nature climate change

ARTICLES

https://doi.org/10.1038/s41558-020-0857-2

Check for updates

Fair-share carbon dioxide removal increases major emitter responsibility

Claire L. Fyson[1]✉, Susanne Baur[1], Matthew Gidden[1,2] and Carl-Friedrich Schleussner[1,3]

The Paris Agreement long-term temperature goal is to be achieved on the basis of equity. Accomplishing this goal will require carbon dioxide removal (CDR), yet existing plans for CDR deployment are insufficient to meet potential global needs, and equitable approaches for distributing CDR responsibilities between nations are lacking. Here we apply two common burden-sharing principles to show how CDR responsibility could be shared between regions in 1.5 °C and 2 °C mitigation pathways. We find that fair-share outcomes for the United States, the European Union and China could imply 2–3 times larger CDR responsibilities this century compared with a global least-cost approach. We illustrate how delaying near-term mitigation affects the CDR responsibilities of major emitters: raising emission levels in 2030 by one gigatonne generates about 20–70 additional gigatonnes of CDR responsibility over this century. An informed debate about equitable CDR contributions will be essential to achieve much-needed progress in this area.

There is growing political awareness of the need for and benefits of decarbonizing the global economy. However, many policy makers have yet to acknowledge the inevitable need for carbon dioxide removal (CDR) to meet the Paris Agreement's long-term temperature goal of limiting warming to 1.5 °C. The amount of CDR required will depend on the pace of global progress in reducing emissions; early action to rapidly decarbonize and reduce the overall need for CDR will be essential[1,2]. Nevertheless, all modelled pathways that limit warming to 1.5 °C rely on CDR in some form: first to offset difficult-to-eliminate residual emissions and, if warming exceeds 1.5 °C, to pull atmospheric carbon dioxide (CO_2) concentrations back down[1].

While measures to reduce emissions often come with co-benefits for society (for example, improved energy access, lower costs, cleaner air), the same is not true for many CDR options. In general, CDR technologies do not have direct local benefits, can be costly and can have negative side effects if deployed at large scale[3,4]. These drawbacks might explain the limited progress in planning and deploying CDR at the national level[5]. By signing up to the Paris Agreement, with its goal to balance emissions and removals, governments have already accepted some responsibility for CDR; however, the lack of framing for national CDR obligations means that CDR deployment has become a 'hot potato' in climate policy. Here, we propose that framing CDR as a burden-sharing problem[6] provides a starting point for an informed debate on how to distribute the potentially large global need for CDR among nations.

To adhere to the Paris Agreement's goals, CDR responsibility derived from any burden-sharing regime must be based on the concept of equity[7]. Many different dimensions of equity are relevant in this context. For example, poor and vulnerable populations who are least responsible for causing climate change[4] will be disproportionately affected by overshooting warming targets[8]. Distributional effects may arise if CDR deployment causes competition for resources, such as land and water[1]. Intergenerational equity is also important, as today's failure to reduce emissions increases CDR burdens and climate change impacts for future generations[9–11]. Such equity considerations can be used to encourage stronger and more just climate action, weigh up the trade-offs inherent in addressing climate change and enhance reciprocity and engagement in national and international climate governance[12].

A number of well-established equity approaches have been used to share the remaining carbon budget and mitigation burden[13–21]. These approaches are based on normative assumptions over the relevance of countries' culpability for causing climate change, capability of reducing emissions, equality in opportunities for sustainable development, and/or mitigation potential. According to these approaches, many of the largest emitters have not set sufficiently ambitious emissions reduction targets[13,14,17,18] and are set to exceed, or have already exceeded, their fair shares of the carbon budget[19,20,22]. This brings countries into a 'CO_2 debt'[23,24], requiring large amounts of CDR to bring them in line with what could be considered equitable.

Sharing the global CDR burden using equity-based approaches has received little scientific or political attention[25,26]. Most existing assessments of CDR requirements use the least-cost distributions produced by integrated assessment models (IAMs) rather than burden-sharing approaches. Such assessments are based on the normative assumption that global costs should be minimized. IAMs find feasible pathways to meet global climate goals in a cost-optimal manner, considering technological costs, resource potential and trade-offs with competing development options. IAMs vary, sometimes dramatically, not only in assumptions for CDR technologies (for example, the maximum rate of deployment, discount rates[10]), but also in which technologies are considered. While IAMs offer an economically efficient suggestion of regionally disaggregated CDR deployment[27], they do not yet provide insight into questions of equity or responsibility from either an implementation or a finance perspective.

Equitable carbon removal

In this analysis, we consider how the burden of deploying CDR over the century could be 'fairly' distributed among countries and regions. We use two simple and transparent approaches that are based on the widely used equity principles of responsibility, equality and capability[13,28].

[1]Climate Analytics, Berlin, Germany. [2]International Institute for Applied Systems Analysis, Laxenburg, Austria. [3]Integrative Research Institute on Transformations of Human-Environment Systems (IRI THESys), Humboldt-Universität zu Berlin, Berlin, Germany. ✉e-mail: claire.fyson@climateanalytics.org

