nature sustainability

Article

https://doi.org/10.1038/s41893-023-01130-8

Compensation for atmospheric appropriation

Received: 20 August 2022

Accepted: 18 April 2023

Published online: 05 June 2023

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Andrew L. Fanning [1,2] & Jason Hickel [3,4]

Research on carbon inequalities shows that some countries are overshooting their fair share of the remaining carbon budget and hold disproportionate responsibility for climate breakdown. Scholars argue that overshooting countries owe compensation or reparations to undershooting countries for atmospheric appropriation and climate-related damages. Here we develop a procedure to quantify the level of compensation owed in a 'net zero' scenario where all countries decarbonize by 2050, using carbon prices from IPCC scenarios that limit global warming to 1.5 °C and tracking cumulative emissions from 1960 across 168 countries. We find that even in this ambitious scenario, the global North would overshoot its collective equality-based share of the 1.5 °C carbon budget by a factor of three, appropriating half of the global South's share in the process. We calculate that compensation of US$192 trillion would be owed to the undershooting countries of the global South for the appropriation of their atmospheric fair shares by 2050, with an average disbursement to those countries of US$940 per capita per year. We also examine countries' overshoot of equality-based shares of 350 ppm and 2 °C carbon budgets and quantify the level of compensation owed using earlier and later starting years (1850 and 1992) for comparison.

Global carbon emissions have continued to rise over the past several decades, and concentrations of atmospheric CO_2 have increased dramatically. The 'safe' planetary boundary for emissions—understood as atmospheric concentration of 350 ppm CO_2—was crossed in 1988[1]. As of 2022, atmospheric concentrations are now 415 ppm (ref. 2), and global temperatures have reached 1.1 °C over preindustrial levels[3]. The Paris Agreement commits the world's governments to limiting global temperature rise to 1.5 °C, or well below 2 °C[4]. The remaining carbon budgets associated with these boundaries are being rapidly depleted, and climate damages are accelerating.

Not all countries are equally responsible for the depletion of carbon budgets, however; some nations have contributed more to causing this crisis than others. This disproportionate historical responsibility is problematic from a climate justice perspective that recognizes the atmosphere as a shared commons, to which all people are entitled to a fair and equitable use[5–8]. Scholars have drawn on this principle to argue that carbon budgets should be shared equitably[9–12] and that cumulative emissions in excess of fair shares represent a form of appropriation of atmospheric commons, which has been framed in the language of 'climate debt' and 'climate coloniality'[13–15]. Acknowledging issues of equity is essential to establishing trust and buy-in to the negotiation process[16].

Researchers and climate negotiators have argued that overemitting countries owe compensation or reparations to low-emitting countries for atmospheric appropriation and climate-related damages, which fall disproportionately on poorer countries that have contributed little or nothing to the crisis[17–21]. Paragraph 51 of the Paris Agreement decision document states that the agreement "does not involve or provide a basis for any liability or compensation"[4]. Nonetheless, legal scholars argue that options remain open for the development of a compensation and liability system under the Warsaw International

[1]Doughnut Economics Action Lab, Oxford, UK. [2]Sustainability Research Institute, School of Earth and Environment, University of Leeds, Leeds, UK. [3]Institute of Environmental Science and Technology, Autonomous University of Barcelona, Barcelona, Spain. [4]International Inequalities Institute, London School of Economics and Political Science, London, UK. e-mail: j.e.hickel@lse.ac.uk

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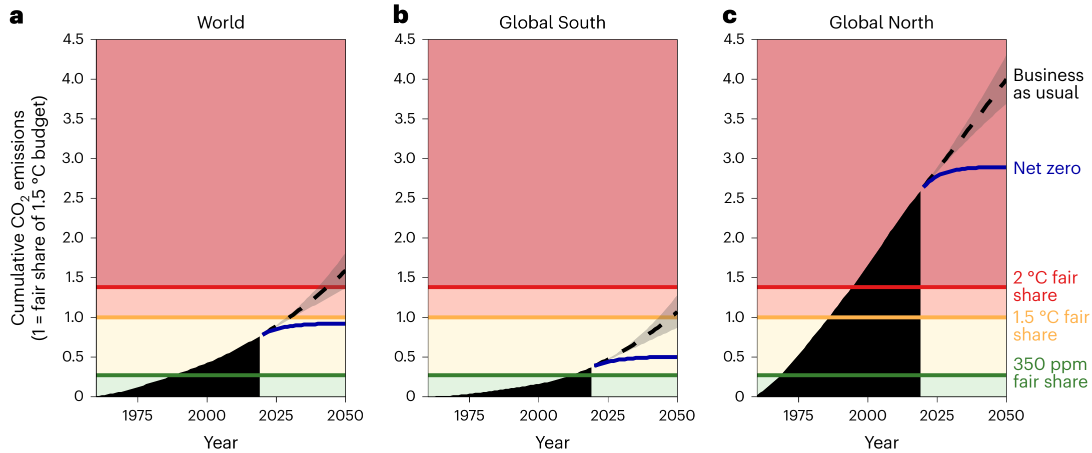

Fig. 1 | World and regional cumulative CO_2 emissions with respect to fair shares of global carbon budgets, historical trends (1960–2019) and scenario trends (2020–2050). a, World. **b**, Global South region. **c**, Global North region. The historical emissions (black area), business-as-usual projected pathway (dashed line) and net-zero pathway (blue line) show cumulative emissions relative to fair shares of the 1.5 °C carbon budget (yellow line), with fair shares of 350 ppm (green line) and 2 °C budgets (red line) also shown. World and regional totals are aggregated from national values. Likely (66%) prediction intervals are shown in lighter tint around the business-as-usual projections. See Extended Data Figs. 1 and 2 for results with cumulative emissions starting from 1850 and 1992, respectively.

Mechanism for Loss and Damage, which was created in 2013[22]. Calls for payments for loss and damage have gained momentum, notably during the twenty-sixth Conference of the Parties (COP26) summit in Scotland[23] and the COP27 summit in Egypt[24], which formally established a loss and damage fund, with details to be clarified at COP28.

This Article adds to this literature—and the broader public debate—by offering an empirical method for quantifying compensation owed for the appropriation of atmospheric commons. Building on earlier work, we use an equality-based fair-share approach to calculate countries' use of established carbon budgets, including for 350 ppm, 1.5 °C and 2 °C (refs. 9,12). This analysis allows us to determine the extent to which nations have exceeded their fair shares of the carbon budgets and appropriated atmospheric commons. We then assess countries' projected future use of the carbon budgets if they carry on with business as usual, as well as if they pursue ambitious emissions reductions to reach 'net zero' by 2050, consistent with limiting warming to 1.5 °C.

The world must make every effort to respect the 1.5 °C limit, as per the Paris Agreement. If some countries appropriate more than their fair shares of the carbon budget, this has important implications. It means overemitters are disproportionately responsible for damages caused by global warming but also that other countries must effectively forgo the full use of their own fair shares to keep the world on track for 1.5 °C, mitigating more rapidly than would otherwise be required. One way to quantify the monetary value of atmospheric appropriation is by representing overshoot emissions in terms of carbon prices. In this Article, we use marginal abatement costs from the Intergovernmental Panel on Climate Change Sixth Assessment Report (IPCC-AR6) scenarios consistent with limiting global warming to 1.5 °C.

Our results provide an indication of how compensation for atmospheric appropriation can be quantified in a way that accounts for historical and current responsibilities, but it is beyond the scope of this study to provide a framework for practical implementation. However, we note that the climate reparations literature is increasingly considering the politics, governance and practicalities of such an approach, and our results may be useful inputs to inform the ongoing 'Glasgow Dialogue on Loss and Damage' established during COP26[17,23–26].

Results

Our first step is to estimate levels of atmospheric appropriation by tracking historical cumulative emissions with respect to equality-based fair shares of the 350 ppm, 1.5 °C and 2 °C carbon budgets across 168 countries from 1960 to 2019, together with two forward-looking estimates between 2020 and 2050, namely (1) business-as-usual projections based on historical trends (with 'likely' or 66% prediction intervals) and (2) net-zero scenarios with country-specific mitigation rates that bring CO_2 emissions in each country from 2020 levels to 0.1 tonnes per capita in 2050 (see Extended Data Fig. 1 for country-specific mitigation rates). We also analyse the sensitivity of our cumulative results to the 1960 start date by conducting two parallel analyses starting in 1850 and 1992 (the year the United Nations Framework Convention on Climate Change was established), respectively. The estimation procedures are described in detail in Methods.

At the global scale, we find that cumulative emissions since 1960 are currently around three times beyond the 350 ppm carbon budget (exhausted in 1988), and a global emissions mitigation rate of more than 10% per year between 2020 and 2050 is needed for net zero, which would respect the 1.5 °C carbon budget (Fig. 1a). However, our business-as-usual projections suggest the world will likely deplete the 1.5 °C carbon budget by 2030 (2028–2032) and the 2 °C carbon budget by 2044 (2039–2049). We note that the 1.5 °C carbon budget and the 2 °C carbon budget are both substantially larger—and therefore riskier—than the safe 350 ppm carbon budget that respects the climate change boundary proposed by ref. 1.

We performed a regional analysis to assess the depletion of carbon budgets by the global North and global South: the global North here refers to the United States, Europe, Canada, Australia, New Zealand, Japan and Israel, while the global South refers to the rest of Asia, Africa and the Americas.

There are 129 countries from the global South in our analysis, which are home to more than 80% of the total population, but their aggregate cumulative emissions surpassed fair shares of the 350 ppm carbon budget only in 2012—more than two decades after the world as a whole (Fig. 1b). If this group of countries collectively pursued ambitious mitigation following our net-zero scenario between 2020 and 2050, it would use only 50% of its 1.5 °C fair share. Our business-as-usual projections suggest this group of global South countries would likely remain within its fair share of the 2 °C carbon budget by 2050 but would likely overshoot its fair share of the 1.5 °C carbon budget in 2048 (2043–2053), judging from historical trends.

