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Fairness considerations in global mitigation investments

Shonali Pachauri[1], Setu Pelz[1], Christoph Bertram[2], Silvie Kreibiehl[3], Narasimha D. Rao[1,4], Youba Sokona[5,6], Keywan Riahi[1]

Current mitigation finance flows are inadequate and unfair

Despite overwhelming evidence that the world needs to make rapid and substantial investments in climate mitigation in this decade to meet the ambitious goals of the Paris Agreement (*1*–*3*), political and financial barriers continue to hinder mitigation efforts (*2*). Global mitigation investment pathways modeled in the sixth assessment report (AR6) of the Intergovernmental Panel on Climate Change (IPCC) reach global climate goals in a cost-effective manner. These are agnostic about who should finance these and how to fairly allocate costs and benefits of mitigation efforts. We apply equity considerations to global cost-effective mitigation investment needs and derive "fair-share" regional contributions, which describe the direction and magnitude of interregional financial flows that align with each consideration. We find that flows from North America and Europe to other regions would have to increase substantially relative to present levels to meet the Paris Agreement goals under most equity considerations.

Progress on the alignment of financial flows with low greenhouse gas (GHG) emissions pathways remains slow (*3*). In 2019 and 2020, annual global climate finance flows were about USD (2015) 630 billion (with more than 90% for mitigation), but growth has slowed recently. The IPCC's AR6 stresses that these flows must increase globally by a factor between three and six to meet average annual needs until 2030 to avoid the most dangerous impacts of climate change. Adequate capital and liquidity for this is globally available, as is evident from the USD 2.4 trillion world energy investment in 2022 estimated by the International Energy Agency. The IPCC report also states that "accelerated financial international cooperation is a critical enabler of a low-greenhouse gas and just transition." In particular, adequate international support for near-term investment is essential to ensure that national policies are put in place to attract the required finance in this decade.

Global mitigation investment needs in the IPCC's AR6 are based on pathways generated by integrated assessment models (IAMs). Several recent critiques of IAMs engage with the history, assumptions, limitations, and normative positioning of such exercises (*4*). Although several studies propose fair global carbon budget–sharing schemes, few focus on equity considerations in the financing of mitigation investments, and these largely disregard near-term investment flows (*5*). We build on literature that argues that cost-effective mitigation investments require recognition of differentiated responsibilities, capabilities, and needs to yield an equitable outcome and be realized (*6*).

Consistent with suggestions in previous literature, we find that distributive justice considerations in global climate mitigation will require substantial interregional finance flows (*7*). Although mitigation activities involve costs that are distinct from investments, our work focuses specifically on modeled estimates of regional mitigation investment needs. This work provides a pathway to address the retrospective and prospective perspectives on climate equity in the literature: first, that wealthier high-emitting countries have historically benefited from fossil energy at the cost of poorer low-emitting countries (*8*), and second, that for cost-effective mitigation pathways to be fair, national and international redistributive measures are likely necessary (*9*). The magnitude and direction of interregional flows that we derive can also serve as input for policy and climate negotiations in the short term to ratchet up mitigation ambition, signal to the international private financial sector the magnitude of the required increase of interregional finance, and guide industrial pathways and value chain development toward a just and sustainable energy transition.

[1]International Institute for Applied Systems Analysis, Laxenburg, Austria. [2]Potsdam Institute for Climate Impact Research, Potsdam, Germany. [3]Germanwatch e.V., Bonn, Germany. [4]Yale School of the Environment, New Haven, CT USA. [5]South Centre, Geneva, Switzerland. [6]University College London, London, UK. Email: pachauri@iiasa.ac.at

Equity considerations and indicators

We begin with the range of cost-effective regional mitigation investment needs in the decade 2020–2030 to achieve targets compatible with well below 2°C and 1.5°C warming, as provided in the IPCC AR6 (*3*). Regions are made up of countries and territories collected into broad geographical groups following the IPCC country grouping (see table S1). Regional mitigation investment needs [defined in supplementary materials (SM) section 2 and table S2], include low-carbon energy-resource extraction, conversion, power generation, transmission, and storage, as well as economy-wide energy efficiency improvements (*3*).

Our subsequent consideration of equity is consistent with principles emerging in the climate equity literature that correspond to considerations of responsibility, capability, and needs, which in turn underlie the notion of "Common but Differentiated Responsibility and Respective Capabilities (CBDR-RC) in light of national circumstances" enshrined in the Paris Agreement (*6*). We apply these equity considerations to allocate "fair-share" regional contributions to annual, cost-effective, global climate mitigation investment needs in the decade 2020–2030 in proportion to the indicators we select for each (see tables S4 and S5).

We draw on the literature in selecting established indicators for regional responsibility and capability and introduce two new indicators that describe regional needs, which have not previously been operationalized in the IAM literature. We measure responsibility (R) as historical cumulative emissions shares. Given divergent views on when countries should be held accountable for their emissions, we implement two periods, one from 1850, accounting for postindustrial contributions, and the other since 1990, the year of the first IPCC assessment report. We consider only emissions of the dominant long-lived climate forcer, carbon dioxide (CO_2), from fossil fuel and industry, because other GHG emissions have not yet been thoroughly explored in the climate equity literature.

For capability (C), we use per capita gross domestic product (GDP) (C-1) and per capita capital stock (C-2), an alternative wealth indicator that reflects the extent of physical fixed assets and infrastructure in an economy. Under the consideration of needs (N), we use the average degree of deprivation across distinct dimensions of human well-being encompassed by the decent living standards (*10*) (N-1) and the modeled share of regional population facing multisector climate risk in the year 2030 (*11*) (N-2). We propose these needs indicators because they are not composites of the others used (such as per capita GDP) and capture both retrospective and prospective aspects of climate equity in terms of achieved human well-being and future vulnerability to climate effects. (See SM for a complete description of the methods used to transform each indicator into a corresponding regional fair-share contribution.)

Global scale finance flows

The IPCC AR6 reported large investment gaps between the recent average investment levels (2017–2020) and cost-effective investment needs over the decade 2020–2030. For most regions, it reported that recent investments were about three to four times lower in magnitude than the cost-effective needs (see the first figure). However, in some regions, the gaps are much wider. We find that these gaps shift dramatically when principles of equity are considered to derive fair-share contributions, requiring large interregional financial flows (see the first figure). Our estimated range of interregional flows to meet fair-share regional contributions is between purchasing power parity (PPP) USD (2015) 248 billion and PPP USD (2015) 1581 billion annually during 2020–2030 (see fig. S1).

