achieve a temperature goal of holding global mean temperature increase to below 1.5°C with 50% probability.



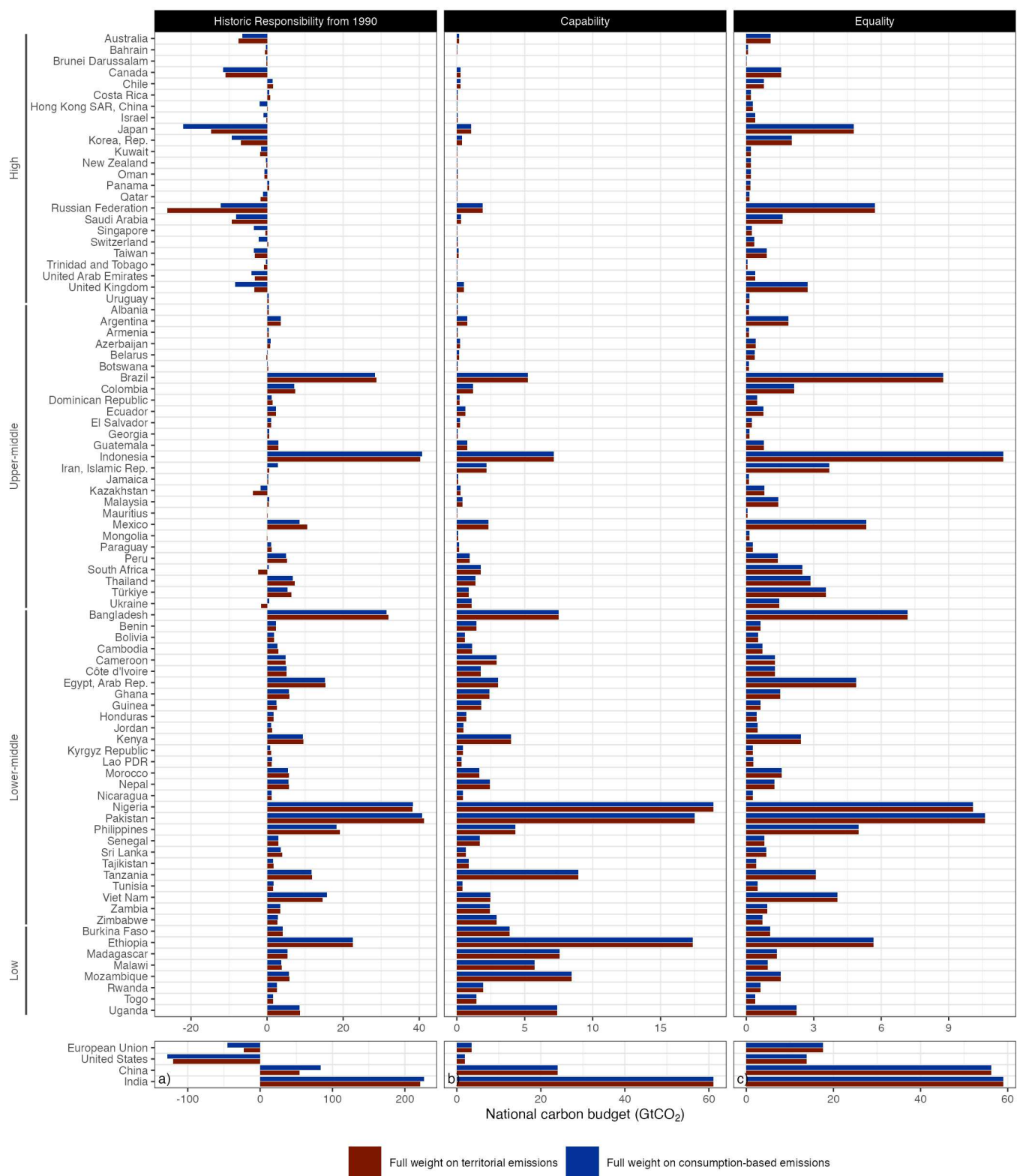
Extended Data Figure 4. **Implied net-zero emission year for different effort-sharing approaches under the dual accounting framework.** Implied net-zero emission year (x-axis) for different effort-sharing approaches, **a** – historic responsibility from 1990 (cumulative equal emissions per capita), **b** – capability (economic and population developments), and **c** – equality (annual equal emissions per capita), and the weight given to territorial versus consumption-based emissions when assigning responsibility to individual jurisdictions (color scale). The allocated global carbon budget aims to achieve a temperature goal of holding global mean temperature increase to below 2°C with 67% probability.