The remaining 39 countries in our analysis are from the global North, and we find this group of high-emitting countries used up its

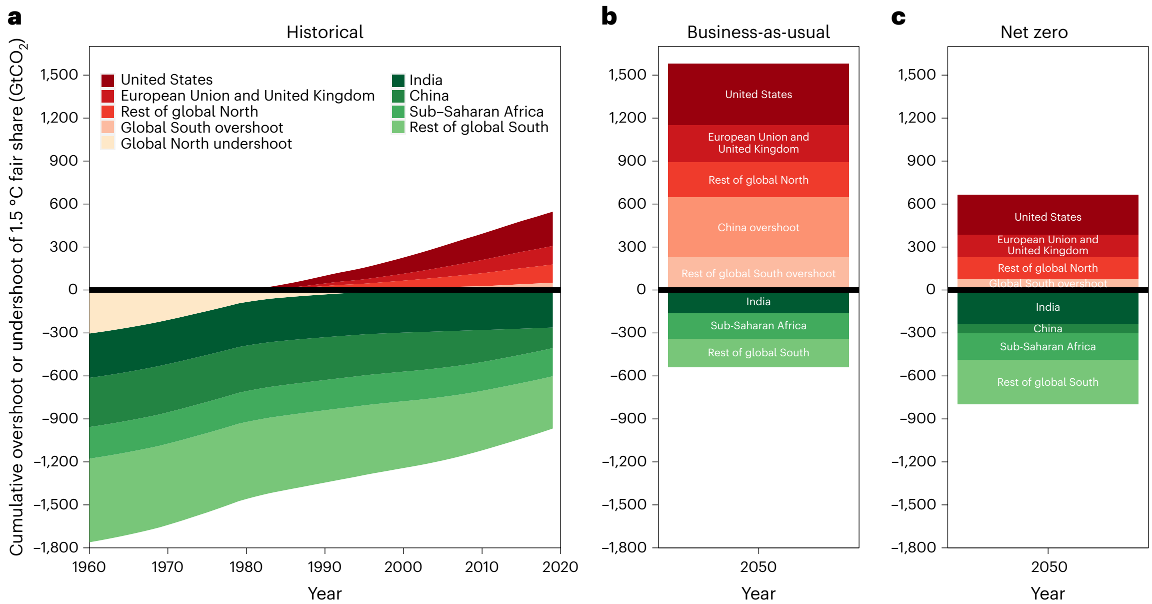

Fig. 2 | Cumulative CO_2 emissions overshoot and undershoot by country group with respect to 1.5 °C fair shares. a, Historical 1960–2019 period. **b**, Business-as-usual median projection in 2050. **c**, Net-zero scenario in 2050. See Extended Data Figs. 3 and 4 for results with cumulative overshoot and undershoot starting from 1850 and 1992, respectively.

collective fair share of the 350 ppm carbon budget by 1969, then overshot its 1.5 °C fair share by 1986 and then surpassed its 2 °C fair share by 1995 (Fig. 1c). As of 2019, this group of countries has already exceeded its collective fair share of the 1.5 °C carbon budget by more than 2.5 times, with cumulative emissions measured from 1960. If this group collectively pursues ambitious mitigation to reach net zero by 2050—as many of these countries have pledged in their Nationally Determined Contributions under the Paris Agreement—our findings suggest its cumulative emissions would still be nearly three times over its 1.5 °C fair share. However, our business-as-usual projections suggest this group of global North countries will likely increase the extent of its cumulative overshoot further to 4.0 times (3.7–4.3) over its fair share of the 1.5 °C carbon budget by 2050.

We find all global North countries overshooting their 1.5 °C fair shares, and they collectively hold responsibility for the majority (91%) of cumulative overshoot between 1960 and 2019. The only countries that stay within their 1.5 °C fair shares over the same period are all in the global South (Fig. 2a). Alarmingly, total cumulative overshoot is likely to triple in absolute terms by 2050 under business-as-usual projections (Fig. 2b). Although we find cumulative overshoot of 1.5 °C fair shares in the United States, Europe and the rest of the global North would likely double in absolute terms by 2050 under business-as-usual projections, their share of total overshoot would fall to 60% due to increasing levels of overshoot from countries in the global South. Notably, we find that China would likely switch from holding 15% of total 1.5 °C undershoot in 2019 to contributing 27% of total overshoot in 2050, according to historical trends.

By contrast, stabilizing carbon emissions by 2050 under net-zero scenarios could limit warming to 1.5 °C, and would likewise stabilize national responsibility for both averting and causing climate breakdown (Fig. 2c). We find total undershoot in our net-zero scenario would be held entirely by countries in the global South (including China), and 89% of total overshoot would be held by the global North (with the remaining overshoot held by high-emitting countries in the global South).

Overall, ambitious mitigation to reach net zero by 2050 in all countries could limit warming to 1.5 °C, but more than half (53%) of the undershooting global South's fair shares would be appropriated in the process to balance the excess emissions of overshooting countries. We find broadly similar results with cumulative emissions starting from 1850 or from 1992, although the fair shares appropriated from undershooting countries are somewhat higher from 1850 (60%; Extended Data Fig. 3) and somewhat lower from 1992 (48%; Extended Data Fig. 4). We use these findings as inputs for the next step in our analysis; to quantify the compensation owed by overshooting countries to undershooting countries for the appropriation of atmospheric commons.

It is well established that there is a strong positive relationship between affluence and ecological pressures, including carbon emissions[27,28]. We investigate this relationship further for our cumulative analysis by comparing the historical level of cumulative emissions (with respect to 1.5 °C fair shares) with cumulative gross domestic product (GDP) per capita from 1960 to 2018 (the most recent year with comparable data for a large number of countries; $N = 151$).

We find nearly 70% of cross-national variability in cumulative GDP per capita can be explained solely by differences in cumulative emissions with respect to fair shares (adj-$R^2 = 0.69$; Fig. 3). There is some variability across countries, notably among former USSR and Eastern European countries, which tend to have relatively higher levels of overshoot at lower levels of income. However, our linear estimates suggest each additional unit of cumulative overshoot beyond a country's 1.5 °C fair share is significantly associated with an increase of more than US$10,000 cumulative GDP per capita ($P < 0.001$; we report all monetary values throughout in constant 2010 prices). These findings support the view that overshooting countries have tended to enrich themselves through appropriating more than their fair shares of the atmospheric commons.

Building on these results, we develop a procedure for allocating financial compensation from overshooting countries to undershooting countries based on each country's cumulative emissions with respect to 1.5 °C fair shares in a world that achieves net zero by 2050. Each overshooting country's cumulative excess emissions in 2050 under its net-zero pathway were annualized and valued in monetary terms from 2020 to 2050 using median (and interquartile range) marginal abatement costs derived from IPCC-AR6 mitigation pathways that limit warming to 1.5 °C with no or limited overshoot ($N = 73$) (ref. 29). The marginal abatement costs of carbon increase over time, for example,

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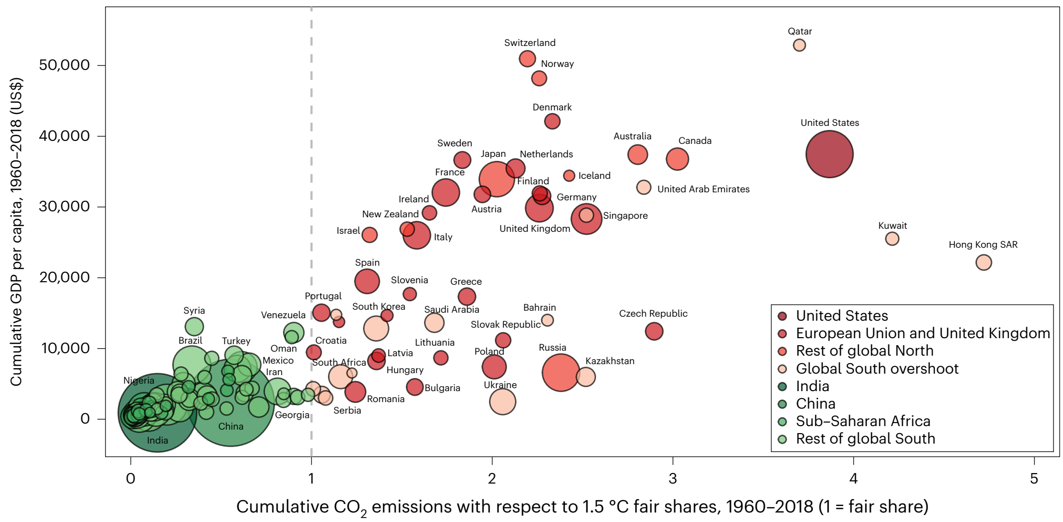

Fig. 3 | Cumulative CO_2 emissions with respect to 1.5 °C fair shares versus cumulative GDP per capita, 1960–2018. Only countries with available GDP data covering the 1960–2018 analysis period are included ($N = 151$). GDP is expressed in constant 2010 prices. A statistical model estimated using two-sided ordinary least squares regression finds the following linear relationship: $y = 10,688x - 31$ with slope and intercept coefficient standard errors of 585 and 809, respectively (adj-R^2: 0.69; F statistic: 333.8 on 1 and 149 d.f.; $P < 2.2 \times 10^{-16}$). One country (Luxembourg) lies beyond the chart area; see Supplementary Data 1 for results for all countries.

US$198 (158–242) per tonne of CO_2 in 2030 and US$547 (394–887) per tonne of CO_2 in 2050. We then distributed the cumulative monetary value of excess emissions from each overshooting country to each undershooting country on the basis of the latter's share of total undershoot emissions in 2050 under our net-zero scenario. The procedure is described in detail in Methods.

We find that cumulative financial compensation from overshooting countries to undershooting countries in a world that achieves net zero between 2020 and 2050 can be valued at US$192 (141–298) trillion (Fig. 4). The average annual compensation for each year over the 31-year period is equivalent to US$6.2 (4.5–9.6) trillion per year, or approximately 8% (6%–11%) of world GDP in 2018. Importantly, this value should be seen as compensation for the appropriation of undershooting countries' 1.5 °C fair shares to avoid climate breakdown and is therefore additional to fairness considerations surrounding the costs incurred by countries to actually transition to net-zero emissions or to adapt to a 1.5 °C warmer world[30].

Total financial compensation due to undershooting countries decreases when historical responsibility for climate breakdown is 'forgiven' by assessing cumulative emissions from a later start date (and vice versa for an earlier start date), ranging from US$109 (80–170) trillion from 1992 and US$238 (175–371) trillion from 1850 (Extended Data Fig. 5). We find the United States, the European Union and the United Kingdom owe around two-thirds of the total financial compensation from overshooting countries, irrespective of the start year. Conversely, India and the undershooting countries of sub-Saharan Africa are owed around half of the total financial compensation for giving up their 1.5 °C fair shares to achieve net zero, regardless of when cumulative emissions start. By contrast, our results for China are more sensitive to the start year, ranging from 2% of total overshoot from 1992 to 16% of total undershoot from 1850.