The magnitude of interregional financial flows required is lowest (i.e., closest to cost-effective needs) when considering responsibility for historical cumulative CO_2 emissions since 1990 (R-2) and highest when considering the capabilities of regions (C-1 and C-2). With the exception of R-2, fair-share contributions under any equity consideration would be far higher than cost-effective needs in North America and Europe and lower in Africa, South and Southeast Asia, and Latin America. That is, regional cost-effective investment needs in low- and middle-income countries (LMICs) are higher than their fair-share contributions under most equity considerations (see the second figure). Accounting for cumulative CO_2 emissions since 1990 favors North America and Europe over other regions that experienced much of their industrial growth in recent decades. By contrast, we see that capability- and needs-based allocations (C- and N-) require substantial [PPP USD (2015) 657 billion to PPP USD (2015) 1.581 trillion] mitigation finance flows to regions dominated by LMICs to bridge the gap between regional cost-effective investment needs and fair-share contributions. As a practical matter, and given differing notions of fairness, policy-makers may want to combine and weight equity considerations to find consensus on representing fair efforts in international negotiations. The adoption of more ambitious pledges in LMICs may depend on such consensus to guide stronger commitments to international financial flows. To aid this, we have developed a tool that allows for selection and weighting of equity considerations and corresponding indicators (https://data.ece.iiasa.ac.at/fairmitigation/).

Implications of fairness

Globally, climate mitigation investment gaps must be bridged to meet the agreed temperature goals of the Paris Agreement. How to finance global cost-effective climate mitigation investment needs across regions is still debated. We show that near-term interregional financial flows consistent with respecting equity principles enshrined in the Paris Agreement are substantial. Our proposal helps derive both the magnitude and directions of interregional flows that are necessary to incorporate selected considerations of equity, providing a way to integrate principles of equity into established approaches for developing global cost-effective mitigation scenarios. Importantly, our results indicate that interregional flows must be scaled up no matter which combination of our selected equity considerations and indicators we consider.

This work is consistent with other recent efforts to consider equity more explicitly in modeled mitigation pathways through alternative methods, such as applying specific social welfare functions, projecting degrowth in the Global North or more convergent growth futures, and explicitly accounting for regional populations in poverty to safeguard and exclude them from mitigation efforts in the near term. In reflecting on recent critiques of the AR6 IPCC mitigation pathways, we show here that cost-effective mitigation pathways are consistent with CBDR-RC as enshrined in the Paris Agreement when equity considerations guide the allocation of necessary financial flows (*4*). Future modeling efforts that explicitly represent the finance sector and specific economic instruments can also help derive fair interregional flows endogenously.

Our proposal and accompanying tool to derive fair-share near-term regional contributions to global mitigation investment needs does not yet address the much-needed investments to meet both regional climate adaptation needs and loss and damages, which are a priority for most LMICs (*12*). Moreover, we recognize that the current target of USD 100 billion per year promised by developed nations for climate action in developing nations under the Paris Agreement has been problematic. Among the key complexities of this target is that it serves, at times, two distinct purposes: both to redistribute resources from developed to developing nations and to mobilize the scale of finance needed to achieve the Paris Agreement targets (*13*). It also does not clearly differentiate between adaptation and mitigation needs.

Although our work exploring the magnitude and direction of interregional financial flows that must be mobilized under different considerations of equity can inform negotiations, agreement around new targets for mitigation and adaptation cost support as well as international redistribution will clearly need to deal with these issues. What is clear from our results is that even when considering responsibility for historical cumulative CO_2 emissions since 1990 (R-2), which is an indicator most favorable to regions of the Global North, the magnitude of annual interregional flows just for mitigation action alone must increase substantially to PPP USD (2015) 250 billion to PPP USD (2015) 570 billion in the near term.

Several caveats apply to our proposal. There are other justice considerations and intraregional distributional concerns that we do not consider, such as claims for committed climate impacts or how local benefits and returns can be fairly distributed. Interregional financial flows, as implied by our paper, can be mobilized through a number of different instruments, and each may have its own implications in terms of political feasibility and economic effectiveness. This is particularly important because regional investment risk profiles differ, which may also hinder financial flows. Finally, we do not address the wider issue of the distribution of macroeconomic costs and benefits resulting from the investments, which may change over time and require adaptive frameworks to motivate ambitious global mitigation strategies. A recent proposal toward fair-efforts metrics suggests one approach to account for true costs of mitigation technologies and nonmonetary benefits that may help advance this understanding (*14*).

Clear institutional and regulatory frameworks are needed to mobilize the magnitude of finance that is required to achieve globally agreed upon climate targets. Agreement on how to redirect international and domestic finance toward urgent near-term mitigation investments and climate adaptation efforts will be critical. Continued neglect of differentiated responsibilities, capabilities, and needs in the regional allocation of mitigation investment contributions risks lose-lose outcomes. Interregional cooperation will be necessary to move past this gridlock. Our work describes one pathway toward finding consensus by embedding distinct considerations of distributional justice in the derivation of "fair" regional contributions to globally cost-effective mitigation investment needs. This can inform estimates of the support required to bridge interregional financing gaps. Progress here will serve as a clear signal to governments, industry, and nongovernment actors and will be crucial for building the necessary momentum in regions where finance is scarce.

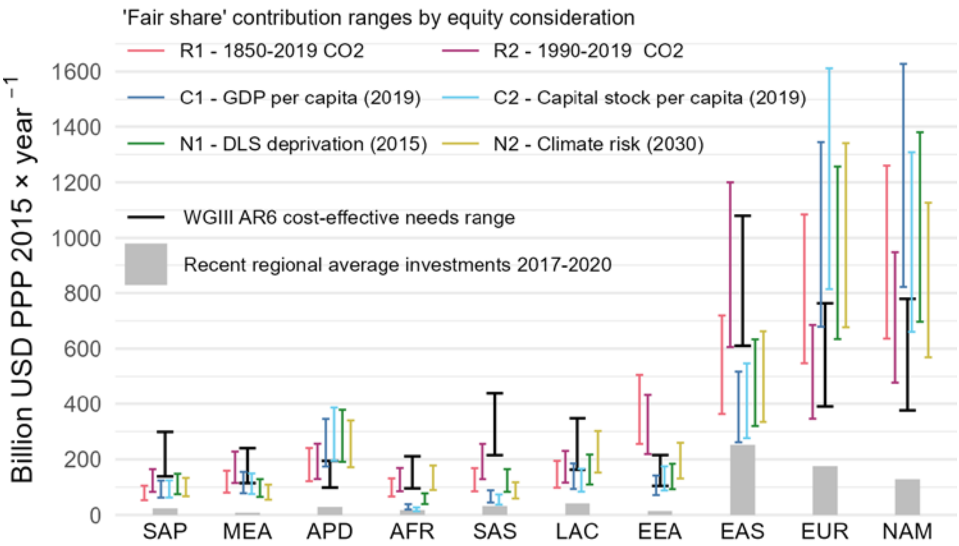

Figure 1 (A): The IPCC AR6 range of annual regional cost-effective investment needs in the decade 2020-2030 aligned with the well below 2°C and 1.5°C compatible targets (black), reflecting the lower-bound and upper-bound of the scenarios; 'fair-share' regional contributions to these by distinct considerations of equity (colors), with the range corresponding to the lower-bound and upper-bound; and recent regional average investments 2017-2020 (grey bars).