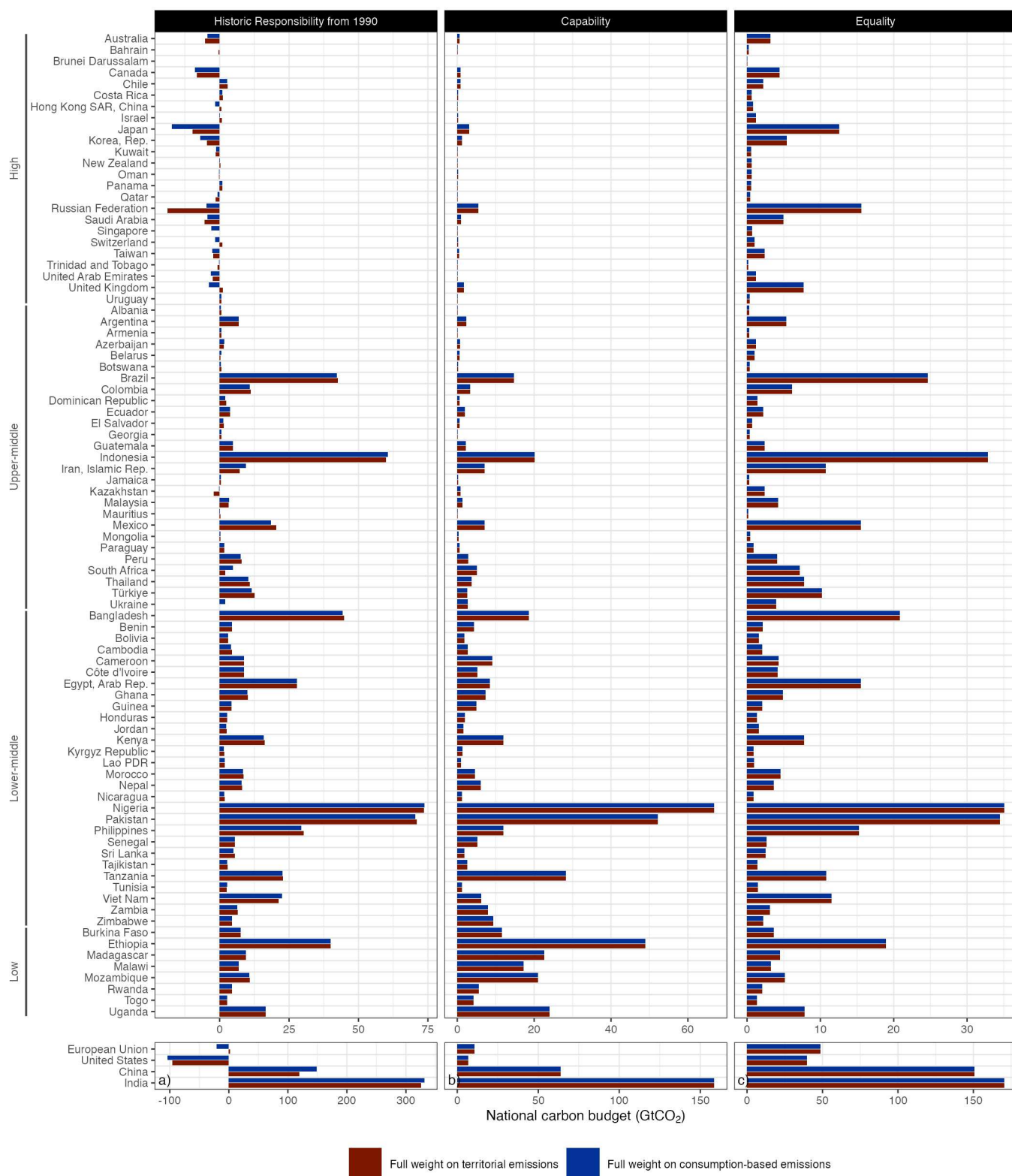
Extended Data Figure 5. **Implied net-zero emission year for different effort-sharing approaches under the dual accounting framework – European Union member states.** Implied net-zero emission year (x-axis) for different effort-sharing approaches, **a** – historic responsibility from 1990 (cumulative equal emissions per capita), **b** – capability (economic and population developments), and **c** – equality (annual equal emissions per capita), and the weight given to territorial versus consumption-based emissions when assigning responsibility to individual jurisdictions (color scale). The allocated global carbon budget aims to achieve a temperature goal of holding global mean temperature increase to below 1.5°C with 50% probability.