We find the United States holds the single largest climate debt to undershooting countries at US$2.6 (1.9–4.0) trillion per year, on average, which is equivalent to 15% (11–23%) of its annual GDP in 2018 (Fig. 5a). Other overshooting regions owe non-trivial amounts, ranging from 6% to 19% of their annual GDP on a yearly basis.

Meanwhile, the annual financial compensation to undershooting countries in sub-Saharan Africa for achieving net zero by 2050 would be US$1.4 (1.0–2.2) trillion per year, which represents 111% (82–173%) of their regional GDP in 2018 (Fig. 5b). Financial compensation to India on a yearly basis would be equivalent to 66% (48–102%) of its GDP in 2018, and compensation to the rest of the undershooting global South, excluding China, would represent 22% (16–34%) of its regional GDP. The climate credit due to China for achieving net zero would be US$0.5 (0.4–0.8) trillion per year on average, or 6% (4–9%) of its GDP in 2018.

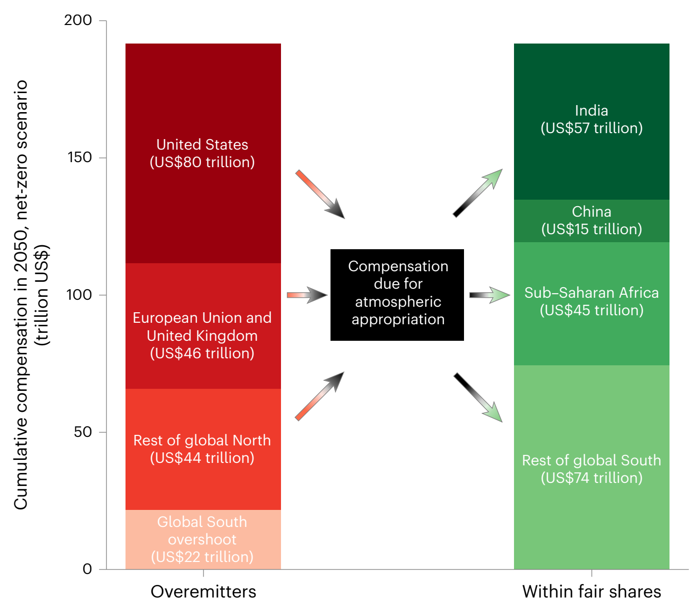

Fig. 4 | Cumulative compensation due from overshooting country groups to undershooting country groups (relative to 1.5 °C fair shares) based on the historical period from 1960 to 2019 and net-zero scenario from 2020 to 2050. Cumulative compensation is expressed in constant 2010 prices. See Extended Data Fig. 5 for results with cumulative financial compensation by country group starting from 1850 and 1992 and Supplementary Data 1 for results for all countries.

At the country scale, we find the average monetary value of excess emissions appropriated by the 67 overshooting countries in

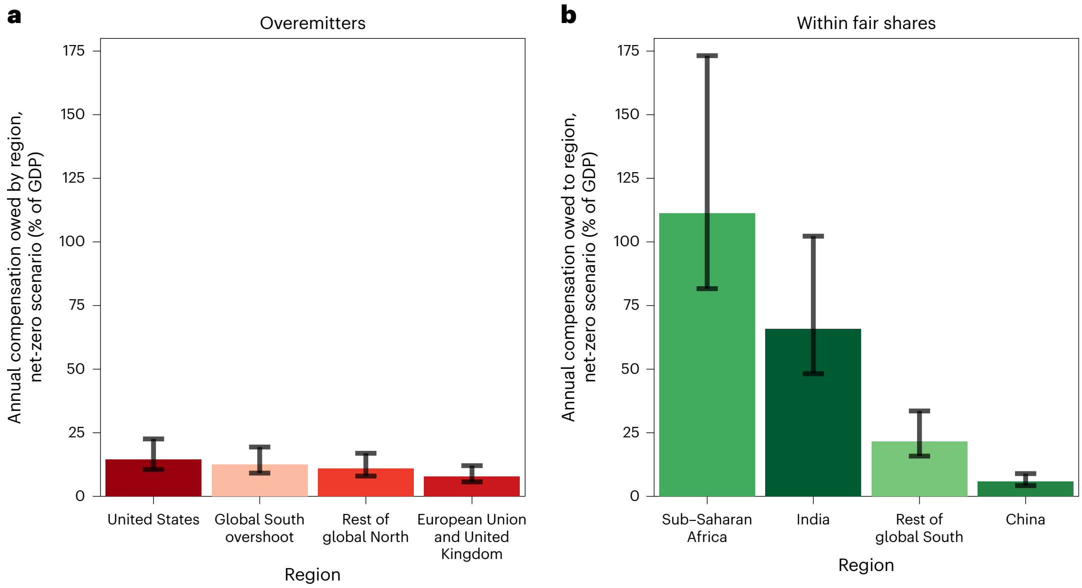

Fig. 5 | Average annual compensation by country group relative to average GDP by region in 2018 based on the historical period from 1960 to 2019 and net-zero scenario from 2020 to 2050. a, Overemitting country groups. **b**, Country groups within their fair shares. Annual compensation is calculated from median carbon price values, with error bars calculated from the upper and lower bounds of the interquartile range of carbon prices, derived from IPCC-AR6 scenario pathways that limit warming to 1.5 °C with no or limited overshoot (N = 73). See Extended Data Figs. 6 and 7 for results starting from 1850 and 1992, respectively.

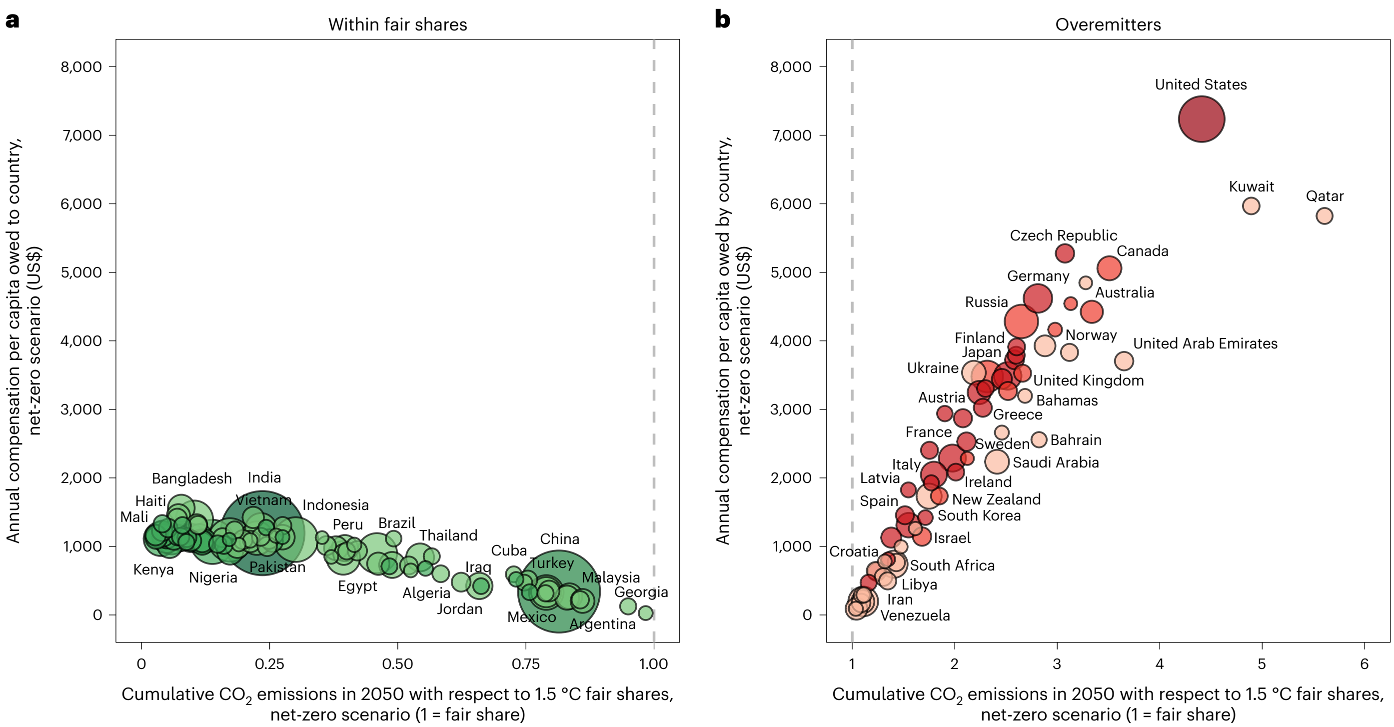

Fig. 6 | Cumulative CO_2 emissions in 2050 relative to 1.5 °C fair shares versus average compensation per capita across countries, based on the historical period from 1960 to 2019 and net-zero scenario from 2020 to 2050. a, Average annual per capita compensation owed to countries within their fair shares (N = 101). **b**, Average annual per capita compensation owed by overemitting countries (N = 67). Compensation is expressed in constant 2010 prices. Colours are as per Fig. 3. Country circles are sized according to population. Two countries (Hong Kong SAR (China) and Luxembourg) lie beyond the chart area; see Supplementary Data 1 for results for all countries.

our analysis would be US$2,700 (1,980–4,200) per capita per year in a world that achieves net zero between 2020 and 2050. Our results suggest that this monetary value converts to an average compensation of US$940 (690–1,470) per capita per year across the 101 undershooting countries in our analysis that would have had their fair shares appropriated, which are home to most of humanity.

Ten countries would have more than 95% of their fair shares of the 1.5 °C budget appropriated to stabilize global emissions under our net-zero scenario—all in sub-Saharan Africa—and the majority of undershooting countries ($N = 55$) would sacrifice more than 75% of their fair shares, including India. We find this group of low-emitting countries would be entitled to receive an average annual financial compensation of US$1,160 (850–1,800) per capita from overshooting countries to begin making reparations for the appropriation of nearly the entirety of their fair shares of the 1.5 °C budget (88%, on average; Fig. 6a). Meanwhile, undershooting countries that would have less of their fair shares appropriated would likewise be entitled to less financial compensation. For example, countries with less than 25% of their fair shares appropriated in a world that achieves the net-zero target by 2050, including China, would be entitled to receive US$280 (200–430) per capita per year, on average ($N = 13$).