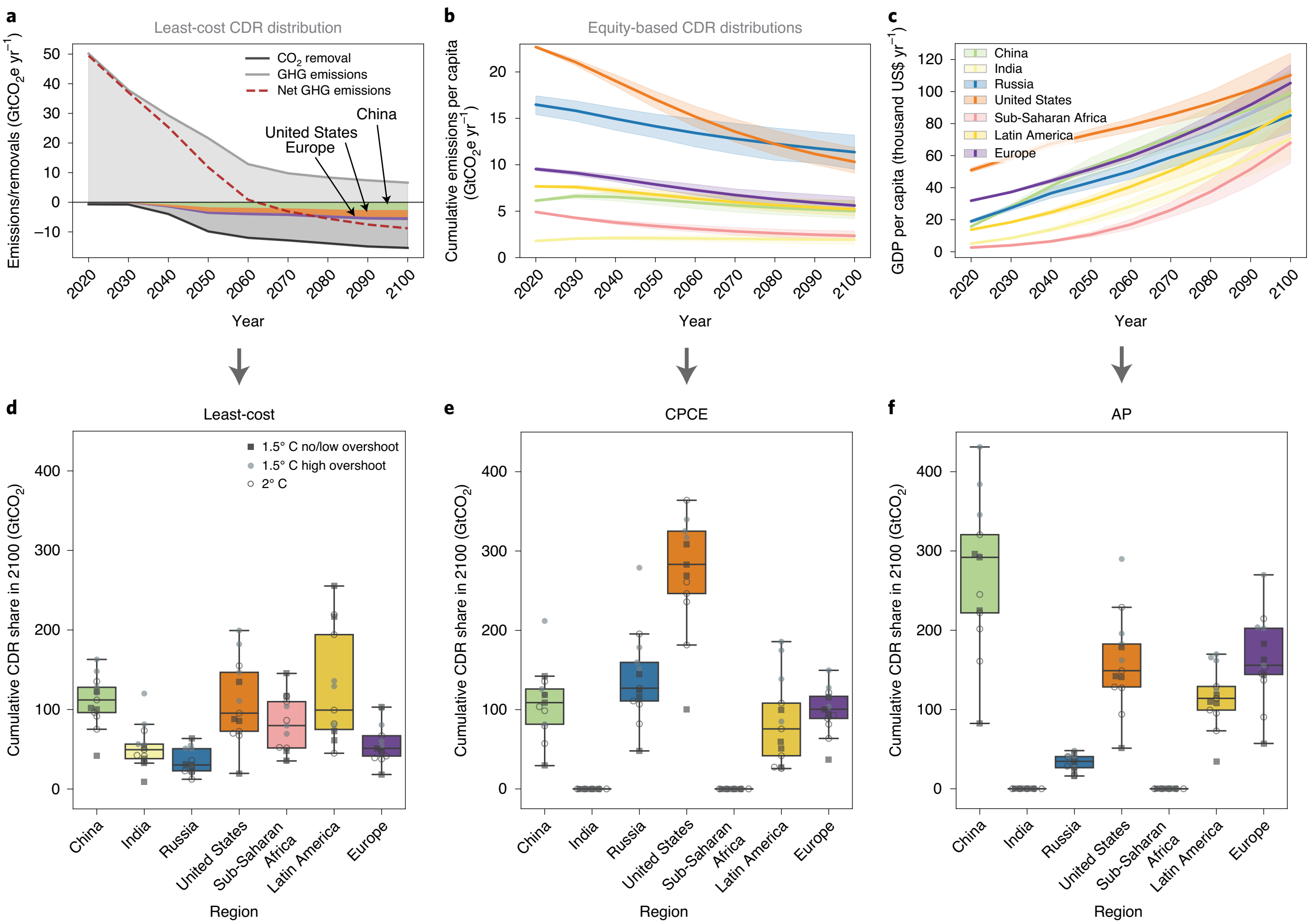


Fig. 1 | Illustration of CDR distribution under different equity approaches. **a**, GHG emissions and removals for an illustrative mitigation pathway. The regional contributions of China (light green) and the United States (orange) are highlighted as part of the total CDR (blue). **b**,**c**, Temporal evolution of cumulative emissions per capita (**b**) and GDP per capita (**c**) underlying the CPCE and AP equity approaches for seven world regions under the same illustrative pathway; shaded areas show the spread across assessed least-cost pathways. **d**, Regional distribution of CDR for assessed least-cost pathways. **e**,**f**, Regional distribution based on the CPCE and AP equity approaches, respectively. Symbols show results for pathways that limit warming to 1.5 °C with no or limited overshoot (squares), that overshoot 1.5 °C by a high margin (closed circles) and that limit end-century warming to 2 °C (open circles). Coloured bars show the median, 25th and 75th percentiles across all pathways, with whiskers indicating the 5th and 95th percentiles. See Extended Data Fig. 1 and Supplementary Table 1 for a comparison of CDR shares in 2050 and 2100. Supplementary Fig. 2 shows the results for the AP approach if countries/regions with a below-average GDP per capita are not excluded.

The 'cumulative per capita emissions' (CPCE) approach reflects both equality and responsibility for past and future emissions. Following the 'polluter pays' principle, the CPCE approach assumes that countries with the highest cumulative emissions per person should shoulder more of the CDR burden. This can be justified because CDR is needed to remove the emissions already released, as well as future unmitigated emissions. We take cumulative emissions from 1990, when global scientific consensus on climate change was signified by the release of the first IPCC assessment report. This choice of baseline year represents a value judgement, and other baselines years could also be justified[21].

The second equity approach, 'ability to pay' (AP), assumes that governments with more resources (higher gross domestic product (GDP) per capita) are more capable of paying for CDR deployment. We assume that countries with below-average GDP per capita do not hold responsibility for CDR deployment, regardless of their total GDP, on the basis that meeting basic needs takes precedence over carbon removal[21] (see Methods). This GDP per capita threshold is similar to the welfare threshold used in other capability-based burden-sharing schemes[29,30].

Of course, these approaches are not exhaustive of all possible equity approaches and are not necessarily 'equitable' by all definitions. For example, other approaches for sharing near-term emission reductions have incorporated measures of human development and income distribution[22,31]. Projections of these indicators are less common and have high variability/uncertainty[32]; hence, we do not include such approaches in our analysis. We also do not consider consumption-based emission levels[33], the distributional effects of different CDR options or the responsibilities of non-state actors. However, our approaches represent two important dimensions of equity that are reflected in the Paris Agreement[34], 'common but differentiated responsibilities' and 'respective capabilities', and their application is simple and transparent. Therefore, in our view, they can meaningfully illustrate the relevance of equity considerations for CDR deployment without precluding the application of other equity concepts and approaches in future work on the topic.

Our analysis uses the global cumulative CDR required in mitigation pathways produced by IAMs, which is then distributed among regions and countries using the equity approaches described in the preceding (see Methods and Fig. 1). Notably, the global need for

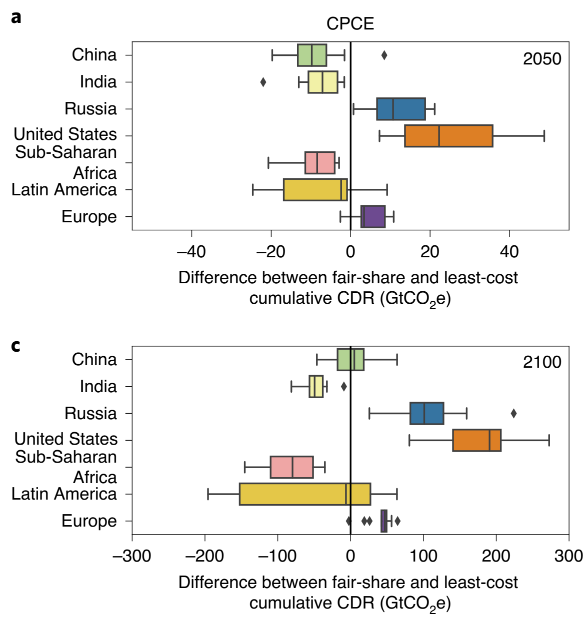


Fig. 2 | Comparison of CDR fair shares with cost-optimal distributions. a–d, The differences between cumulative CDR allocations under burden-sharing and cost-optimal approaches for seven world regions. Results for all assessed pathways under the CPCE (**a**,**c**) and AP (**b**,**d**) equity approaches are provided for the years 2050 (**a**,**b**) and 2100 (**c**,**d**). Coloured bars show the median and 25th and 75th percentiles across all scenarios, with whiskers indicating the 5th and 95th percentiles; outliers are indicated with diamonds. Note the difference in scales between the plots for 2050 and 2100. Supplementary Figs. 3–5 show results for each model.