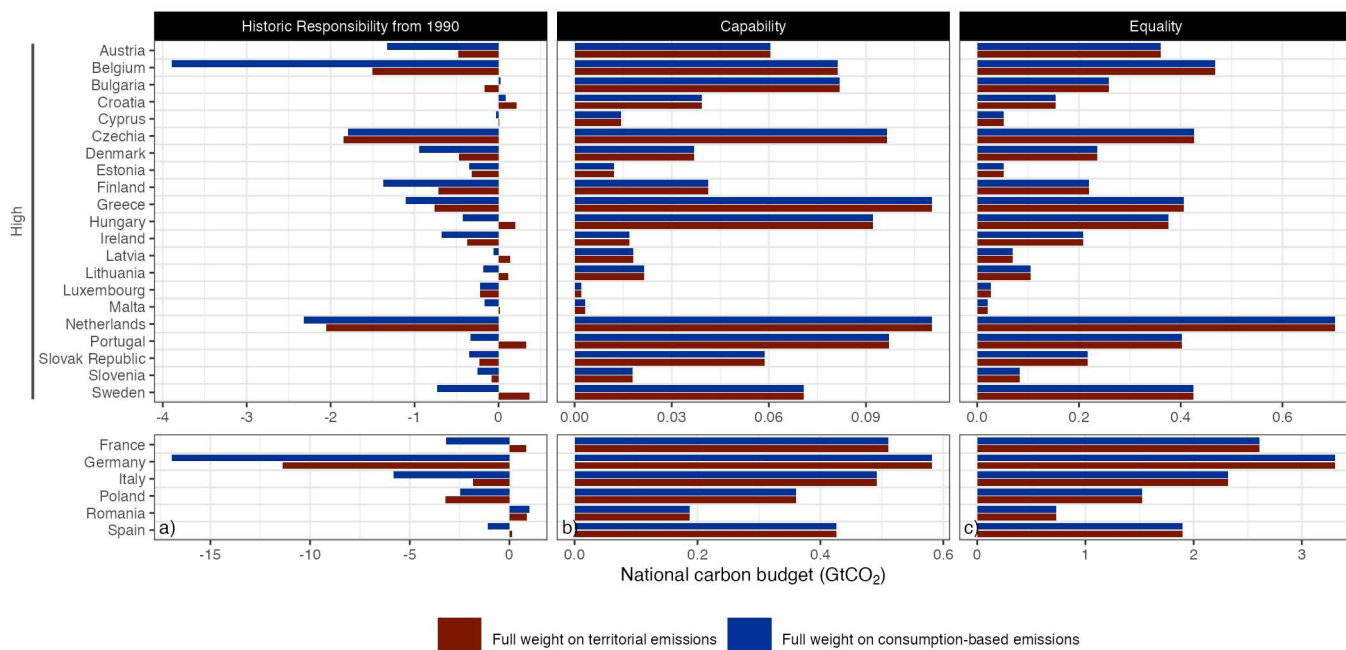
Extended Data Figure 6. **Implied net-zero emission year for different effort-sharing approaches under the dual accounting framework – European Union member states.** Implied net-zero emission year (x-axis) for different effort-sharing approaches, **a** – historic responsibility from 1990 (cumulative equal emissions per capita), **b** – capability (economic and population developments), and **c** – equality (annual equal emissions per capita), and the weight given to territorial versus consumption-based emissions when assigning responsibility to individual jurisdictions (color scale). The allocated global carbon budget aims to achieve a temperature goal of holding global mean temperature increase to below 2°C with 67% probability.