Similarly, Fig. 6b shows overshooting countries closer to their fair shares would owe less compensation than countries who are far beyond their fair shares under our net-zero scenario. We find overshooting countries with excess emissions more than three times beyond their fair shares, such as Qatar and the United States, would owe US$5,750 (4,220–8,950) per capita per year to undershooting countries, on average ($N = 12$). Meanwhile, overshooting countries with excess emissions less than 50% beyond their fair shares, such as Iran and Venezuela, would be entitled to pay US$520 (380–800) per capita per year, on average ($N = 18$).

Discussion

Our results reveal the global North has already more than exhausted its equality-based fair share of both the 1.5 °C and 2 °C carbon budgets, regardless of whether fair shares are calculated from 1850, 1960 or 1992. Any further emissions on their part will entail further appropriation of the fair shares of other countries. By contrast, the global South as a region remains well within its fair share of the 1.5 °C budget. In an ambitious net-zero-by-2050 mitigation scenario, 50% of the South's fair shares would be appropriated by wealthy nations. We find that compensation worth US$192 trillion would be owed to the undershooting nations of the global South by 2050, with an average disbursement to those countries of US$940 per capita per year.

The compensation framework we propose here is in line with existing calls for reparations in payment of climate debts, which could be adapted and applied in practice on a yearly basis using observed carbon emission values and rigorous scenario analyses hosted by a competent international authority, such as the Warsaw International Mechanism for Loss and Damage. The benefits of this country-specific framework are (1) it acknowledges historical responsibility by overemitting countries, (2) it provides fair compensation to countries still within their fair shares and (3) it can accommodate changes in emissions trajectories and carbon prices over time. The financial contributions that we quantify here should be seen as rough first approximations.

There are debates about what year to use as a baseline for calculating responsibility for historical emissions, with studies often providing a range of different start dates[7,10,31]. We take a similar approach, considering 1960 to be a reasonable mid-range baseline while providing parallel analyses of cumulative emissions from 1850, a common early baseline, and from 1992, the year that the United Nations Framework Convention on Climate Change was established. We consider 1960 to be a reasonable basis for compensation given that scientific understanding of the influence on atmospheric CO_2 and temperature from burning fossil fuels was well understood[32–34], and beginning to be communicated to the general public[35], by the 1950s. Notably, we agree with the view that disregarding emissions before the 1990s represents an unjust way to measure historical responsibility[10,11] given the importance of historical emissions noted in the preamble of the convention itself. Nevertheless, our results show undershooting countries would be entitled to substantial compensation—more than US$100 trillion—even with a 1992 baseline.

We note that the net-zero scenarios shown in Fig. 1 look highly unlikely, as indicated by our business-as-usual projections. Indeed, the latest IPCC-AR6 synthesis report indicates that existing government policies have the world on track for 3.2 °C warming by 2100[36]. This underscores the need for much more dramatic action than governments are presently planning. Relying on supply-side efficiency improvements and technological change alone are likely to be inadequate[37].

There is growing consensus that demand-side options that reduce unnecessary production and consumption, and shift to already-existing low-carbon technologies, could substantially reduce emissions while reducing inequality and improving human well-being[38]. In addition, mitigation consistent with 1.5 °C will probably require global North governments to adopt transformative post-growth and degrowth policies that reduce aggregate energy use directly and enable faster decarbonization[39–44]. Ultimately, we should understand net-zero policy as a minimum and aspire for regenerative economic systems that generously store carbon, cycle water and nurture biodiversity by consciously emulating nature's designs and processes[45,46].

The analysis presented here is necessarily limited by our methodological choices, which could be improved with further research. First, while national fair shares are calculated on the basis of the equality-based principle of atmospheric commons, other sharing principles exist and could be explored[47]. Second, we use carbon prices from scenarios that limit warming to 1.5 °C to quantify the value of overshoot emissions and compensation because they are consistent with our net-zero scenario and readily available in IPCC-AR6, but other approaches may be equally valid. These could include other 'loss-based' approaches (focusing on the value of appropriated fair shares in terms of GDP gains and losses, for example) or 'damage-based' approaches (focusing on the costs of climate-related damages)[18]. Third, our compensation estimates are based on historical and projected responsibility for emissions with no adjustments for country-specific needs or capabilities[10,48]. Fourth, although our business-as-usual projections include uncertainty ranges, our analysis does not fully explore uncertainties in historical estimates of emissions, population or GDP.

Finally, while emissions are normally calculated at the national level, the aggregate figures obscure significant inequalities within countries. There is evidence that per capita emissions among the poorest half of the populations in wealthy countries, such as France, the United Kingdom and the United States, are already close to the 2030 climate targets set by these countries[49]. Responsibility for excess emissions is held largely by the wealthy classes who have high lifestyle emissions and who wield disproportionate power over provisioning systems and national policy[50].

Methods

This section summarizes how we collected historical data, estimated forward-looking projections and scenarios, calculated fair shares and distributed financial compensation to (from) countries on the basis of their cumulative undershoot (overshoot) of fair shares.

Time-series data

We collected publicly available time-series data on population[51,52], CO_2 emissions[53–56], GDP[57,58] and carbon prices[29] from international sources. We combined data from multiple sources to create country-level time series spanning the relatively long 1850–2019 historical period covered by our analysis (see Supplementary Table 1 for summary descriptions of each indicator used in our analysis).

Following refs. 9,12, our approach prioritizes consumption-based CO_2 emissions data available for a large number of countries from the Eora Multi-Regional Input–Output database (excluding land use, land-use change and forestry)[54,56]. Unlike territorial emissions accounting, consumption-based accounting accounts for the upstream emissions embodied in imports and exports and better reflects the principle of equal access to atmospheric commons. However, consumption-based data were available only from 1970, so we obtained territorial CO_2 emissions from the PRIMAP-HISTTP dataset (v.2.3.1)[53,55]

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for the earlier 1850–1969 period. We acknowledge that our analysis does not fully explore uncertainties in the historical estimates of CO_2 emissions, which can vary substantially across countries and tend to be larger for consumption-based emissions due to the additional reliance on multi-regional input–output tables to account for trade flows[59].

Overall, our methods yielded a balanced panel of 168 countries with CO_2 emissions and population data spanning the 1850–2019 period and a slightly smaller balanced panel of 151 countries with GDP data (in constant 2010 US$) spanning the 1960–2018 period. See Supplementary Data 1 for results for all countries and Supplementary Information for additional indicator-specific methods that we used to construct each series.

Projecting business-as-usual trends

We projected business-as-usual trends in CO_2 emissions for each country on the basis of annual observations over the 1960–2019 period, following the dynamic statistical forecasting methods described by ref. 12. These methods selected the best-fitting estimate from two distinct model classes for each country—(1) an exponential smoothing (ETS) state space model and (2) an autoregressive integrated moving averages (ARIMA) model—based on an automatic forecasting procedure described in detail by ref. 60 and enabled by the forecast package in R[61]. These time-variant nonlinear statistical models are preferable to linear estimation models (such as ordinary least squares regression) because they can account for patterns within the data and give greater weight to more recent observations.

For each country, the best-fitting estimate within each model class (ETS and ARIMA) was selected by using an automated procedure that estimates and compares a large number of defined parameter variations to fit the historical data of each country (30 for ETS and at least 17 for ARIMA)[60] and chooses the model that minimizes Akaike's information criterion, corrected for small-sample bias (AIC_c). Following ref. 61, the final best-fitting estimate across model classes for each country was selected on the basis of a time-series cross-validation algorithm that minimizes mean standard error (as AIC_c cannot be used to select models across different classes). This best-fitting model for each country was used to project median estimates of CO_2 emissions from 2020 to 2050, together with 66%, or 'likely', prediction intervals. We joined these projected values to 2050 with our historical database and calculated cumulative emissions for each country, starting from 1850, 1960 and 1992.

Calculating net-zero scenarios

We calculated net-zero scenarios by reducing each country's 2020 level of CO_2 emissions per capita to converge at 0.1 tonnes per capita in 2050. We derived country-specific mitigation pathways that reduced emissions at a constant rate using a simple exponential function, or

$$r_n = \frac{\ln(0.1_{n,t_{2050}} / CO_{2_{n,t_{2020}}})}{(2050 - 2020) + 1}$$

where r is the mitigation rate required for country n to reach 0.1 tonnes CO_2 per capita in 2050, starting from its initial projected level in 2020.

Although this per capita approach reduces global emissions by 97% over the 31-year period, we note that it allows 0.9 $GtCO_2$ emissions in 2050 due to the asymptotic nature of the exponential function combined with a global population of ~9.4 billion people, which would need additional carbon dioxide removal technologies to truly achieve net zero. We have chosen this formula for transparency and simplicity (we use the same method for all countries), but we acknowledge that country-specific mitigation pathways can be derived in many ways, ideally considering respective national needs and capabilities. See Extended Data Fig. 1 for country-specific mitigation rates, which range from 17–20% per year in the highest-emitting countries, such as Qatar and the United States, to 0–3% per year in the lowest-emitting countries of sub-Saharan Africa, such as Malawi and Somalia.

We converted these mitigation rates into annual net-zero CO_2 time series between 2020 and 2050 for each country n in each year t by solving the exponential function on an annual basis and multiplying this per capita series by UN population projections (medium fertility variant) over the same period, or

$$\mathrm{NetZero}_{n,t} = (CO_{2_{n,t_{2020}}} \times e^{(t-2020)r_n}) \times \mathrm{population}_{n,t}$$

We joined these scenario values to 2050 with our historical database and calculated cumulative emissions for each country, starting from 1850, 1960 and 1992.

Deriving remaining global carbon budgets

We obtained global carbon budgets remaining from 2020 with a 66% likelihood of limiting global warming to 1.5 °C and 2 °C from IPCC-AR6 (400 $GtCO_2$ and 1,150 $GtCO_2$, respectively)[3]. However, the IPCC-AR6 carbon budgets include CO_2 sources from both fossil fuel combustion and land-use change, but our country-level data exclude emissions from land-use change.