CDR in our analysis is independent of the equity concept deployed and is purely the result of a failure of mitigation efforts to stay within the carbon budget for a given temperature limit. The distribution of CDR across regions is then affected by the share of gross emissions per capita produced by each region over the century (CPCE) or their relative per capita GDPs (AP) (Fig. 1).

We use pathways that sample different socioeconomic and technological progress storylines (Shared Socioeconomic Pathways (SSP) 1, 2, 5; see Methods) and span a range of CDR deployment totals that are representative of the IPCC *Special Report on Global Warming of 1.5 °C* (SR1.5) scenario set[35,36] (Supplementary Fig. 1). Pathways that overshoot 1.5 °C require very large amounts of CDR to bring the global temperature back down, presenting sustainability challenges[1] as well as considerable uncertainties in the carbon cycle response[37].

For reasons outlined in the preceding, the CDR burden can be considered to differ from the burden of reducing emissions since the former tends to be more expensive and entails fewer co-benefits. Hence, for simplicity, we focus on sharing only the CDR burden and assume that emission reductions follow the cost-optimal distribution provided in each pathway. This does not preclude the application of equity schemes to net emissions, which would give a different result for the CDR burden distribution.

Our approach is technology neutral as it focuses on who should pay for CDR deployment rather than what potential portfolio of CDR options could be used in each region. Nevertheless, we note that the mitigation pathways used for this analysis feature only a limited number of CDR options, predominantly bioenergy with carbon capture and storage, afforestation and reforestation. Other options, such as soil carbon sequestration, direct air capture and storage, and enhanced weathering, are also available[38], and IAMs are increasingly featuring these technologies in their CDR portfolios.

As a benchmark for our analysis, we compare our estimated fair shares for CDR deployment with the least-cost distribution provided in modelled pathways (Figs. 1 and 2). Our results show that the regions where models find CDR deployment to be most cost efficient are not those with the greatest responsibility or capability. Under the CPCE scheme, the United States is allocated the largest CDR burden, with a median share that is three times as large as under a least-cost approach. Russia, Latin America, Europe and China are each allotted less than half of the United States' burden. Compared with the least-cost shares (Figs. 1 and 2), this is a four-fold increase in the median share for Russia, a doubling for Europe, little change for China and a small decrease for Latin America (with a large range across pathways, some showing an increased share) (see also Supplementary Table 1).

The AP scheme shows a very different distribution. China is allotted the largest burden of all regions under the AP approach, with about 2.5 times its least-cost and CPCE allocations. Europe also receives a larger burden under this scheme for all pathways, with more than three times its least-cost share and about 1.5 times its CPCE share, while the United States' median share is much smaller than under the CPCE approach, and only 1.5 times its least-cost allocation. Latin America receives its largest share under the AP approach, with a much smaller spread across pathways than under the CPCE and least-cost approaches, and Russia's share remains similar to its least-cost allocation.

Other regions (sub-Saharan Africa, India) have little to no CDR obligations under both equity schemes, reflecting their relatively low per capita emissions and GDP. The relative shares across regions are similar in 2050 and in 2100, but with substantially smaller absolute volumes of CDR required by 2050 (Extended Data Fig. 1).

For each equity approach, the distribution of CDR burdens varies between model pathways. Compared with pathways that fail to limit warming to 1.5 °C and then return to that warming level after a high overshoot (closed circles in Fig. 1, hereinafter 'high overshoot pathways'), those that limit warming to 1.5 °C with no or limited overshoot (squares, hereinafter '1.5 °C pathways'[1]) tend to require less CDR overall. Different socioeconomic pathways[39] and mitigation strategies also affect GDP and emissions trajectories for each region, thereby altering the distribution of assigned fair shares.

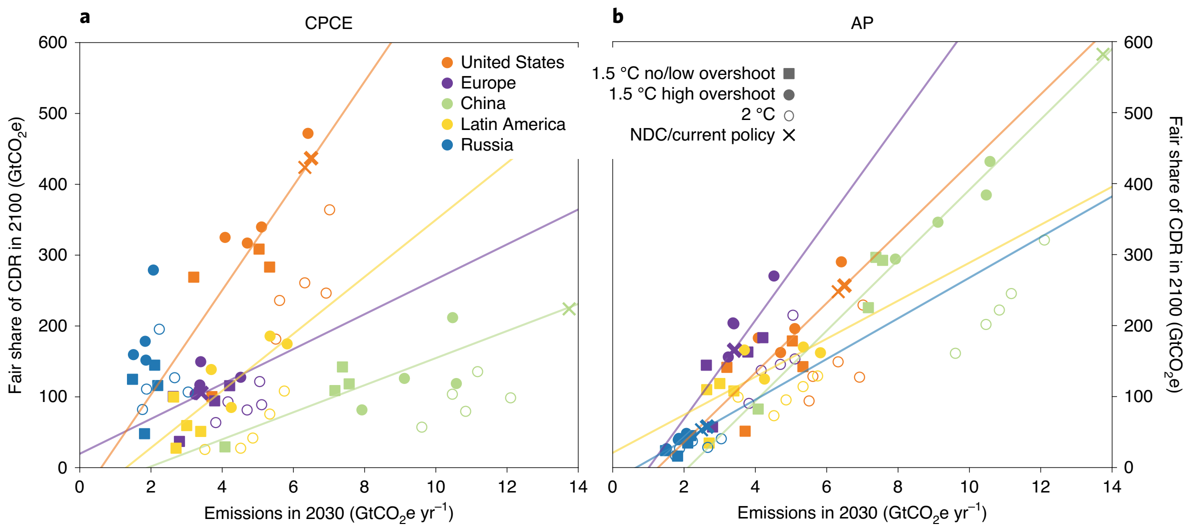


Fig. 3 | Relationship between near-term emissions reductions and long-term CDR burdens. a,b, Comparison of cumulative twenty-first-century CDR fair shares for each region with gross emissions in 2030 for the CPCE (**a**) and AP (**b**) equity approaches. Symbols show the temperature limit for each scenario: 1.5 °C with no/low overshoot (squares), 1.5 °C with high overshoot (closed circles) and 2 °C (open circles). Regression lines for all 1.5 °C pathways (including high-overshoot pathways) are given at the regional level (see Supplementary Table 3 for results of the regression; see Supplementary Fig. 6 for regression lines for each temperature limit). Note that panel **a** lacks a line for Russia as the regression outcome was not robust. Crosses show where estimated 2030 emission levels under the current NDCs for the United States, Europe, China and Russia (data from Climate Action Tracker[43], see Methods) would fall on the regression lines (thick/thin crosses corresponding to low/high 2030 emissions estimates; for China the high estimate is off the scale).