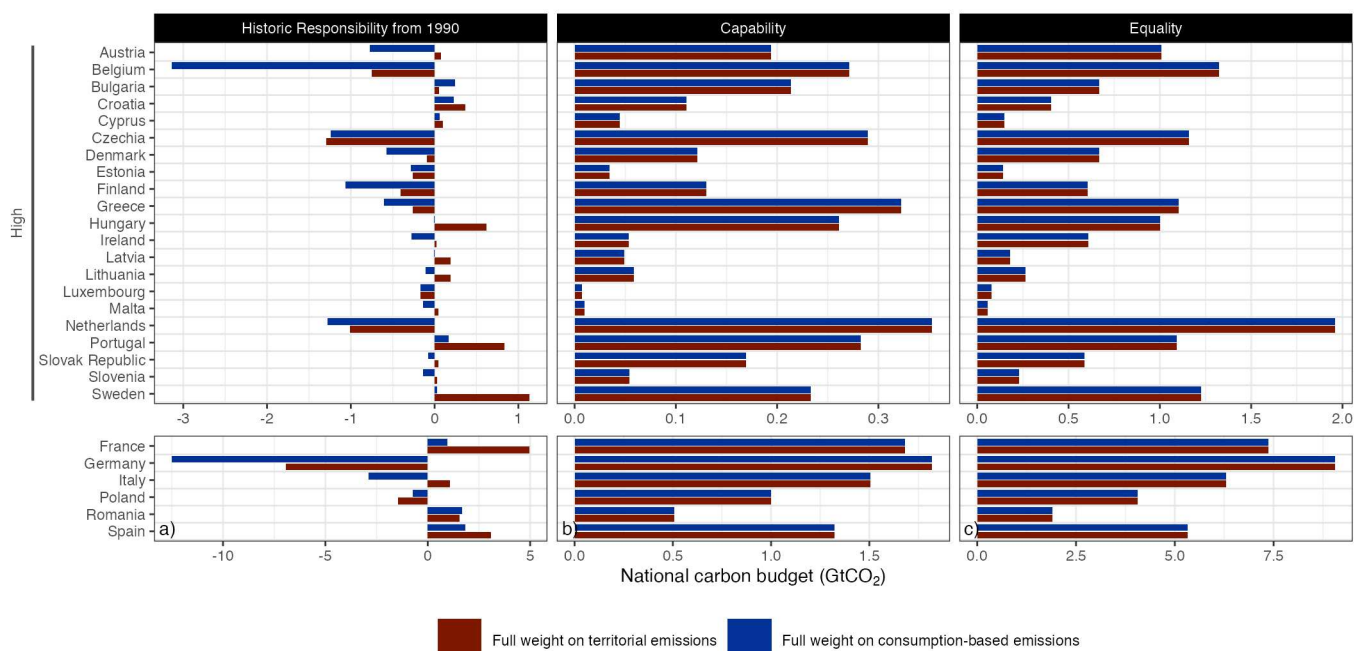
Extended Data Figure 7. **National carbon budget estimates for different effort-sharing approaches.** National carbon budgets (x-axis) for different effort-sharing approaches, **a** – historic responsibility from 1990 (cumulative equal emissions per capita), **b** – capability (economic and population developments), and **c** – equality (annual equal emissions per capita), and when full weight is given to territorial (red) or consumption-based (blue) emissions in assigning responsibility to individual jurisdictions. The allocated global carbon budget aims to achieve a temperature goal of holding global mean temperature increase to below 1.5°C with 50% probability.



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Extended Data Figure 9. **National carbon budget estimates for different effort-sharing approaches – European Union member states.** National carbon budgets (x-axis) for different effort-sharing approaches, **a** – historic responsibility from 1990 (cumulative equal emissions per capita), **b** – capability (economic and population developments), and **c** – equality (annual equal emissions per capita), and when full weight is given to territorial (red) or consumption-based (blue) emissions in assigning responsibility to individual jurisdictions. The allocated global carbon budget aims to achieve a temperature goal of holding global mean temperature increase to below 1.5°C with 50% probability.



Extended Data Figure 10. **National carbon budget estimates for different effort-sharing approaches – European Union member states.** National carbon budgets (x-axis) for different effort-sharing approaches, **a** – historic responsibility from 1990 (cumulative equal emissions per capita), **b** – capability (economic and population developments), and **c** – equality (annual equal emissions per capita), and when full weight is given to territorial (red) or consumption-based (blue) emissions in assigning responsibility to individual jurisdictions. The allocated global carbon budget aims to achieve a temperature goal of holding global mean temperature increase to below 2°C with 67% probability.