To account for this difference, we obtained data on the shares of fossil fuel and land-use change in total anthropogenic emissions from ref. 62 and calculated ten-year averages over the most recent decade (90% and 10%, respectively). On the basis of these shares, we disaggregated the fossil fuel component of the IPCC global carbon budgets remaining from 2020 for 1.5 °C and 2 °C (360 $GtCO_2$ and 1,035 $GtCO_2$, respectively) and calculated 1.5 °C and 2 °C carbon budgets starting from 1850, 1960 and 1992.

In contrast to the 1.5 °C and 2 °C boundaries, there is no carbon budget remaining from 2020 for the 350 ppm climate boundary (CO_2 concentrations are already greater than 415 ppm and rising[2]). We set the 350 ppm carbon budgets starting from 1850 and 1960 equal to their respective cumulative global totals in 1988 (the year that CO_2 concentrations crossed this boundary). See Supplementary Table 2 for the numerical global carbon budgets that we derived for the different climate boundaries and start years used in the analysis.

Distributing national fair shares of global carbon budgets

There are different 'top-down' sharing principles that could be used to distribute global carbon budgets to countries, including equality, historical responsibility, respective capabilities, geographical needs and sovereignty[47]. Building on refs. 9,12, we developed an equality-based method that considers historical responsibility and distributes a given global carbon budget into national fair shares according to a given country's population as a share of the global population, with populations averaged over a given analysis period ($\overline{\mathrm{population}}$), or

$$\text{fair-share}^{b}_{n,t_{\mathrm{start:end}}} = CO_2\ \mathrm{budget}^{b}_{\mathrm{world},t_{\mathrm{start}}} \times \left(\frac{\overline{\mathrm{population}_{n,t_{[\mathrm{start:end}]}}}}{\overline{\mathrm{population}_{\mathrm{world},t_{[\mathrm{start:end}]}}}} \right)$$

where the fair share for each country n is a function of the given climate boundary, b, and the cumulative analysis period, $t_{\mathrm{start:end}}$. In our case, we analysed three climate boundaries (b = 350 ppm, 1.5 °C and 2 °C) and three analysis periods with distinct starting years that each ended in 2050 (t_{start} = 1850, 1960 and 1992; t_{end} = 2050).

On the basis of the available parameter combinations, we calculated a total of eight separate fair-share values for each country using the preceding equation. Overall, our approach is underpinned by the view that all people hold a right to an equitable and fair use of the atmospheric commons. It is motivated by our specific research question, which asks whether the level of cumulative overshoot beyond a country's fair share of global carbon budgets could serve as the basis for making climate reparations to others who are unable to make full use of their own fair shares in a net-zero world. Notably, national fair shares may change depending on the analysis period, as population shares can change with respect to the global population over time.

Comparing cumulative emissions with respect to fair shares

We present cumulative emissions with respect to fair shares of global carbon budgets in two ways. In the first case, we follow a normalization procedure similar to that employed by ref. 12, which involves dividing national cumulative emissions values by a given fair-share value on an annual basis. More specifically, all the cumulative emissions and fair-shares data for a given country, climate boundary and year were normalized for each cumulative analysis period by dividing them by that country's 1.5 °C fair share, so this fair share is always assigned the value of one. This normalization approach anchors the 1.5 °C fair share in absolute terms (it is always one, regardless of the data), which is useful to illustrate and compare cumulative emission pathways with respect to fair shares of multiple budgets across diverse countries and regions on an equivalent scale, as shown in Fig. 1 (and Extended Data Figs. 1 and 2).

In the second case, national fair shares of each global carbon budget were subtracted from countries' cumulative emission pathways on an annual basis to calculate the extent to which these countries have either overshot or stayed within their fair shares in each analysis period, building on the approach described by ref. 9, or

$$\text{cumulative over(under)shoot}_{n,t}^{b,s} = \text{fair share}_{n,t_{\text{start:end}}}^{b} - \text{cumulative emissions}_{n,t}^{b,s}$$

where cumulative overshoot (or undershoot) for each country n in each year t is a function of the given climate boundary b and the given scenario pathway s (business as usual or net zero). This approach provides a quantification of national responsibility for overshooting fair shares of a given climate boundary in absolute terms of each country's excess emissions (or undershoot emissions). These values were summed to give total overshoot (or undershoot), and responsibility was defined on the basis of the proportion of this total held by each country, as shown in Fig. 2 (and Extended Data Figs. 3 and 4).

Compensation from overshooting to undershooting countries

We distributed financial compensation from overshooting countries to undershooting countries (both with respect to 1.5 °C fair shares) using median carbon prices from 2020–2050 derived from the IPCC-AR6 scenario database[29] and each country's net-zero scenario pathway.

We derived median (and interquartile range) marginal abatements costs of carbon over the 2020–2050 period on the basis of the 73 scenarios in the IPCC-AR6 database that report 5-year values from 2025 with a 50% likelihood of limiting warming to 1.5 °C with no or limited overshoot. Notably, these year-specific carbon prices account for the expectation of increasing marginal abatement costs over the coming decades. See Supplementary Table 3 for a summary of the numerical values we used over the 2020–2050 period and Supplementary Information for additional details.

We used these carbon prices to quantify the climate debt incurred by overshooting countries' cumulative excess emissions beyond their 1.5 °C fair shares under our net-zero scenario as follows:

$$\text{overshootdebt}_i = \sum_{t=2020}^{2050}\left(\left(\frac{\text{cumulativeovershoot}_{i,t=2050}}{(2050-2020)+1}\right)\times \text{carbonprice}_t\right)$$

where each overshooting country i's cumulative overshoot emissions in 2050 were annualized uniformly over the 31-year period and multiplied by the respective carbon price in year t. Summing country i's excess emissions valued in monetary terms over the 2020–2050 period yielded an estimate of the total overshoot debt incurred by its cumulative overshoot of 1.5 °C fair shares for each analysis period in a world that achieves net zero between 2020 and 2050.

We then distributed the monetary overshoot debt from each overshooting country to each undershooting country as a credit, or

$$\text{undershootcredit}_j = \sum_{i_1}^{i_k}\left(\text{overshootdebt}_i \times \left(\frac{\text{cumulativeundershoot}_{j,t=2050}}{\text{cumulativeundershoot}_{\text{total},t=2050}}\right)\right)$$

where the sum of the overshoot debt from each overshooting country $i_1, i_2, \ldots, i_k$ was distributed to undershooting country j on the basis of the latter's share of total undershoot emissions in 2050 in each analysis period under our net-zero scenario.

Additional limitations

Some additional methodological limitations are worth noting. The data used in our analysis include only CO_2 emissions and no other greenhouse gases; they do not include emissions from land-use change. Our business-as-usual projections consider time trends, but additional variables could be explored to unpack our country-specific trends, such as population, affluence and technology[63]. Notably, the net-zero convergence scenario we have used here does not account for the principle of common but differentiated responsibilities in light of respective national capabilities, by which countries with greater means, and with higher cumulative emissions, must decarbonize faster than the rest of the world (and vice versa for countries with lesser means). Although methods that consider respective capabilities are emerging[10], often based on an income-based minimum threshold that excludes poorer countries from mitigation requirements, we have not applied them to our analysis for simplicity. It is not clear whether excluding poorer countries from mitigation would be beneficial for them in our framework, given that they would be entitled to additional compensation for achieving net zero by 2050, and these funds could go towards improving respective capabilities. A useful step for future research could be to account for country-specific decarbonization trajectories and/or to account for existing national commitments of varying strengths.

Reporting summary

Further information on research design is available in the Nature Portfolio Reporting Summary linked to this article.

Data availability

Data sources for each indicator are described in the Time-series data subsection of Methods in the manuscript and summarized in Supplementary Table 1. The databases used in the study include (1) population data from Gapminder and UN Population Division World Population Prospects 2019, (2) CO_2 emissions data from the PRIMAP-hist database and the EORA MRIO database, (3) GDP data from the Maddison project database and the World Bank World Development Indicators database and (4) carbon price data from the IPCC-AR6 scenarios database. The data produced in the analysis are included in the Supplementary Information spreadsheet accompanying this article. The data are also available via an interactive webpage (https://goodlife.leeds.ac.uk/atmospheric-appropriation/) that allows users to query the dataset and visualize charts similar to Fig. 1 and Fig. 6 for all countries.

Code availability

The data analysis was conducted using R (v.4.0.2). Beyond this base R version, our analysis is dependent on several R packages. We used the tidyverse suite of packages (v.1.3.0) for organizing, manipulating and visualizing the data. We also used the zoo package (v.1.8-8) and the forecast package (v.8.13) for time-series analysis functionality and the ggpubr package (v.0.4.0) for additional data visualization functionality. The source data and custom R code used to generate the analysis are archived on Zenodo (v.1.0.0) at https://doi.org/10.5281/zenodo.7779453.

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Acknowledgements

We are grateful to K. Raworth for providing comments on an earlier manuscript. J.H. was supported by the European Research Council REAL—ERC-2022-SYG reference number 101071647 and the María de Maeztu Unit of Excellence (CEX2019–374 000940-M) grant from the Spanish Ministry of Science and Innovation.

Author contributions

A.L.F. and J.H. conceptualized the study. A.L.F. contributed data collection, visualization, analysis, writing and editing. J.H. contributed analysis, writing and editing.

Competing interests

The authors declare no competing interests.