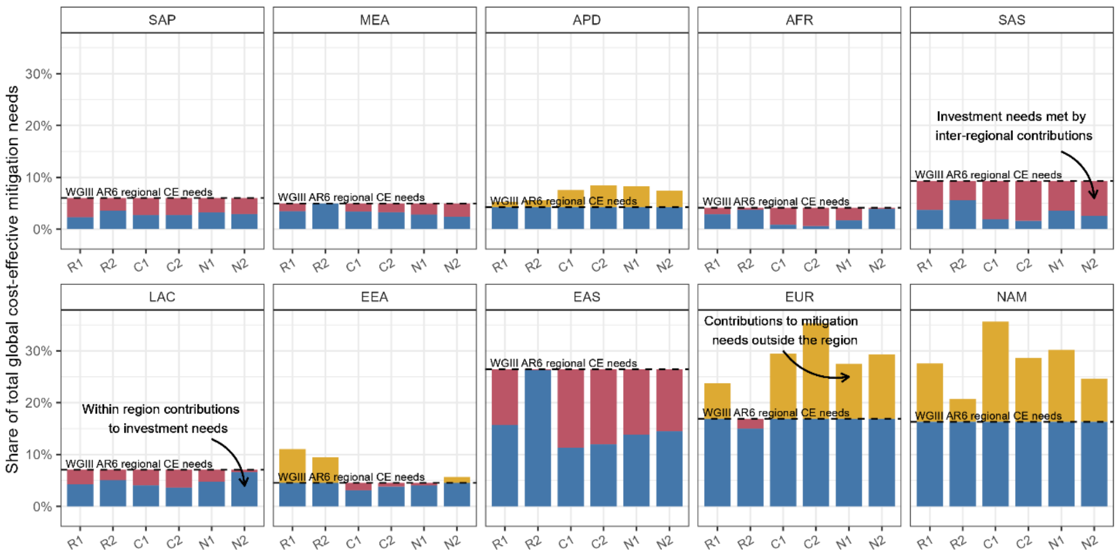

Figure 1 (B): Regional lower-bound cost-effective mitigation investment needs and 'fair-share' contributions as shares of total lower-bound global mitigation investment needs (See SM Fig S2 for upper-bound shares). Regional 'fair-share' contributions to within-region mitigation investment needs (blue) describe the total within-region needs met by countries in the region. Inter-regional 'fair-share' contributions (yellow) describe the regional contributions to global mitigation investment needs outside of the region. Regional 'fair-share' gaps (red) describe within-region mitigation needs met by contributions from other regions. See SM Fig S3 for investment needs and contributions as shares of regional GDP. Regions in (A-B) are defined as follows: SAP - South-East Asia and developing Pacific, MEA - Middle East, APD - Asia-Pacific Developed, AFR - Africa, SAS - Southern Asia, LAC - Latin America and Caribbean, EEA - Eastern Europe and West-Central Asia, EAS - Eastern Asia, EUR - Europe, NAM - North America.

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Supplementary Materials

Title: Fairness considerations in global mitigation investments

Authors: Shonali Pachauri[1], Setu Pelz[1], Christoph Bertram[2], Silvie Kreibiehl[3], Narasimha D. Rao[1,4], Youba Sokona[5,6], Keywan Riahi[1]

Affiliations: [1]International Institute for Applied Systems Analysis, [2]Potsdam Institute for Climate Impact Research, [3]Germanwatch e.V., [4]Yale School of the Environment, [5]South Centre, [6]University College London

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Tables and figures

1. IPCC R10 regional groupings

Table S1 Country and territory allocations to ten regions (IPCC R10).