The difference between our fair share CDR distributions and least-cost outcomes from IAMs indicates the potential volume of international CDR transfers exchanged under a burden-sharing system where countries most responsible for CDR pay for its deployment. Such information is relevant for understanding the possible scale of future financial transfers for CDR. A positive difference in Fig. 2 indicates countries with greater CDR obligations than their least-cost share, and vice versa. For 1.5 °C pathways, shifting from a cost-optimal distribution to a fair one would entail the transfer of 86–404 $GtCO_2$ (or 292–507 $GtCO_2$ for high-overshoot scenarios) (see Supplementary Table 2). This is equivalent to at least one-fifth (and up to 100%) of the carbon budget remaining in 2020 for a 50% likelihood of limiting warming to 1.5 °C (around 400 $GtCO_2$[40]).

Near-term determinants of CDR responsibility

By comparing pathways with different temperature outcomes (1.5 °C, high overshoot or 2 °C) and socioeconomic scenarios, we assess the relationship between national climate action over the next decade and the distribution of future CDR responsibilities. For both equity schemes, we find that delaying near-term emissions reductions produces an enlarged CDR burden for each region (Fig. 3 and Supplementary Fig. 6). This goes beyond the direct impact of increased near-term emissions on global CDR needs, as slowed near-term decarbonization (and hence, higher emissions in and up to 2030) also implies carbon lock-in effects[41], which hamper long-term emissions reductions beyond 2030. The regional distribution of the enlarged global CDR need is then the result of normative concepts underlying each equity approach. Under the AP approach, the distribution across regions is based purely on their relative capacities and is independent of countries' individual emission trajectories. Thus, the AP approach leads to a rather homogeneous distribution of regional CDR obligation increments (Fig. 3b), with an average across regions of ~40 Gt of additional cumulative CDR per Gt of emissions in 2030 for 1.5 °C and high-overshoot pathways (see Supplementary Table 3). Note that the mean obligation gradient in the AP case is greater than the gradient in the least-cost case (Supplementary Fig. 6) as the burden is shared between fewer, richer countries.

In the CPCE approach, the fair share for each region is directly linked to its cumulative emissions trajectory. If delayed near-term emission reductions (and associated lock-in effects) disproportionately increase the cumulative emissions per capita of one region, this results in a steeper increase in that region's share of the total CDR burden. This is an important normative inference that comes from the dependence of the CPCE approach on cumulative emissions and population size. The result is a larger diversity in the regional CDR obligations that arise from delayed emission reductions (Fig. 3a). For example, the United States and Latin America have relatively steep relationships between near-term emissions and CDR obligations: across 1.5 °C and high-overshoot scenarios, each extra Gt of emissions in 2030 implies ~70 and ~40 Gt of additional CDR by 2100, respectively. China's CDR burden increases at a lower rate, at ~20 extra Gt of CDR for each Gt of emissions in 2030 (see Supplementary Table 3). For Russia, factors other than 2030 emission levels appear to dominate the twenty-first-century CDR burden under the CPCE approach.

These results clearly illustrate the burden that each region's next generations could inherit if their governments do not put stronger near-term mitigation measures in place. Governments are collectively on track for much higher levels of warming and slower emission reduction rates than the pathways used here[42]. As they bring forward enhanced pledges in their Nationally Determined Contributions (NDCs), governments should consider how their near-term emission reductions will affect their long-term CDR obligations. To estimate the implications of current policies for future CDR burdens, we use our derived relationships between 2030 emissions and century-long CDR responsibility under each equity scheme (Fig. 3) and extrapolate these to the 2030 emission levels under the Climate Action Tracker's NDC and current policy projections[43]. We estimate that China, the United States and the European Union are on track for up to ~650, ~440 and ~170 $GtCO_2$ of CDR obligations, respectively (depending on the equity scheme chosen, see Supplementary Table 4), equivalent to ~50, ~70 and ~40 years' worth of their present-day emissions excluding land-use, land-use change and forestry (LULUCF). If each were to halve their 2030

target emission levels (consistent with what is required globally to limit warming to 1.5 °C[1]), their cumulative CDR burdens would fall by about 130–420 $GtCO_2$ (China), 160–250 $GtCO_2$ (United States) and 40–120 $GtCO_2$ (European Union).

The established relationships between 2030 emission levels and CDR obligations are contingent on the representation of near- to long-term emission reductions and national versus global mitigation efforts in the ensemble of IAM pathways analysed. Although the set of pathways used here is representative of the spread in CDR amounts across a wider ensemble of mitigation pathways (Supplementary Fig. 1), a more systematic exploration of these interrelations might alter quantitative estimates.

A range of other equity regimes and interpretations exist[18,28,44,45], and the examination of two burden-sharing regimes in our analysis is by no means meant to be exclusive. In addition, we acknowledge that responsibility may not lie solely with governments, but could also be borne by other entities such as major carbon-producing companies[46,47]. However, rather than exploring the full spectrum of different burden-sharing regimes, the purpose of our analysis is to illustrate that equity-based regional CDR distributions could differ substantially from commonly used cost-optimal approaches[36]. Awareness of who bears moral responsibility for deploying or paying for CDR, and how near-term emission reductions can reduce the CDR burden, may help governments to develop more equitable climate action targets and strategies. Answering these questions requires consideration of numerous value judgements, including whether to consider fairness (in terms of responsibility, capability or equality) at the regional, national, subnational or even individual level.

Implications for mitigation under the Paris Agreement

Our analysis of regional distributions under different equity regimes is technology neutral, leaving open how fair-share CDR obligations could be met. In principle, countries may decide to fulfil their fair-share obligations by either deploying CDR domestically or financing deployment elsewhere. Such decision making should incorporate important ethical considerations while also being informed by assessments of regional CDR potentials, taking into account potential carbon storage, sustainability and cost implications, and governance architectures[1,38,48–50]. Regional assessments should go beyond the limited options deployed in most IAMs to comprehensively assess a range of different approaches. For example, land- and water-constrained countries could still achieve substantial amounts of CDR through approaches such as direct air capture[51] that require little land and water input at the expense of higher costs[3].

Should countries choose to use financial transfers and carbon markets to achieve their CDR obligations, the risks posed by weak market governance could be substantial. Even if a minor share of the equity-implied CDR redistribution is transferred internationally, stringent rules and transparent accounting for doing so under the Paris Agreement's Article 6 market mechanisms would be paramount[52]. Distributional impacts of financial flows associated with such transfers also warrant examination (with possible revenues on the order of US$10–100 trillion over the century, see Methods).

These findings underscore the relevance of burden-sharing principles for assessing regional CDR responsibilities and illustrate the substantial differences between equity and least-cost approaches. In addition to international dimensions of equity, considerations of intergenerational equity (including in the national context) merit specific attention. With current NDCs setting the world on track for around 3 °C of warming, failure to substantially lower anticipated emission levels in 2030 would likely result in national CDR obligations being impossible to fulfil without compromising other sustainable development objectives[2]. Our analysis highlights the urgent need for much stronger climate targets if governments are to deliver on their responsibility for protecting those vulnerable to climate change impacts while avoiding undue burden on future generations.