Additional information

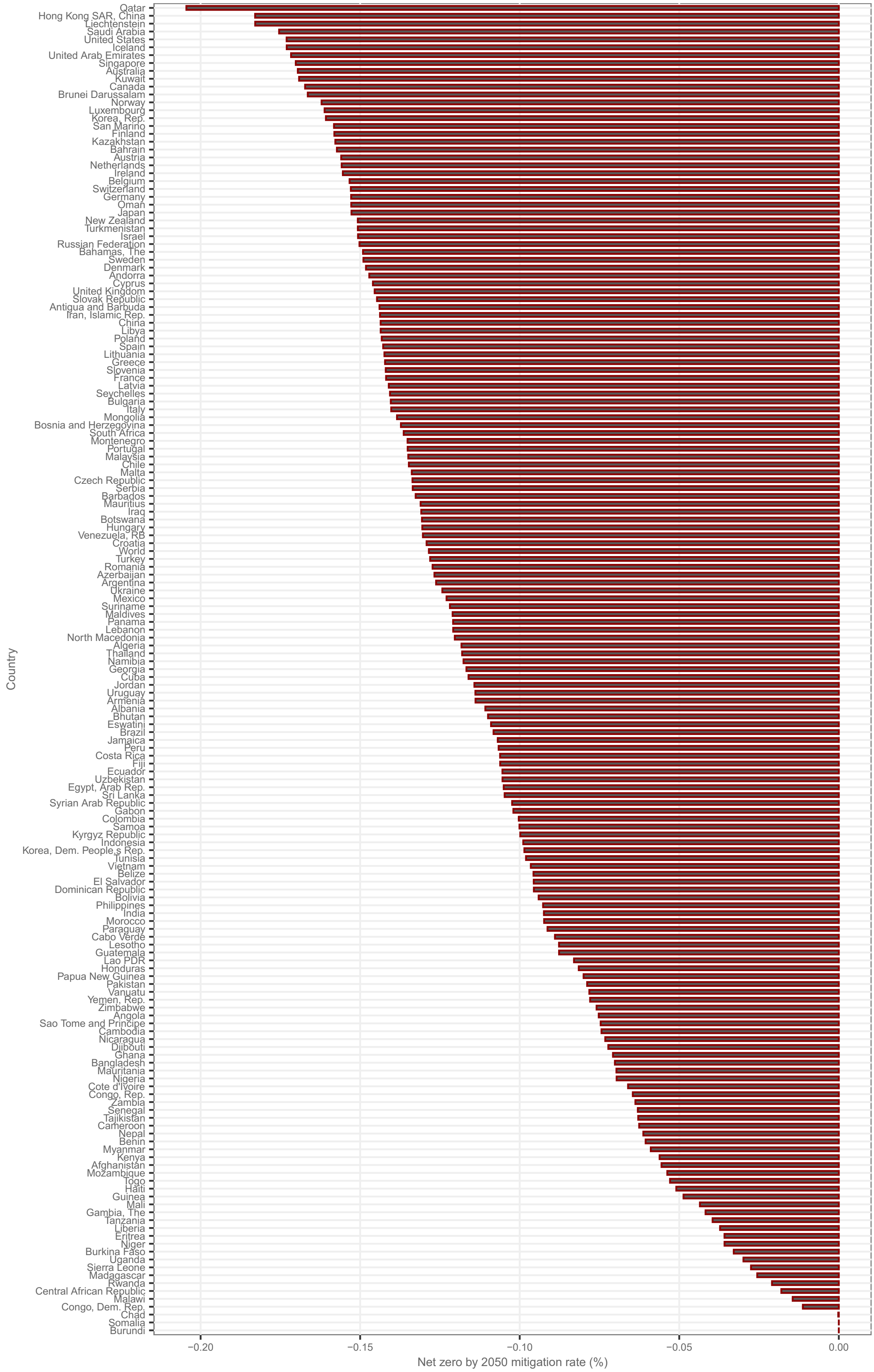
Extended data is available for this paper at https://doi.org/10.1038/s41893-023-01130-8.

Supplementary information The online version contains supplementary material available at https://doi.org/10.1038/s41893-023-01130-8.

Correspondence and requests for materials should be addressed to Jason Hickel.

Peer review information *Nature Sustainability* thanks J. Roberts, Matthew Jones and the other, anonymous, reviewer(s) for their contribution to the peer review of this work.

https://doi.org/10.1038/s41893-023-01130-8



Extended Data Fig. 1 | Mitigation rates for country-specific levels of CO_2 emissions to converge to 0.1 tonnes CO_2 per capita in all countries over the 2020–2050 period. Mitigation rates are calculated by reducing country-specific levels of emissions at a constant rate from 2020 levels to 0.1 tonnes per capita in 2050 using a simple exponential function, as described in Methods (N = 168 plus World).

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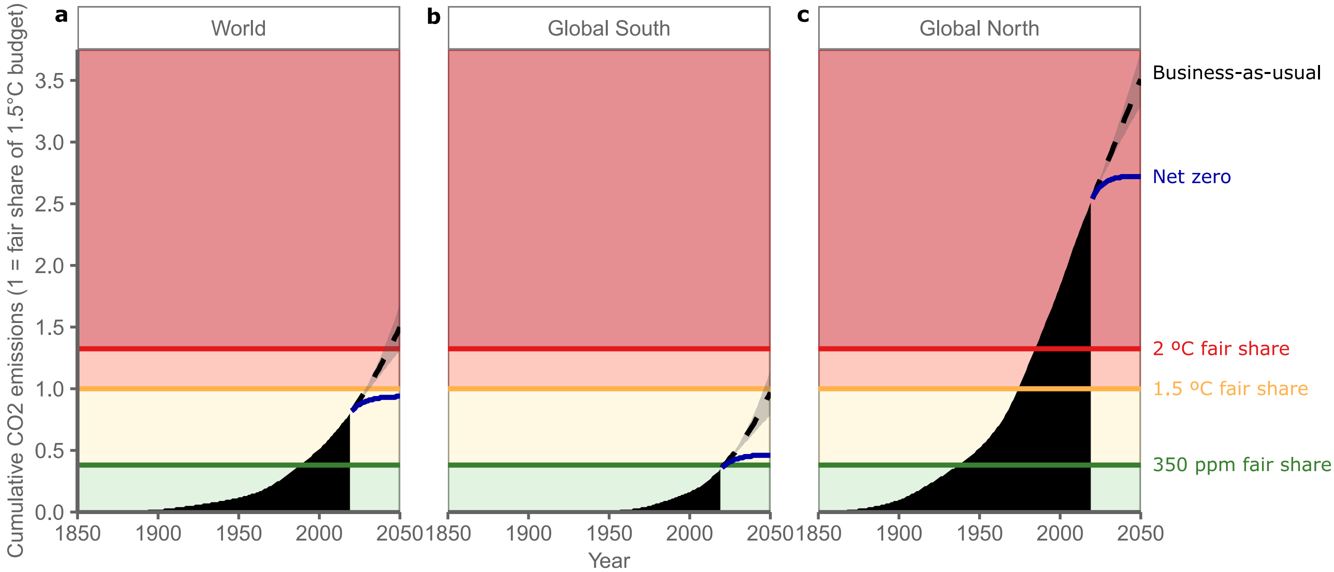

Extended Data Fig. 2 | World and regional cumulative emissions with respect to fair shares of global carbon budgets, historical trends (1850–2019) and scenario trends (2020–2050). **a**, world, **b**, global South region, and **c**, global North region. The lines and colours are used as per Fig. 1 in the Main text.

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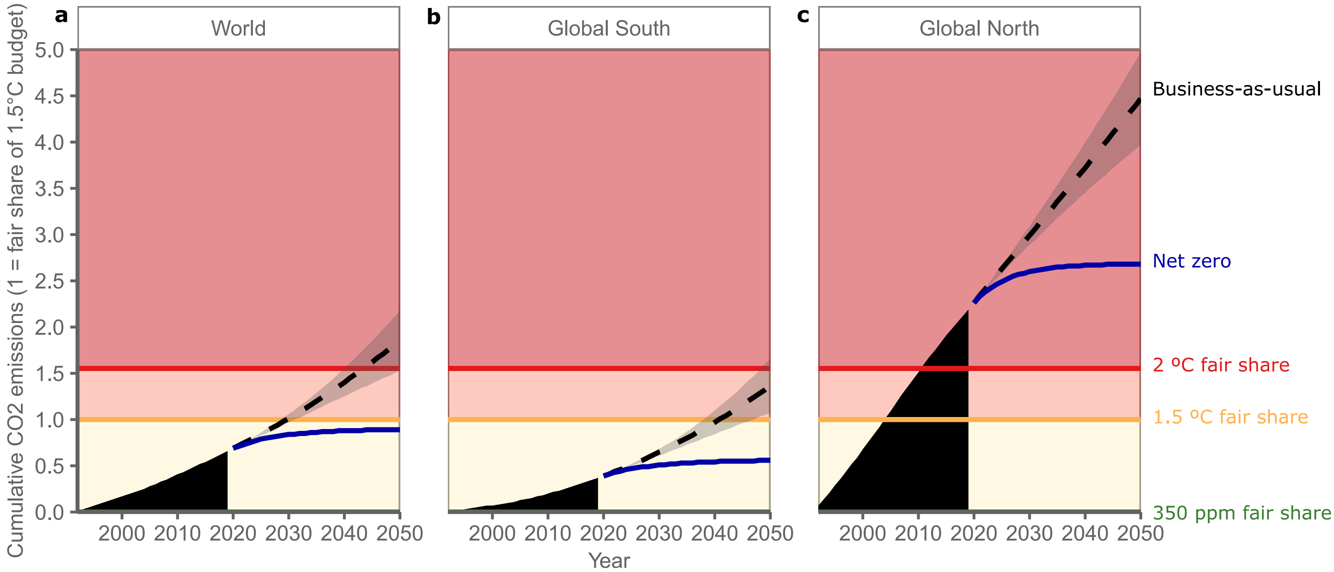

Extended Data Fig. 3 | World and regional cumulative emissions with respect to fair shares of global carbon budgets, historical trends (1992–2019) and scenario trends (2020–2050). **a**, world, **b**, global South region, and **c**, global North region. The lines and colours are used as per Fig. 1 in the Main text.