RGN	Region name	ISO3C	Country name
SAP	South-East Asia and developing Pacific	ASM, BRN, KHM, COK, FJI, PYF, GUM, IDN, KIR, LAO, MYS, MHL, FSM, MMR, NRU, NCL, NIU, MNP, PLW, PNG, PHL, PCN, WSM, SGP, SLB, THA, TLS, TKL, TON, TUV, UMI, VUT, VNM, WLF	American Samoa, Brunei Darussalam, Cambodia, Cook Islands, Fiji, French Polynesia, Guam, Indonesia, Kiribati, Lao PDR, Malaysia, Marshall Islands, Micronesia, Fed. Sts., Myanmar, Nauru, New Caledonia, Niue, Northern Mariana Islands, Palau, Papua New Guinea, Philippines, Pitcairn, Samoa, Singapore, Solomon Islands, Thailand, Timor-Leste, Tokelau, Tonga, Tuvalu, United States Minor Outlying Islands, Vanuatu, Vietnam, Wallis and Futuna
MEA	Middle East	BHR, IRN, IRQ, ISR, JOR, KWT, LBN, OMN, QAT, SAU, SYR, ARE, PSE, YEM	Bahrain, Iran, Islamic Rep., Iraq, Israel, Jordan, Kuwait, Lebanon, Oman, Qatar, Saudi Arabia, Syrian Arab Republic, United Arab Emirates, West Bank and Gaza, Yemen, Rep.
APD	Asia-Pacific Developed	AUS, CXR, CCK, HMD, JPN, NZL, NFK	Australia, Christmas Island, Cocos (Keeling) Islands, Heard Island and McDonald Islands, Japan, New Zealand, Norfolk Island
AFR	Africa	DZA, AGO, BEN, BWA, IOT, BFA, BDI, CPV, CMR, CAF, TCD, COM, COD, COG, CIV, DJI, EGY, GNQ, ERI, ETH, ATF, GAB, GMB, GHA, GIN, GNB, KEN, LSO, LBR, LBY, MDG, MWI, MLI, MRT, MUS, MYT, MAR, MOZ, NAM, NER, NGA, REU, RWA, SHN, STP, SEN, SYC, SLE, SOM, ZAF, SSD, SDN, SWZ, TZA, TGO, TUN, UGA, ESH, ZMB, ZWE	Algeria, Angola, Benin, Botswana, British Indian Ocean Territory, Burkina Faso, Burundi, Cabo Verde, Cameroon, Central African Republic, Chad, Comoros, Congo, Dem. Rep., Congo, Rep., Côte d'Ivoire, Djibouti, Egypt, Arab Rep., Equatorial Guinea, Eritrea, Ethiopia, French Southern Territories, Gabon, Gambia, The, Ghana, Guinea, Guinea-Bissau, Kenya, Lesotho, Liberia, Libya, Madagascar, Malawi, Mali, Mauritania, Mauritius, Mayotte, Morocco, Mozambique, Namibia, Niger, Nigeria, Réunion, Rwanda, Saint Helena, Ascension and Tristan da Cunha, São Tomé and Príncipe, Senegal, Seychelles, Sierra Leone, Somalia, South Africa, South Sudan, Sudan, Swaziland, Tanzania, Togo, Tunisia, Uganda, Western Sahara, Zambia, Zimbabwe
SAS	Southern Asia	AFG, BGD, BTN, IND, MDV, NPL, PAK, LKA	Afghanistan, Bangladesh, Bhutan, India, Maldives, Nepal, Pakistan, Sri Lanka
LAC	Latin America and Caribbean	AIA, ATG, ARG, ABW, BHS, BRB, BLZ, BOL, BES, BVT, BRA, VGB, CYM, CHL, COL, CRI, CUB, CUW, DMA, DOM, ECU, SLV, FLK, GUF, GRD, GLP, GTM, GUY, HTI, HND, JAM, MTQ, MEX, MSR, ANT, NIC, PAN, PRY, PER, PRI, BLM, SXM, SGS, KNA, LCA, MAF, VCT, SUR, TTO, TCA, URY, VEN, VIR	Anguilla, Antigua and Barbuda, Argentina, Aruba, Bahamas, The, Barbados, Belize, Bolivia, Bonaire, Sint Eustatius and Saba, Bouvet Island, Brazil, British Virgin Islands, Cayman Islands, Chile, Colombia, Costa Rica, Cuba, Curaçao, Dominica, Dominican Republic, Ecuador, El Salvador, Falkland Islands (Malvinas), French Guiana, Grenada, Guadeloupe, Guatemala, Guyana, Haiti, Honduras, Jamaica, Martinique, Mexico, Montserrat, Netherlands Antilles, Nicaragua, Panama, Paraguay, Peru, Puerto Rico, Saint Barthélemy, Sint Maarten (Dutch part), South Georgia and the South Sandwich Islands, St. Kitts and Nevis, St. Lucia, St. Martin (French part), St. Vincent and the Grenadines, Suriname, Trinidad and Tobago, Turks and Caicos Islands, Uruguay, Venezuela, RB, Virgin Islands (U.S.)
EEA	Eastern Europe and West-Central Asia	ARM, AZE, BLR, GEO, KAZ, KGZ, MDA, RUS, SCG, TJK, TKM, UKR, UZB	Armenia, Azerbaijan, Belarus, Georgia, Kazakhstan, Kyrgyz Republic, Moldova, Russian Federation, Serbia and Montenegro, Tajikistan, Turkmenistan, Ukraine, Uzbekistan
EAS	Eastern Asia	CHN, HKG, PRK, KOR, MAC, MNG, TWN	China, Hong Kong SAR (China), Korea, Dem. People's Rep., Korea, Rep., Macao SAR (China), Mongolia, Taiwan (China)
EUR	Europe	ALA, ALB, AND, AUT, BEL, BIH, BGR, HRV, CYP, CZE, DNK, EST, FRO, FIN, FRA, DEU, GIB, GRC, GGY, VAT, HUN, ISL, IRL, IMN, ITA, JEY, LVA, LIE, LTU, LUX, MLT, MCO, MNE, NLD, MKD, NOR, POL, PRT, ROU, SMR, SRB, SVK, SVN, ESP, SJM, SWE, CHE, TUR, GBR	Åland Islands, Albania, Andorra, Austria, Belgium, Bosnia and Herzegovina, Bulgaria, Croatia, Cyprus, Czech Republic, Denmark, Estonia, Faroe Islands, Finland, France, Germany, Gibraltar, Greece, Guernsey, Holy See, Hungary, Iceland, Ireland, Isle of Man, Italy, Jersey, Latvia, Liechtenstein, Lithuania, Luxembourg, Malta, Monaco, Montenegro, Netherlands, North Macedonia, Norway, Poland, Portugal, Romania, San Marino, Serbia, Slovak Republic, Slovenia, Spain, Svalbard and Jan Mayen, Sweden, Switzerland, Turkey, United Kingdom
NAM	North America	BMU, CAN, GRL, SPM, USA	Bermuda, Canada, Greenland, Saint Pierre and Miquelon, United States

2. Annual least-cost mitigation investment needs by region

We use the modelled regional cost-effective annual mitigation investment needs in the decade 2020-2030, provided in Figure 25 of the IPCC WGIII AR6 Technical Summary (IPCC, 2022). This describes where climate mitigation investments ought to occur in a cost-effective manner in alignment with Article 3.3 of the UNFCCC and the Paris Agreement and takes no position on the intra- and inter-regional distribution of the necessary financial flows to meet the needed investments.

These estimated cost-effective regional investment needs are described in the source figure as ranges from the lower-bound to the upper-bound of all corresponding scenarios (C1-C3). These investment needs are compiled from a range of sources to arrive at a comprehensive estimate. A large share of investments are in the electricity sector, for which data from several Integrated Assessment Models is being used (see Table 15.3 in IPCC WGIII AR6). The regional results of different electricity sector technology types cover a total of between 141 and 310 C1-C3 scenarios from a range of different models, with varying model structures, parametric estimation of technology costs and some variation in socio-economic drivers (though the middle-of-the road SSP2 narrative clearly dominates the scenario set). The scenario set, however, does not represent a statistical sample, which is why no rigorous statements about probabilities of estimated values within the range can be given.

We aggregate these regional mitigation investment needs to determine the total global annual cost-effective mitigation investment needs, which ranges from approximately 2.31 USD Trillion PPP (2015) x year^{-1} to 4.57 USD Trillion PPP (2015) x year^{-1}. We show this in the table below also including the estimated annual average regional mitigation finance flows for the years 2017-2020, sourced from the same figure. We use this as a proxy for the recent average regional mitigation investments in later analyses. This sums to a global total of approximately 724 USD Billion PPP (2015) x year^{-1} over the years 2017-2020.

Table S2 Annual regional average mitigation investments and model-based investment needs.