Online content

Any methods, additional references, Nature Research reporting summaries, source data, extended data, supplementary information, acknowledgements, peer review information; details of author contributions and competing interests; and statements of data and code availability are available at https://doi.org/10.1038/s41558-020-0857-2.

Received: 5 February 2020; Accepted: 23 June 2020;
Published online: 27 July 2020

References

1. Summary for Policymakers. In *Special Report on Global Warming of 1.5 °C* (eds Masson-Delmotte, V. et al.) (WMO, 2018).
2. Strefler, J. et al. Between Scylla and Charybdis: delayed mitigation narrows the passage between large-scale CDR and high costs. *Environ. Res. Lett.* **13**, 044015 (2018).
3. Smith, P. et al. Biophysical and economic limits to negative CO_2 emissions. *Nat. Clim. Change* **6**, 42–50 (2016).
4. Summary for Policymakers. In *Special Report on Climate Change and Land* (eds Shukla, P. R. et al.) (IPCC, 2019).
5. Nemet, G. F. et al. Negative emissions—part 3: innovation and upscaling. *Environ. Res. Lett.* **13**, 063003 (2018).
6. Ringius, L., Torvanger, A. & Underdal, A. Burden sharing and fairness principles in international climate policy. *Int. Environ. Agreem.* **2**, 1–22 (2002).
7. Lawrence, P. & Reder, M. Equity and the Paris Agreement: legal and philosophical perspectives. *J. Environ. Law* **31**, 511–531 (2019).
8. Schleussner, C.-F. et al. 1.5 °C hotspots: climate hazards, vulnerabilities, and impacts. *Annu. Rev. Environ. Resour.* **43**, 135–163 (2018).
9. Rogelj, J. et al. A new scenario logic for the Paris Agreement long-term temperature goal. *Nature* **573**, 357–363 (2019).
10. Emmerling, J. et al. The role of the discount rate for emission pathways and negative emissions. *Environ. Res. Lett.* **14**, 104008 (2019).
11. Geiges, A. et al. Incremental improvements of 2030 targets insufficient to achieve the Paris Agreement goals. *Earth Syst. Dynam.* (in the press).
12. Klinsky, S. et al. Why equity is fundamental in climate change policy research. *Glob. Environ. Change* **44**, 170–173 (2017).
13. Höhne, N., den Elzen, M. & Escalante, D. Regional GHG reduction targets based on effort sharing: a comparison of studies. *Clim. Policy* **14**, 122–147 (2014).
14. Robiou Du Pont, Y. et al. Equitable mitigation to achieve the Paris Agreement goals. *Nat. Clim. Change* **7**, 38–43 (2017).
15. Kartha, S., Baer, P., Athanasiou, T. & Kemp-Benedict, E. The Greenhouse Development Rights framework. *Clim. Dev.* **1**, 147–165 (2009).
16. Winkler, H., Letete, T. & Marquard, A. Equitable access to sustainable development: operationalizing key criteria. *Clim. Policy* **13**, 411–432 (2013).
17. Pan, X., Elzen, M., den, Höhne, N., Teng, F. & Wang, L. Exploring fair and ambitious mitigation contributions under the Paris Agreement goals. *Environ. Sci. Policy* **74**, 49–56 (2017).
18. den Elzen, M. G. J., Höhne, N., Brouns, B., Winkler, H. & Ott, H. E. Differentiation of countries' future commitments in a post-2012 climate regime. *Environ. Sci. Policy* **10**, 185–203 (2007).
19. Raupach, M. R. et al. Sharing a quota on cumulative carbon emissions. *Nat. Clim. Change* **4**, 873–879 (2014).
20. van den Berg, N. J. et al. Implications of various effort-sharing approaches for national carbon budgets and emission pathways. *Climatic Change* https://doi.org/10.1007/s10584-019-02368-y (2019).
21. Fleurbaey, M. et al. in *Climate Change 2014: Mitigation of Climate Change* (eds Edenhofer, O. et al.) 283–350 (Cambridge Univ. Press, 2014).
22. Winkler, H. et al. *Equitable Access to Sustainable Development: Contribution to the Body of Scientific Knowledge* (BASIC expert group, 2011).
23. McMullin, B., Price, P., Jones, M. B. & McGeever, A. H. Assessing negative carbon dioxide emissions from the perspective of a national "fair share" of the remaining global carbon budget. *Mitig. Adapt. Strateg. Glob. Change* https://doi.org/10.1007/s11027-019-09881-6 (2019).
24. Gignac, R. & Matthews, H. D. Allocating a 2 °C cumulative carbon budget to countries. *Environ. Res. Lett.* **10**, 075004 (2015).
25. Peters, G. P. & Geden, O. Catalysing a political shift from low to negative carbon. *Nat. Clim. Change* **7**, 619–621 (2017).
26. Mace, M. J., Fyson, C. L., Schaeffer, M. & Hare, W. L. *Governing Large-Scale Carbon Dioxide Removal: Are We Ready?* (Carnegie Climate Governance Initiative, 2018).