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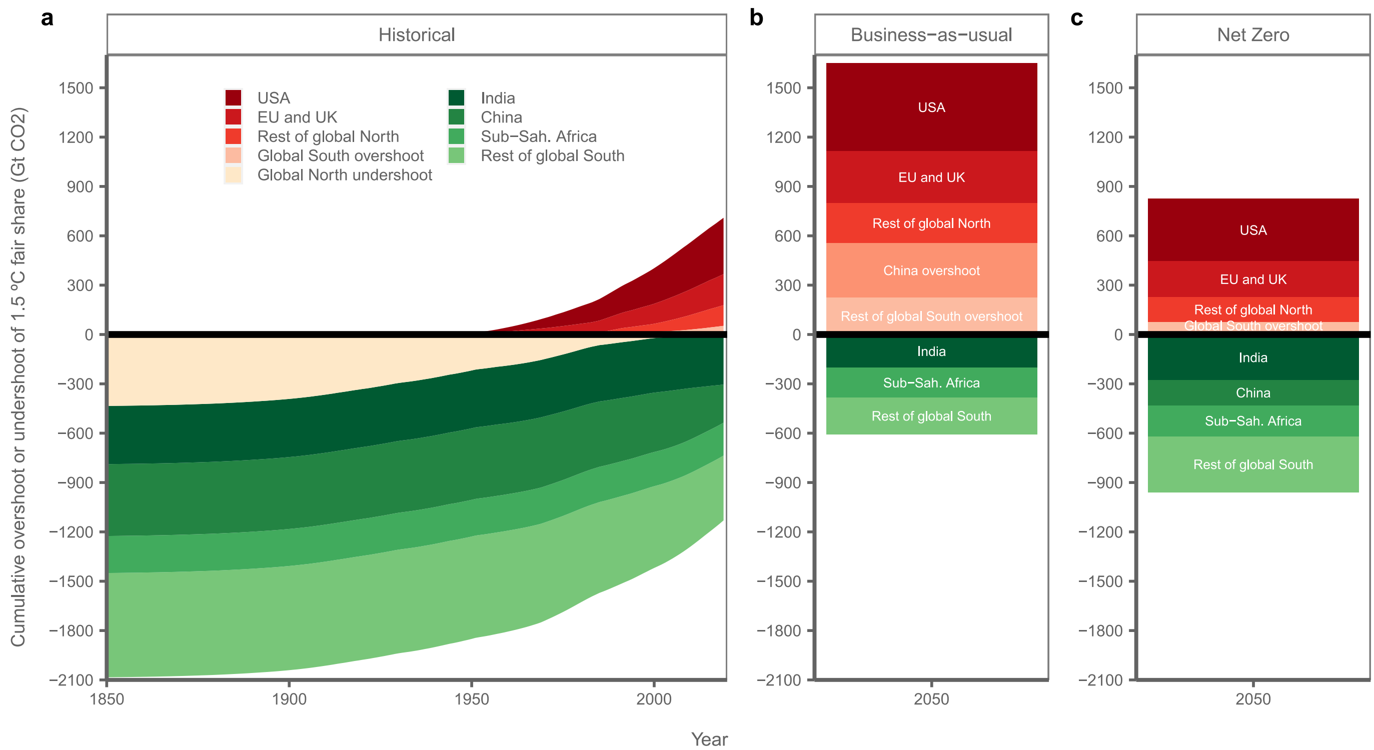

Extended Data Fig. 4 | Cumulative emissions overshoot and undershoot by country group with respect to 1.5 °C fair shares, from 1850 start year. a, historical 1850–2019 period, **b**, business-as-usual median projection in 2050, and **c**, net zero scenario in 2050.

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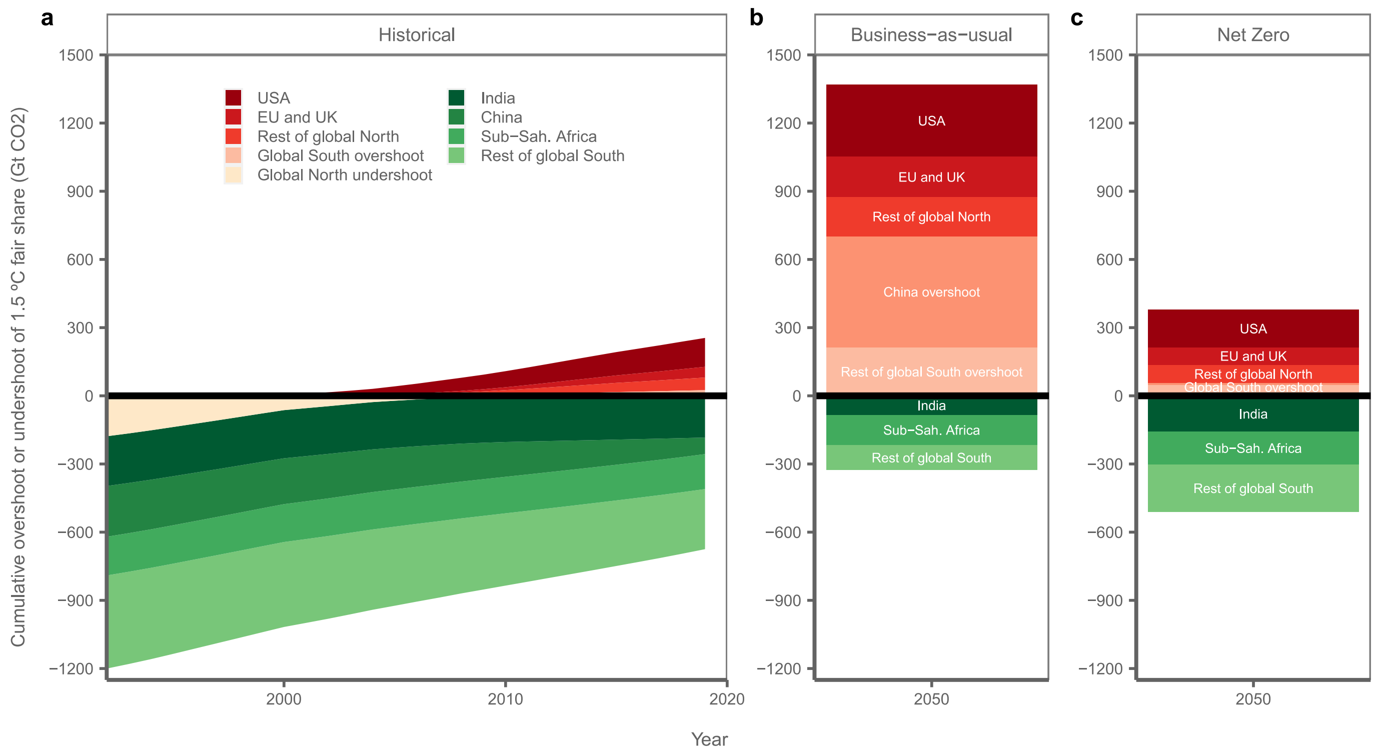

Extended Data Fig. 5 | Cumulative emissions overshoot and undershoot by country group with respect to 1.5 °C fair shares, from 1992 start year. **a**, historical 1992–2019 period, **b**, business-as-usual median projection in 2050, and **c**, net zero scenario in 2050. Note that the wedge showing overshoot in China under the net zero scenario in 2050 (7 Gt CO_2) is very small relative to the axis scale, and is not labelled in the figure due to a lack of space.

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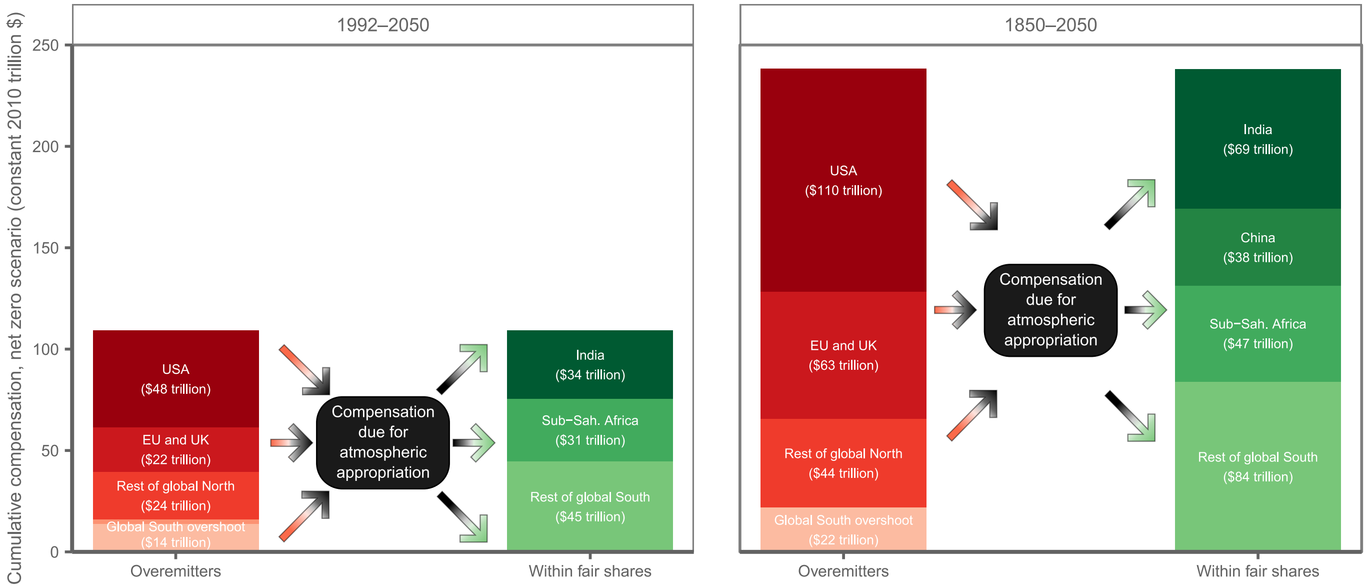
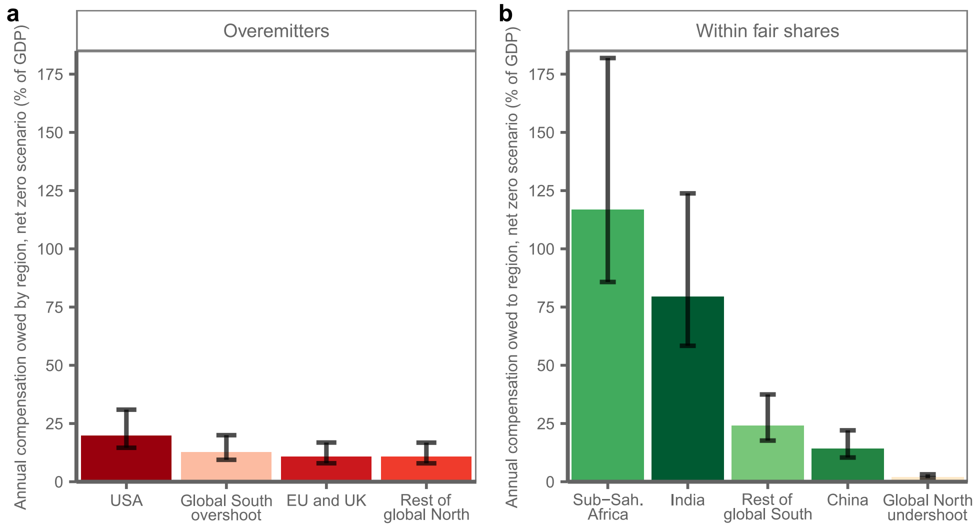


Extended Data Fig. 6 | Cumulative compensation due from overshooting country groups to undershooting country groups (relative to 1.5 °C fair shares), based on different historical start years to 2019 and net zero scenario from 2020–2050. a, 1992–2050 period, and **b**, 1850–2050. Note that the wedge showing cumulative compensation owed by China starting from 1992 ($2 trillion) is very small relative to the axis scale, and is not labelled in the figure due to a lack of space.

https://doi.org/10.1038/s41893-023-01130-8



Extended Data Fig. 7 | Average annual compensation by country group relative to average GDP by region in 2018, based on the historical period from 1850–2019 and net zero scenario from 2020–2050. a, overemitting country groups, and **b**, country groups within fair shares. Annual compensation is calculated from median carbon price values, with error bars calculated from the upper and lower bounds of the interquartile range of carbon prices, derived from IPCC-AR6 pathways that limit warming to 1.5 °C with no or limited overshoot (N = 73).