R10	Region	Avg. 2017-2020	Lower-bound	Upper-bound
SAP	South-East Asia and developing Pacific	24.0	138.8	298.7
MEA	Middle East	8.4	114.7	240.1
APD	Asia-Pacific Developed	29.2	98.6	194.4
AFR	Africa	17.8	95.7	210.9
SAS	Southern Asia	32.2	214.9	439.7
LAC	Latin America and Caribbean	41.8	162.9	347.6
EEA	Eastern Europe and West-Central Asia	14.3	104.6	215.3
EAS	Eastern Asia	252.2	610.3	1079.8
EUR	Europe	175.7	390.1	763.0
NAM	North America	128.7	376.0	779.0
TOT	Global	724.3	2306.6	4568.5

Note: These aggregates reflect model-based investment pathways compatible with 1.5°C and well-below 2C targets between 2020-2030 (USD Billion PPP x year^{-1}). Source: IPCC WGIII AR6 TS.25.

3. Equity considerations and indicators

Our considerations of equity draw upon emerging principles in the climate equity literature outlined in Table S3 below, and a recent critical review of ethical choices underlying analyses of 'equitable' contributions to international mitigation investment needs (Dooley et al., 2021). The latter piece describes common considerations of equity in alignment with the terminology of the Paris Agreement, also shown in Table S3 below.

Table S3 Emerging principles in the climate justice literature and associated equity considerations

<table>
<tr><th>Principle[1]</th><th>Justification</th><th>Equity considerations</th></tr>
<tr><td>Polluter Pays</td><td>Burdens should be borne in proportion to how much an agent has emitted.</td><td rowspan="3">Responsibility
Capability
Needs</td></tr>
<tr><td>Ability to Pay</td><td>The greater an agent's ability to pay the greater the proportion of the cost that they should be expected to pay.</td></tr>
<tr><td>Beneficiary Pays</td><td>Agents should pay because, and to the extent that, they have benefited from the activities that involve the emission of greenhouse gases.</td></tr>
</table>

We follow recent guidance on the application of considerations of equity in climate mitigation analysis (Dooley et al., 2021). First, we are explicit in the equity principles and considerations we consider and our quantification of these to reflect differing notions of what comprises 'fairness'. Second, we conduct and present our work across all ten IPCC regional groupings and present resulting allocations across all of these[2]. Third, we do not aggregate equity considerations, rather, we are explicit in presenting the different allocations corresponding to distinct equity considerations, informing both an understanding of equity considerations as well as how to distinguish cost-effective investment needs from fair-share contributions under distinct notions of 'fairness'.

Responsibility

Our first equity consideration is linked directly to the principle of Polluter Pays. Under this consideration, we consider regions with larger historical emissions to carry a proportionally larger share of contributions to finance global mitigation investment needs in the decade 2020-2030. We quantify this consideration by using historical emissions across two time periods, 1850-2019 and 1990-2019, and focus on CO_2-FFI emissions as the dominant long-lived climate forcer given the historical nature of the analysis. We do not consider non-CO_2 GHG and LULUCF emissions here as their contribution to climate and principles of allocation haven't yet been thoroughly explored in the climate equity literature. The years of analysis we select have been used previously in an exercise similar to ours where starting years of 1850 and 1990 were combined with different considerations of capacity in the Climate Equity Reference Framework (Holz et al., 2022) and applied in deliberation with international civil society organizations for the purpose of the Civil Society Equity Review (Holz et al., 2018). Here we restrict our analysis to end in the year 2019 as this is the last year before the decade of analysis (2020-2030).

[1] A discussion of these principles, related debates and a much broader discussion of climate equity and justice is provided by (Caney, 2021), found at https://plato.stanford.edu/entries/justice-climate/#BurdSharQues

[2] Here we must nevertheless note that our regional analysis does not describe intraregional differences, which will certainly matter for more marginalized countries in highly heterogenous regions such as AFR, MEA, LAC.

Capability

Our second equity consideration is closely linked with the principle of Ability to Pay (prospective) and could also be ascribed to the principle of Beneficiary Pays (retrospective) insofar as wealth accumulation as it stands today is largely built on past emissions. Under this consideration, we consider regions more wealthy and thus more capable of financing mitigation investments to carry a proportionally larger share of contributions to finance global mitigation investment needs in the decade 2020-2030. We quantify this consideration by using per-capita GDP, which is a flow, and per-capita capital stock, which is a cumulative stock valued in dollars in the year in question. For both of these indicators we take the value for the year 2019, the year before the decade of analysis (2020-2030).

Needs

Our third equity consideration is linked to both the principle of Beneficiary Pays and the principle of Ability to Pay. Under this consideration, we consider it morally defensible for regions with higher needs to contribute a proportionally smaller share of contributions to finance global mitigation investment needs in the decade 2020-2030. We define regional needs in two distinct ways. First, as the degree of multi-dimensional deprivation in access to Decent Living Standards (DLS), which is defined as the average deprivation across all DLS dimensions in the year 2015 (Rao & Min, 2018; Kikstra et al., 2021). Second, as acute multi-sector climate risk, which is defined as the share of regional population both exposed to at least moderate climate risks through the water-land-energy sectors and having an income below 20USD/capita/day in 2030, the last year of our analysis (Byers et al., 2018). Here we consider a middle of the road socioeconomic scenario projection (SSP2, (Fricko et al., 2017; Kc & Lutz, 2017; Riahi et al., 2017) and take the midpoint between exposure effects at 1.5°C and 2.0°C, as most scenarios with likely chance of below 2°C still overshoot 1.5°C with peak warming of around 1.7°C in the 2050s. Using population of 2030 reflects the lower-bound of expected climate exposure effects faced by populations alive in 2030 and later in this century, as population growth is expected through mid-century, particularly in developing countries. We are careful to use indicators that do not overlap with others, which rules out the commonly applied Human Development Index, as this composite multi-dimensional aggregate contains GDP per capita.

Composite considerations

We do not make attempts to combine the equity considerations or weight the indicators we consider but provide an accompanying tool - https://data.ece.iiasa.ac.at/fairmitigation/ - that allows for the selection and weighting of indicators.

4. Description of indicators and data sources

Table S4 Overview of indicators and data sources corresponding to each equity consideration.