27. Köberle, A. C. The value of BECCS in IAMs: a review. *Curr. Sustain. Renew. Energy Rep.* **6**, 107–115 (2019).
28. Clarke, L. et al. in *Climate Change 2014: Mitigation of Climate Change* (eds Edenhofer, O. et al.) Ch. 6 (Cambridge Univ. Press, 2014).
29. Jacoby, H. D., Schmalensee, R., Wing, I. S. & Prinn, R. G. *Toward a Useful Architecture for Climate Change Negotiations* Joint Program Report Series Report 49 (MIT Joint Program on the Science and Policy of Global Change, 1999).
30. Den Elzen, M. G. J. & Lucas, P. L. The FAIR model: a tool to analyse environmental and costs implications of regimes of future commitments. *Environ. Model. Assess.* **10**, 115–134 (2005).
31. Baer, P., Fieldman, G., Athanasiou, T. & Kartha, S. Greenhouse Development Rights: towards an equitable framework for global climate policy. *Camb. Rev. Int. Aff.* **21**, 649–669 (2008).
32. Rao, N. D., Sauer, P., Gidden, M. & Riahi, K. Income inequality projections for the Shared Socioeconomic Pathways (SSPs). *Futures* **105**, 27–39 (2019).
33. Kartha, S. et al. Cascading biases against poorer countries. *Nat. Clim. Change* **8**, 348–349 (2018).
34. Schleussner, C.-F. et al. Science and policy characteristics of the Paris Agreement temperature goal. *Nat. Clim. Change* **6**, 827–835 (2016).
35. Huppmann, D. et al. IAMC 1.5 °C scenario explorer and data hosted by IIASA. *Zenodo* https://doi.org/10.5281/zenodo.3363345 (2019).
36. Rogelj, J. et al. in *Special Report on Global Warming of 1.5 °C* (eds Masson-Delmotte, V., et al.) Ch. 2 (WMO, 2018).
37. Tokarska, K. B., Zickfeld, K. & Rogelj, J. Path independence of carbon budgets when meeting a stringent global mean temperature target after an overshoot. *Earths Future* **7**, 1283–1295 (2019).
38. Fuss, S. et al. Negative emissions—part 2: costs, potentials and side effects. *Environ. Res. Lett.* **13**, 063002 (2018).
39. Riahi, K. et al. The Shared Socioeconomic Pathways and their energy, land use, and greenhouse gas emissions implications: an overview. *Glob. Environ. Change* **42**, 153–168 (2017).
40. Nauels, A. et al. *ZERO IN on the Remaining Carbon Budget and Decadal Warming Rates. The CONSTRAIN Project Annual Report 2019* (CONSTRAIN, 2019).
41. Luderer, G. et al. Residual fossil CO_2 emissions in 1.5–2 °C pathways. *Nat. Clim. Change* **2018**, 626–633 (2018).
42. Rogelj, J. et al. Paris Agreement climate proposals need a boost to keep warming well below 2 °C. *Nature* **534**, 631–639 (2016).
43. *Climate Action Tracker* Country Assessments September 2019 (Climate Action Tracker, 2019).
44. Winkler, H. et al. Countries start to explain how their climate contributions are fair: more rigour needed. *Int. Environ. Agreem.* **18**, 99–115 (2018).
45. Meinshausen, M. et al. National post-2020 greenhouse gas targets and diversity-aware leadership. *Nat. Clim. Change* **5**, 1098–1106 (2015).
46. Shue, H. Responsible for what? Carbon producer CO_2 contributions and the energy transition. *Climatic Change* **144**, 591–596 (2017).
47. Frumhoff, P. C., Heede, R. & Oreskes, N. The climate responsibilities of industrial carbon producers. *Climatic Change* **132**, 157–171 (2015).
48. Bednar, J., Obersteiner, M. & Wagner, F. On the financial viability of negative emissions. *Nat. Commun.* **10**, 1783 (2019).
49. Minx, J. C. et al. Negative emissions—part 1: research landscape and synthesis. *Environ. Res. Lett.* **13**, 063001 (2018).
50. Hansson, A. et al. Preconditions for bioenergy with carbon capture and storage (BECCS) in sub-Saharan Africa: the case of Tanzania. *Environ. Dev. Sustain.* https://doi.org/10.1007/s10668-019-00517-y (2019).
51. Wohland, J., Witthaut, D. & Schleussner, C.-F. Negative emission potential of direct air capture powered by renewable excess electricity in Europe. *Earths Future* **6**, 1380–1384 (2018).
52. Schneider, L. et al. Double counting and the Paris Agreement rulebook. *Science* **366**, 180–183 (2019).

Methods

Historical data. Historical GHG emissions data from 1990 to 2015, excluding LULUCF, are taken from the PRIMAP-hist version 2 database (using global-warming-potential values from the IPCC's Fourth Assessment Report)[53]; LULUCF emissions for the same period are taken from FAOSTAT[54]. Historical population data are from the World Bank World Development Indicators 2016 dataset[55].

Model data. We select scenarios to analyse that provide the level of detail and regional scope required to estimate equitable CDR values and that are representative of the range of pathways in the SR1.5 scenario set[35] (see Supplementary Fig. 1). Projected emissions, CDR, population and GDP (in purchase power parity rather than at the market exchange rate) are taken from the outputs of REMIND (SSP1–1.9, SSP2–1.9, SSP5–1.9, SSP1–2.6, SSP2–2.6, SSP5–2.6)[56,57], IMAGE (SSP1–1.9, SSP2-LF)[57,58] and MESSAGE (LED[59], SSP1–1.9, SSP2–1.9, SSP1–2.6, SSP2–2.6)[39,58]. Pathways were categorized according to the degree of overshoot, following ref. [36]. To provide bounding estimates for CDR used in scenarios, we include a scenario with very low values of CDR by design (the Low Energy Demand scenario from MESSAGE[59], which explicitly excludes carbon capture and storage) and a scenario that is based on an early dependence on fossil fuels and hence overshoots the Paris Agreement 1.5 °C warming limit (SSP5–19)[56]. Extension to other scenarios was constrained by the availability of data.

We assume that positive emissions follow least-cost pathways (that is, no equity principle is applied to gross emissions). CDR is the sum of negative emissions from bioenergy with carbon capture and storage and from land-based sequestration (that is, afforestation and reforestation). Other forms of CDR are not included in most current model pathways, but we assume the total amount of CDR required would not differ substantially under different CDR portfolios.

Regions. To compare results for the three models, we use a common set of countries and regions, comprising the largest emitters as well as those regions that are often allocated large amounts of CDR in least-cost pathways: China, EU28, India, Russia, the United States, Latin America and sub-Saharan Africa. Note that there is variation in how models define each region; for example, MESSAGE includes a wider set of countries in its US ('NAM'), China ('CPA'), India ('SAS') and Russia ('FSU') regions. Some countries (for example, Japan, Australia, Canada) are not included because of differences in regional allocation across models. Information on and results for model-specific regions are provided in Supplementary Figs. 4–6.

Equity calculations. *Cumulative emissions per person-year.* We calculate the global average cumulative GHG emissions per person in each year by dividing the cumulative global emissions ($E_{c,glob}$) since 1990 by the cumulative global population ($P_{c,glob}$) over the same period. Multiplying this number with the cumulative population of each region ($P_{c,r}$) gives us each region's fair share of cumulative emissions. For each region, r, that has higher actual cumulative emissions than its fair share, we calculate the 'excess emissions' ($E_{x,r}$) in each year as the difference between the region's cumulative emissions ($E_{c,r}$) and its fair share:

$$E_{x,r} = E_{c,r} - \frac{E_{c,glob}}{P_{c,glob}} \times P_{c,r}$$

For each year, we then give each of these regions a share of the cumulative global CDR ($CDR_{c,glob}$) deployment since 1990 that is proportional to the region's excess emissions, to give the cumulative CDR for the region ($CDR_{c,r}$):

$$CDR_{c,r} = CDR_{c,glob} \times \frac{E_{x,r}}{\sum_r E_{x,r}}$$

In this way, we allocate CDR responsibility to only those regions that have emitted more emissions over time than in a world with equal cumulative emissions per capita.