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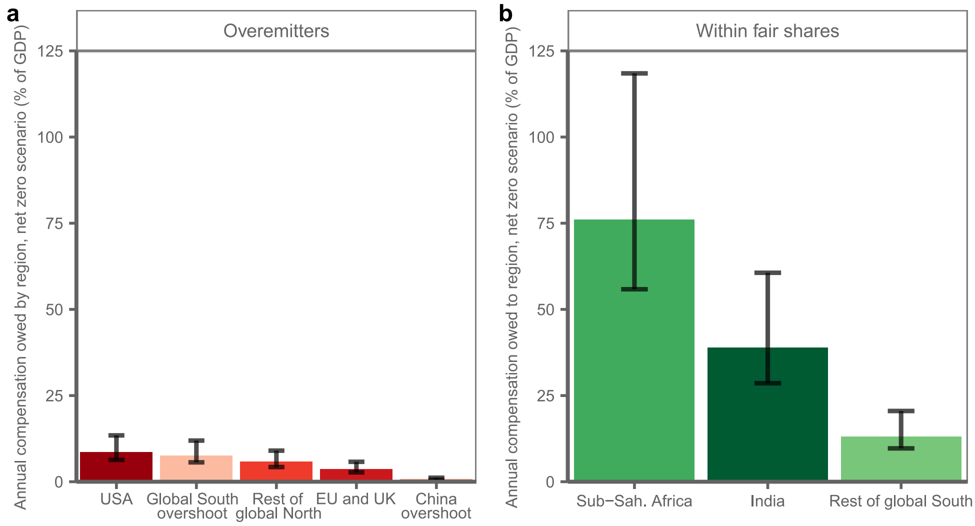

Extended Data Fig. 8 | Average annual compensation by country group relative to average GDP by region in 2018, based on the historical period from 1992–2019 and net zero scenario from 2020–2050. a, overemitting country groups, and **b**, country groups within fair shares. Annual compensation is calculated from median carbon price values, with error bars calculated from the upper and lower bounds of the interquartile range of carbon prices, derived from IPCC-AR6 pathways that limit warming to 1.5 °C with no or limited overshoot (N = 73).

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Last updated by author(s): Mar 23, 2029

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n/a	Confirmed	
☐	☒	The exact sample size (n) for each experimental group/condition, given as a discrete number and unit of measurement
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☒	☐	A description of all covariates tested
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☐	☒	For null hypothesis testing, the test statistic (e.g. F, t, r) with confidence intervals, effect sizes, degrees of freedom and P value noted *Give P values as exact values whenever suitable.*
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Our web collection on statistics for biologists contains articles on many of the points above.

Software and code

Policy information about availability of computer code

Data collection	Data was collected manually from publicly available online international datasets using Google Chrome.
Data analysis	The data analysis was conducted using R (v4.0.2). Above and beyond this base R version, our analysis is dependent on several R packages. We used the "tidyverse" suite of packages (v1.3.0) for organising, manipulating, and visualising the data. We also used the "zoo" package (v1.8-8) and the "forecast" package (v8.13) for time series analysis functionality, and the "ggpubr" package (v0.4.0) for additional data visualisation functionality. The source data and custom R code used to generate the analysis are archived on Zenodo (v1.0.0) at https://doi.org/10.5281/zenodo.7779453.

For manuscripts utilizing custom algorithms or software that are central to the research but not yet described in published literature, software must be made available to editors and reviewers. We strongly encourage code deposition in a community repository (e.g. GitHub). See the Nature Portfolio guidelines for submitting code & software for further information.

Data

Policy information about availability of data

All manuscripts must include a data availability statement. This statement should provide the following information, where applicable:

- Accession codes, unique identifiers, or web links for publicly available datasets
- A description of any restrictions on data availability
- For clinical datasets or third party data, please ensure that the statement adheres to our policy

Data sources for each indicator are described in the 'Time-series data' sub-section of Methods in the manuscript and summarised in Supplementary Table 1. The databases used in the study include (i) population data from Gapminder and UN Population Division World Population Prospects 2019, (ii) CO2 emissions data from the PRIMAP-hist database and the EORA MRIO database, (iii) GDP data from the Maddison project database and the World Bank World Development Indicators database, and (iv) carbon price data from the IPCC-AR6 scenarios database. The data produced in the analysis are included in the Supplementary Information spreadsheet accompanying this article. The data are also available via an interactive webpage (https://goodlife.leeds.ac.uk/atmospheric-appropriation/), which allows users to query the dataset and visualise charts similar to Figure 1 and Figure 6 for all countries.

Human research participants

Policy information about studies involving human research participants and Sex and Gender in Research.

Reporting on sex and gender	There is no reporting by sex or gender in this study.
Population characteristics	This study includes reporting by total national population, aggregate national carbon dioxide emissions, and national gross domestic product. The national data were collected from existing datasets that are publicly available. National populations were categorised into global North and global South groups using the same protocol employed by Hickel et al. (2022) "National responsibility for ecological breakdown: a fair-shares assessment of resource use, 1970–2017", which is based on a core-periphery understanding of the global capitalist economic system as proposed by theories of underdevelopment, such as dependency theory and world systems theory. In general, the global North here refers to the United States, Europe, Canada, Australia, New Zealand, Japan, and Israel, while the global South refers to the rest of Asia, Africa, and the Americas. The specific categorisation of each country included in the study is defined in the Supplementary Information spreadsheet.
Recruitment	There were no participants recruited for this study.
Ethics oversight	This study uses publicly available secondary data from existing datasets, and therefore does not require formal ethics oversight.

Note that full information on the approval of the study protocol must also be provided in the manuscript.

Field-specific reporting

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☐ Life sciences ☒ Behavioural & social sciences ☐ Ecological, evolutionary & environmental sciences

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Behavioural & social sciences study design

All studies must disclose on these points even when the disclosure is negative.

Study description	This study includes a (desk-based) quantitative time series analysis of national carbon emissions relative to population-based fair shares, using secondary data obtained from publicly available international datasets.
Research sample	The national-level research sample (N = 168) was collected from existing datasets and it includes as many countries in the world as possible, given the availability of comparable time series data starting from 1850 for carbon dioxide emissions and total population. There is no reporting by demographic characteristics in this study (e.g. age, sex, etc.) All the existing dataset sources used in this study are described in Methods and summarised in Supplementary Table 1.
Sampling strategy	Given the finite number of countries in the world, the cross-country sampling strategy for this study followed a non-probability purposive sampling procedure aiming to include as many countries as the availability of internationally comparable quantitative time-series data would allow. No within-country sample size calculation was performed in order to project the dynamic statistical "business-as-usual" trends to 2050 for CO2 emissions for each country, based on historical data between 1960 and 2019. According to Hyndman and Athanasopoulos' (2019) "Forecasting: Principles and Practice", rules-of-thumb minimum sample sizes for various time series models are unsubstantiated in theory and practice -- minimum sample sizes for time series forecasts will depend on the number of parameters to be estimated and the amount of randomness in the data. We followed these authors' suggestion that choosing the model with the minimum AICc value is the best approach for relatively short time series, like our 60-year period,

because it allows both the number of parameters and the amount of noise to be taken into account (see Methods for a full description of our estimation procedure).

Data collection	National data were collected from secondary sources provided by international datasets publicly available to download as spreadsheets (.csv or .xslx file formats). There were no participants involved in the desk-based study and the researchers were not blinded to the study hypothesis. The data sources and time series used for each indicator are described in Methods and summarised in Supplementary Table 1.
Timing	The data used in our analysis were collected online from publicly available sources during the first half of 2022, and the overall time series start date (1850) and stop date (2019) were determined by the earliest and most recent years of comparable data available with near-global country coverage at the time of data collection. Notably, although more recent territorial-based CO2 emissions were available for 2020, there is a 1-year lag on reliable consumption-based carbon dioxide emissions estimates for a large number of countries. However, we considered this lag acceptable for our purposes as consumption-based estimates that account for international trade are widely recognised to better reflect responsibility for environmental burdens than territorial estimates.
Data exclusions	We excluded 42 countries due to wholly missing observations in at least one of the carbon dioxide emissions and population indicator series, often countries with very small populations (N = 33), or due to very poorly modelled consumption-based CO2 emissions series estimated by the Eora MRIO compared to territorial values, which we detected using statistical outlier tests and box plots (N = 9). In addition, we also removed several within-country negative values in the consumption-based emissions data, and adopted a protocol developed by Fanning et al. (2022) "The social shortfall and ecological overshoot of nations" to test for within-country extreme statistical outlier spikes and troughs relative to the territorial emissions data (defined as 4 times beyond the interquartile range), interpolating linearly to fill the missing values in both cases.
Non-participation	The analysis uses national-level data; no participants were recruited to take part in this study.
Randomization	The analysis uses national-level data; there was no recruitment of participants for allocation into experimental groups. Randomization was not relevant because the study does not allocate countries into experimental control and treatment groups.

Reporting for specific materials, systems and methods

We require information from authors about some types of materials, experimental systems and methods used in many studies. Here, indicate whether each material, system or method listed is relevant to your study. If you are not sure if a list item applies to your research, read the appropriate section before selecting a response.

Materials & experimental systems

n/a	Involved in the study
☒	☐ Antibodies
☒	☐ Eukaryotic cell lines
☒	☐ Palaeontology and archaeology
☒	☐ Animals and other organisms
☒	☐ Clinical data
☒	☐ Dual use research of concern

Methods

n/a	Involved in the study
☒	☐ ChIP-seq
☒	☐ Flow cytometry
☒	☐ MRI-based neuroimaging