Consideration	Abbr.	Indicator / Unit	Description	Source
Responsibility	R1	1850 CO2FFI ($GtCO_2$)	Historical cumulative net anthropogenic fossil fuel and industry (CO_2-FFI) emissions per R10 region (1850–2019), excluding net CO_2 from land use, land-use change, forestry (CO_2-LULUCF).	IPCC AR6 SPM.2B, https://doi.org/10.48490/g19x-6k84
Responsibility	R2	1990 CO2FFI ($GtCO_2$)	Historical cumulative net anthropogenic fossil fuel and industry (CO_2-FFI) emissions from 1990-2019, in tons of CO_2, excluding net CO_2 from land use, land-use change, forestry (CO_2-LULUCF).	IPCC AR6 Ch2, https://zenodo.org/record/6483002#.YtAU5HZBxD8
Capability	C2	GDP per Capita in 2019 (USD PPP 2017 / capita)	Total gross domestic product (GDP) per capita, for the year 2019. Calculated as the ratio of the total GDP, PPP (constant 2017 international $) to the total regional population. Both variables are taken from the World Bank's World Development Indicators (WDI). GDP: NY.GDP.MKTP.PP.KD; Population: SP.POP.TOTL. Aggregation to R10 regions is conducted by summing the country GDP and populations and then calculating the ratio.	WDI, https://data.worldbank.org/indicator/NY.GDP.MKTP.PP.KD https://data.worldbank.org/indicator/SP.POP.TOTL
Capability	C2	Capital stock per capita in 2019 (USD PPP 2017 / capita)	Total capital stock per capita, for the year 2019. Calculated as the ratio of total capital stock (constant 2017 US$) to the total population for the year 2019. Capital stock data is taken from the Penn World Tables and population data is taken from the WDI. Aggregation to R10 regions is conducted by summing the country populations and capital stock and then calculating the ratio.	Feenstra, Inklaar, & Timmer (2015), https://doi.org/10.1257/aer.20130954 www.ggdc.net/pwt https://data.worldbank.org/indicator/SP.POP.TOTL
Needs	N1	Decent living standards deprivation in 2015 (average % deprived across all dimensions)	The average share of regional population estimated deprived across all dimensions of the decent living standards for the year 2015 (last available). Estimates at the country level are determined by taking the average of the rates of deprivation across all DLS dimensions. The heuristics used to generate the distinct rates of deprivations across all dimensions are described in detail by Kikstra et al. (2021) and the theoretical foundation is provided by Rao & Min (2018). Aggregation to the R10 regions is conducted by taking the weighted average of country average deprivations, using populations in 2015 as weights.	Rao & Min, (2018), https://doi.org/10.1007/s11205-017-1650-0 Kikstra et al. (2021) https://doi.org/10.1088/1748-9326/ac1c27
Needs	N2	Climate risk in 2030 (% of regional population)	The share of regional population facing acute climate risk in 2030. This is defined as the share of population facing at least moderate risk of multi-sector climate exposure in the year 2030 and having an income below 20USD / capita / day. Multi-sector climate exposure is calculated as the aggregate of land-water-energy sector exposure. We use exposure derived under SSP2 and take the midpoint between 1.5°C and 2°C pathways. Further detail is provided by Byers et al. (2018). Aggregation to R10 regions is conducted by summing at risk populations and total populations and then calculating the ratio.	Byers et al. (2018), https://doi.org/10.1088/1748-9326/aabf45 https://hotspots-explorer.org/

5. Original indicator data summary

Table S5 Table of original regional values for indicators corresponding to each equity consideration

R10	R1 - 1850 CO2FFI (Gt)	R2 - 1990 CO2FFI (Gt)	C1 - GDP / capita (2019) (USD PPP 2017 / cap.)	C2 - Capital stock / capita (2019) (USD PPP 2017 / cap.)	N1 - DLS dep. (2015) (avg. % deprived)	N2 - Climate risk (2030) (% at risk)
SAP	37.1	32.3	12423.2	54070.1	39%	23%
MEA	56.0	44.7	24854.4	103676.8	27%	15%
APD	84.6	50.2	42972.2	208046.0	5%	0%
AFR	46.3	33.1	5030.29	15272.40	53%	8%
SAS	59.2	50.1	6369.6	22906.6	47%	40%
LAC	68.5	45.2	16014.4	62058.2	30%	6%
EEA	177.9	85.1	20212.2	107798.8	19%	2%
EAS	253.0	235.4	17183.7	78636.5	26%	9%
EUR	381.5	134.4	42401.7	220096.0	8%	0%
NAM	443.2	185.7	61097.0	212548.0	4%	0%

6. Methods of transformation and allocation

Responsibility – Historical emissions (R1, R2)

We assign higher proportions of regional mitigation investment contributions to regions with higher historical responsibility in terms of emissions. Regional cumulative historical emissions shown in Table S5 are used directly to determine the respective *shares* of cumulative historical emissions. Cumulative historical shares of emissions translate directly to shares of total mitigation investment contributions assigned to the respective region in Table S6.

Capability – GDP per Capita (C1), Capital stock per Capita (C2)

We assign higher proportions of regional mitigation investment contributions to regions with higher capability. As we are working with per capita indicators we must relate these to the actual size of the economies in question before we can derive proportional shares of total investment needs as above. The solution we take is to use the per-capita indicators to determine the proportional share of regional GDP each region should contribute. In this way, each region contributes a share of its GDP in proportion to the per capita indicator value relative to all other regions. Once we have the region's contribution as a proportional share of its GDP, we can then convert this back to the region's total contribution and thus determine its contribution as a share of total global mitigation investment needs ($S_{i,r}$ below).

Mathematically, the operation is simpler. We simply scale indicator values by the corresponding regional GDPs before determining relative shares. That is, we multiply the per capita indicator value for each indicator *i* in region *r* ($V_{i,r}$) by the regional GDP (GDP_r) before determining the relative share $S_{i,r}$ of each scaled $V_{i,r}$ to the total scaled V_i, as shown in Equation (1).

$$S_{i,r} = \frac{V_{i,r} \times GDP_r}{\sum(V_{i,r} \times GDP_r)} \quad (1)$$

These $S_{i,r}$ values then reflect the regional investment contribution shares of total investment needs conditional on regions contributing a relative share of their regional GDP in direct proportion to the per capita indicator values $V_{i,r}$. This ensures that each region contributes a relative percentage of their regional GDP in direct proportion to the per capita indicator values (see accompanying excel worksheet in the online replication archive that walks the reader through this rescaling).

Needs – Decent living standards (N1), Climate risk (N2)

We assign a proportionally higher share of the investment contributions to regions with lower needs. We define lower needs in regions with a smaller share of DLS deprived population and a smaller share of population facing acute near-term climate risk. As these indicators reflect deprivations, we first apply a penalty function that proportionally assigns higher values to regions with lower deprivation. We use a logarithmic function with the caveat that values below 0.01 are replaced with 0.01, reflecting a 'floor' share of deprivation or exposure of 1% of the regional population.

$$\mathrm{f}(x) = \log(1/x) \tag{2}$$

We then carry out an identical rescaling of these indicators as for the per capita indicators above. We thus transform the resulting values to proportional shares conditional on regions contributing a relative share of their regional GDP in direct proportion to the relative indicator values as described in Equation (1) above.