Ability to pay. in each year, we allocate CDR responsibility to only those regions with GDP (at purchasing power parity) per capita above the global average value. Annual global CDR is shared between these regions in proportion to their annual GDP per capita and their population size, using the following formula:

$$CDR_r = \left(\frac{GDP}{cap}\right)_r \times \frac{CDR_{glob}}{GDP_{glob}} \times P_r$$

where, for a given year, CDR_r is the CDR allocation for a region, r, that has a greater GDP per capita than the global average; P_r and $(GDP/cap)_r$ are the population and GDP per capita for region r, respectively; CDR_{glob} is the total global (annual) CDR deployed; and GDP_{glob} is the global GDP. This approach follows that in ref. [22]. The $(GDP/cap)_r$ is calculated as GDP_r/P_r; hence, this formula simplifies to:

$$CDR_r = \frac{GDP_r}{GDP_{glob}} \times CDR_{glob}$$

We include only those regions with an above-average GDP per capita because otherwise regions with a small GDP per capita but a large population (and hence a large GDP) receive a large CDR burden (see Supplementary Fig. 2). Extended Data Fig. 2 illustrates that per capita CDR burdens scale with GDP per capita. We note that using other GDP metrics (such as market exchange rate) might quantitatively affect the results.

CDR shares based on anticipated 2030 emission levels. We use NDC pathways (European Union, China and Russia) and current policy pathways (United States) from the Climate Action Tracker[43] to estimate the CDR burdens implied by anticipated emissions trajectories. We do not include an estimate for Latin America because the Climate Action Tracker does not estimate the impact of all NDCs in the region.

Calculating potential financial flows. Taking the order-of-magnitude range in net-present-value carbon prices over the century from the IPCC SR1.5 (US$10–1,000 tCO_2^{-1}) and assuming the volume of CDR transfers to be 100 $GtCO_2$ (at the lower end of our projected range for 1.5 °C pathways) gives a rough estimate of the order of magnitude of possible financial flows.

Data availability

Data for the IAM scenarios used in this analysis are available at https://data.ene.iiasa.ac.at/iamc-1.5c-explorer/ and on request from the IMAGE, MESSAGE and REMIND modelling groups. Historical emissions data are available from http://dataservices.gfz-potsdam.de/pik/showshort.php?id=escidoc:4736895 (PRIMAP-hist) and http://www.fao.org/faostat/en/#data/GL (FAOSTAT land-use module). Historical population data are available at https://databank.worldbank.org/reports.aspx?source=world-development-indicators (World Bank World Development Indicators).

Code availability

The code used for this analysis is available at https://github.com/SusanneBaurCA/CDR_equity[60].

References

53. Baur, S., Fyson, C. & Schleussner, C.-F. *CDR Equity Analysis* Version 1.0.0. *Zenodo* https://doi.org/10.5281/zenodo.3904162 (2020).
54. Gütschow, J., Jeffery, L., Gieseke, R. & Günther, A. *The PRIMAP-hist National Historical Emissions Time Series (1850–2017)* Version 2.1 (GFZ Data Services, 2019); https://doi.org/10.5880/PIK.2019.018
55. FAOSTAT—Emissions—Land Use (FAO, 2019); http://www.fao.org/faostat/en/#data/GL
56. *World Development Indicators* (World Bank, 2019); https://databank.worldbank.org/data/reports.aspx?source=world-development-indicators
57. Kriegler, E. et al. Fossil-fueled development (SSP5): an energy and resource intensive scenario for the 21st century. *Glob. Environ. Change* **42**, 297–315 (2017).
58. Rogelj, J. et al. Scenarios towards limiting global mean temperature increase below 1.5 °C. *Nat. Clim. Change* **8**, 325–332 (2018).
59. van Vuuren, D. P. et al. Energy, land-use and greenhouse gas emissions trajectories under a green growth paradigm. *Glob. Environ. Change* **42**, 237–250 (2017).
60. Grubler, A. et al. A low energy demand scenario for meeting the 1.5 °C target and sustainable development goals without negative emission technologies. *Nat. Energy* **3**, 515–527 (2018).

Acknowledgements

We thank the IMAGE, MESSAGE and REMIND modelling groups for providing access to their data, J. Strefler for valuable comments, and our reviewers for their constructive feedback. C.L.F. acknowledges support by the German Federal Ministry for the Environment, Nature Conservation and Nuclear Safety (11_II_093_Global_A_SIDS and LDCs). C.-F.S. acknowledges support by the German Federal Ministry of Education and Research (01LS1905A) and from the European Union's Horizon 2020 research and innovation programme under grant agreement No. 821124.

Author contributions

C.L.F. and C.-F.S. conceived and designed the project. S.B. and C.L.F. produced the analysis. M.G. provided data. All authors contributed to the interpretation of the results. C.L.F. wrote the paper with contributions by all authors.

Competing interests

The authors declare no competing interests.

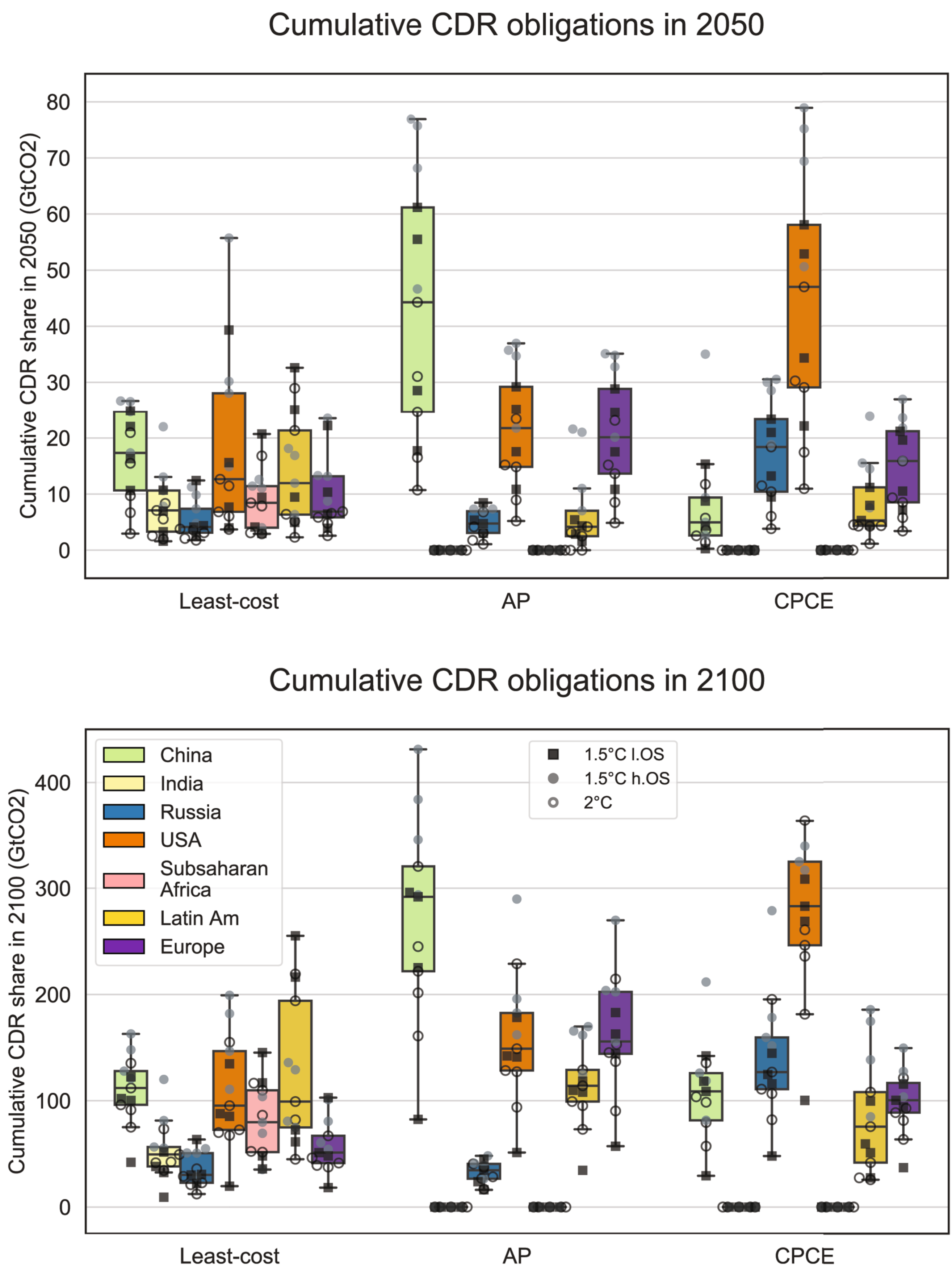
Additional information

Extended data is available for this paper at https://doi.org/10.1038/s41558-020-0857-2.

Supplementary information is available for this paper at https://doi.org/10.1038/s41558-020-0857-2.

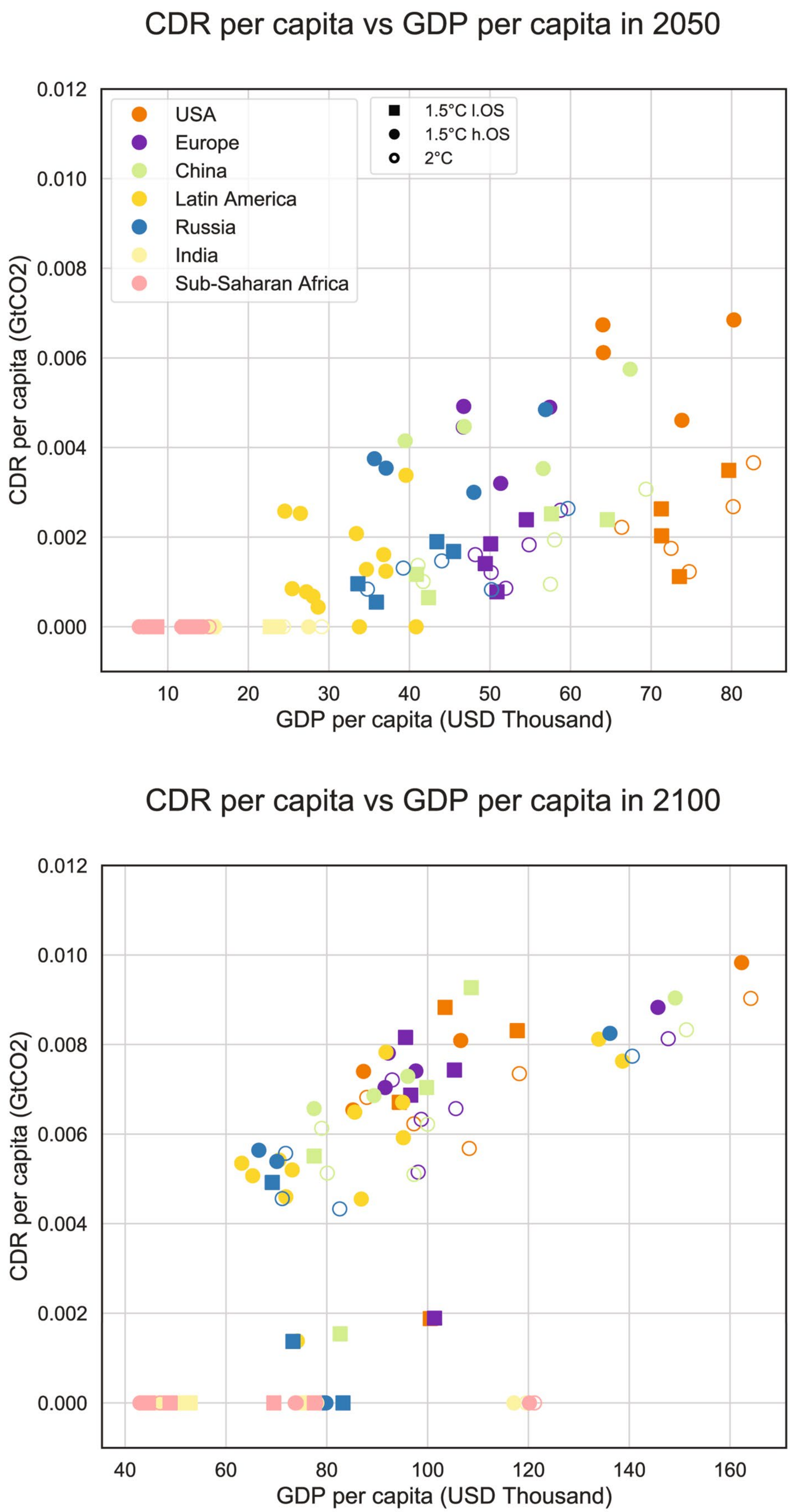
Correspondence and requests for materials should be addressed to C.L.F.

Peer review information *Nature Climate Change* thanks Nicole van den Berg, Johannes Emmerling and Henry Shue for their contribution to the peer review of this work.



Extended Data Fig. 1 | See next page for caption.

Extended Data Fig. 1 | Mid- and end-century CDR shares. CDR shares in 2050 (above) and 2100 (below) for the least-cost, ability to pay and cumulative per capita emissions approaches for all pathways analysed in this study. Coloured bars show the interquartile range of CDR shares for each country / region, with whiskers giving the 5–95 percentiles; symbols show the CDR shares for pathways of different warming levels: 1.5 °C with no or limited overshoot (squares), high overshoot with 1.5 °C at the end of the century (closed circles) and below 2 °C (open circles).



Extended Data Fig. 2 | Per capita CDR versus per capita GDP. CDR obligations per capita for the AP scheme compared with GDP per capita in 2050 (above) and 2100 (below) for the major countries / regions included in this analysis. Squares, filled circles and open circles show the results for 1.5 °C no / low overshoot, 1.5 °C high overshoot and 2 °C pathways respectively. Countries / regions with below average GDP/capita are excluded from CDR obligations.