7. Regional allocations

The resulting regional fair share contributions of annual global mitigation investment needs by equity indicator are shown in Table S5 below. These shares are necessarily identical for both lower- and upper-bound cost-effective mitigation investment needs. RES indicators are translated directly into shares of total mitigation investment needs, whereas CAP and NED indicators are first transformed into relative shares of regional GDP and then into shares of mitigation investment needs as described above (see accompanying excel worksheet in the online replication archive that walks the reader through this rescaling).

Table S6 'Fair' shares of regional contributions to global mitigation investment needs

R10	R1 - 1850 CO2FFI	R2 - 1990 CO2FFI	C1 - GDP / capita (2019)	C2 - Capital stock / capita (2019)	N1 - DLS dep. (2015)	N2 - Climate risk (2030)
SAP	2.3%	3.6%	2.7%	2.7%	3.2%	2.9%
MEA	3.5%	5.0%	3.4%	3.3%	2.8%	2.4%
APD	5.3%	5.6%	7.6%	8.5%	8.3%	7.4%
AFR	2.9%	3.7%	0.9%	0.6%	1.7%	3.9%
SAS	3.7%	5.6%	1.9%	1.6%	3.6%	2.6%
LAC	4.3%	5.0%	4.1%	3.6%	4.8%	6.6%
EEA	11.1%	9.5%	3.1%	3.8%	4.0%	5.7%
EAS	15.7%	26.3%	11.3%	12.0%	13.9%	14.5%
EUR	23.7%	15.0%	29.4%	35.3%	27.5%	29.3%
NAM	27.6%	20.7%	35.6%	28.6%	30.2%	24.7%

8. Additional results

Figure S1 describes the total annual global inter-regional contributions that must occur to align regional cost-effective mitigation investment needs with 'fair-share' regional contributions.

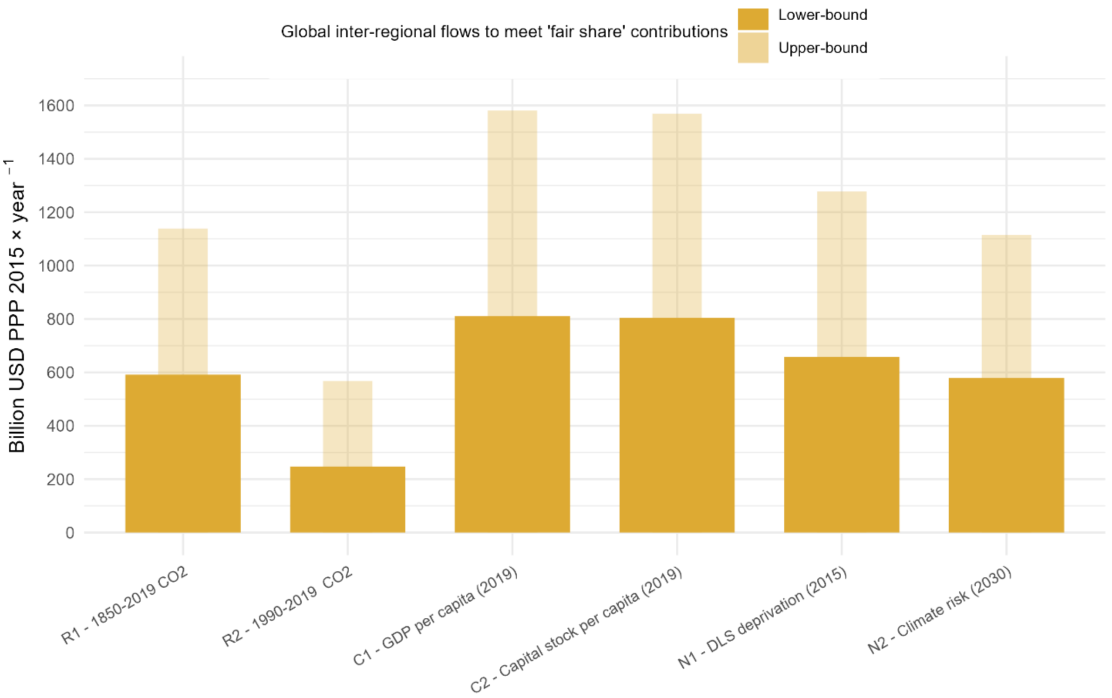

Figure S1 – Necessary annual global inter-regional climate mitigation finance contributions.

Figure 1B in the article describes the lower-bound of mitigation investment needs and corresponding regional contributions as shares of total global lower-bound mitigation investment needs. Figure S2 here is the almost identical alternative using the upper-bound of mitigation investment needs.

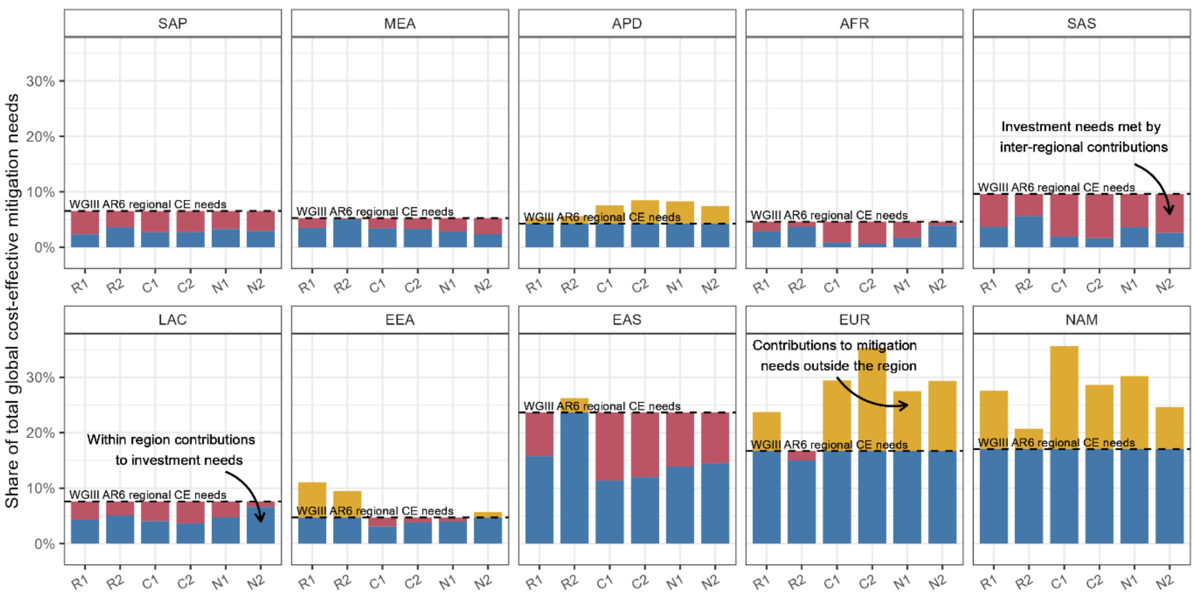

Figure S2 – Regional investment needs and contributions as shares of global needs (upper-bound)

Figure S3 describes both lower- and upper-bound investment needs as shares of regional GDP in 2019 as an alternative visualization of relative regional contributions to cost-effective mitigation needs.

Figure S3 – Regional investment needs and contributions as shares of regional GDP in 2019

9. Missing indicators

The following table describes the countries and territories for which a distinct indicator (or total population as necessary for aggregation) was missing.

Table S7 Overview of countries and territories missing necessary data for each indicator.

Indicator	Countries
R2	Åland Islands; Andorra; Bonaire, Sint Eustatius and Saba; Bouvet Island; British Indian Ocean Territory; Christmas Island; Cocos (Keeling) Islands; Curaçao; French Southern Territories; Guernsey; Heard Island and McDonald Islands; Holy See; Isle of Man; Jersey; Liechtenstein; Monaco; Montenegro; Norfolk Island; Pitcairn; Saint Barthélemy; San Marino; Serbia; Sint Maarten (Dutch part); South Georgia and the South Sandwich Islands; South Sudan; St. Martin (French part); Svalbard and Jan Mayen; United States Minor Outlying Islands; West Bank and Gaza
C1	American Samoa; Andorra; British Virgin Islands; Cuba; Eritrea; Faroe Islands; French Polynesia; Gibraltar; Greenland; Guam; Isle of Man; Korea, Dem. People's Rep.; Liechtenstein; Monaco; New Caledonia; Northern Mariana Islands; Sint Maarten (Dutch part); South Sudan; St. Martin (French part); Syrian Arab Republic; Venezuela, RB; Virgin Islands (U.S.); Yemen, Rep.
C2	Afghanistan; Åland Islands; American Samoa; Andorra; Anguilla; Bonaire, Sint Eustatius and Saba; Bouvet Island; British Indian Ocean Territory; Christmas Island; Cocos (Keeling) Islands; Cook Islands; Cuba; Curaçao; Eritrea; Falkland Islands (Malvinas); Faroe Islands; French Guiana; French Polynesia; French Southern Territories; Gibraltar; Greenland; Guadeloupe; Guam; Guernsey; Guyana; Heard Island and McDonald Islands; Holy See; Isle of Man; Jersey; Kiribati; Korea, Dem. People's Rep.; Libya; Liechtenstein; Marshall Islands; Martinique; Mayotte; Micronesia, Fed. Sts.; Monaco; Montserrat; Nauru; Netherlands Antilles; New Caledonia; Niue; Norfolk Island; Northern Mariana Islands; Palau; Papua New Guinea; Pitcairn; Puerto Rico; Réunion; Saint Barthélemy; Saint Helena, Ascension and Tristan da Cunha; Saint Pierre and Miquelon; Samoa; San Marino; Serbia and Montenegro; Sint Maarten (Dutch part); Solomon Islands; Somalia; South Georgia and the South Sandwich Islands; South Sudan; St. Martin (French part); Svalbard and Jan Mayen; Taiwan (China); Timor-Leste; Tokelau; Tonga; Tuvalu; United States Minor Outlying Islands; Vanuatu; Virgin Islands (U.S.); Wallis and Futuna; Western Sahara
N1	Åland Islands; American Samoa; Andorra; Anguilla; Antigua and Barbuda; Bermuda; Bonaire, Sint Eustatius and Saba; Bouvet Island; British Indian Ocean Territory; British Virgin Islands; Cayman Islands; Christmas Island; Cocos (Keeling) Islands; Cook Islands; Curaçao; Dominica; Eritrea; Falkland Islands (Malvinas); Faroe Islands; French Guiana; French Southern Territories; Gibraltar; Greenland; Guadeloupe; Guernsey; Heard Island and McDonald Islands; Holy See; Isle of Man; Jersey; Kiribati; Liechtenstein; Marshall Islands; Martinique; Mayotte; Monaco; Montserrat; Nauru; Netherlands Antilles; Niue; Norfolk Island; Northern Mariana Islands; Palau; Pitcairn; Réunion; Saint Barthélemy; Saint Helena, Ascension and Tristan da Cunha; Saint Pierre and Miquelon; San Marino; Serbia and Montenegro; Seychelles; Sint Maarten (Dutch part); South Georgia and the South Sandwich Islands; South Sudan; St. Kitts and Nevis; St. Martin (French part); Svalbard and Jan Mayen; Taiwan (China); Tokelau; Turks and Caicos Islands; Tuvalu; United States Minor Outlying Islands; Wallis and Futuna; Western Sahara
N2	Åland Islands; American Samoa; Andorra; Anguilla; Antigua and Barbuda; Aruba; Bahamas, The; Bermuda; Bonaire, Sint Eustatius and Saba; Bouvet Island; British Indian Ocean Territory; British Virgin Islands; Cayman Islands; Christmas Island; Cocos (Keeling) Islands; Cook Islands; Curaçao; Dominica; Falkland Islands (Malvinas); Faroe Islands; French Polynesia; French Southern Territories; Gibraltar; Greenland; Guadeloupe; Guam; Guernsey; Heard Island and McDonald Islands; Holy See; Hong Kong SAR (China); Isle of Man; Jersey; Kiribati; Liechtenstein; Macao SAR (China); Marshall Islands; Martinique; Mayotte; Micronesia, Fed. Sts.; Monaco; Montserrat; Nauru; Netherlands Antilles; New Caledonia; Niue; Norfolk Island; Northern Mariana Islands; Palau; Pitcairn; Réunion; Saint Barthélemy; Saint Helena, Ascension and Tristan da Cunha; Saint Pierre and Miquelon; Samoa; San Marino; Serbia and Montenegro; Seychelles; Sint Maarten (Dutch part); Solomon Islands; South Georgia and the South Sandwich Islands; South Sudan; St. Kitts and Nevis; St. Martin (French part); Svalbard and Jan Mayen; Taiwan (China); Tokelau; Tonga; Turks and Caicos Islands; Tuvalu; United States Minor Outlying Islands; Virgin Islands (U.S.); Wallis and Futuna; Western Sahara; NA

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