

# Understanding equity—efficiency interaction in the distribution of global carbon budgets

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## Abstract

Equity and efficiency are two important factors guiding the mitigation of anthropogenic emissions to achieve the Paris climate goals. Previous studies have proposed a range of allocations of global carbon budgets, but few have quantified the equity—efficiency interaction. Based on an investigation of the existing allocation literature, this study conducts a novel analysis using a ‘mixed’ allocation ‘big-data’ framework to understand the equity—efficiency interaction in the distribution of global carbon budgets under 2 °C and 1.5 °C warming targets. At a global scale, a carbon Gini coefficient and aggregate abatement costs are used as quantitative metrics to reflect equity and efficiency, respectively. Results show an equity—efficiency frontier that reflects the opportunity for the international community to co-improve equity and efficiency on top of existing allocations. However, the frontier also features strong trade-offs to further improve equity and efficiency if national allocations are to be achieved individually. Our analysis verifies that such trade-offs are sensitively dependent on the level of global connection and integration. Linking national mitigation actions and potentials can help promote equity—efficiency synergies and contribute to the efficient achievement of the Paris Agreement’s temperature and equity goals.

**Keywords:** Equity-efficiency interaction; Global carbon budgets; Paris climate goals; Cooperation and finance; Frontier analysis

## 1. Introduction

With the Paris Agreement, the international community has reached a consensus to hold the global average temperature rise well below 2 °C and pursue efforts to limit it to below 1.5 °C (UNFCCC, 2015), which indicates strict carbon budgets and unprecedented mitigation worldwide (Clarke et al., 2014; Rogelj et al., 2018; Riahi et al., 2022). Equity and efficiency are two important factors driving global emissions

reductions under the United Nations Framework Convention on Climate Change (UNFCCC) and the Paris Agreement. The UNFCCC established the principle of equity (UN, 1992), and Article 2.2 of the Paris Agreement emphasized that “this Agreement will be implemented to reflect equity and the principle of common but differentiated responsibilities and respective capabilities”. Multiple ‘equitable’ allocations of global carbon budgets among countries have been proposed in the literature to drive mitigation, reflecting the dissonant circumstances and interests of countries (Lange et al., 2010; Robiou du Pont and Meinshausen, 2018). For example, GCI (2005) proposed a ‘contraction and convergence’ of per capita emissions; Chakravarty et al. (2009) proposed sharing the burden of global CO<sub>2</sub> reductions among high emitters; Baer et al. (2009) proposed a ‘greenhouse development rights’ (GDR) framework; BASIC Experts (2011) proposed their

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allocations based primarily on the responsibility to warming. In contrast to equity, in the literature and in climate change decisions (Clarke et al., 2014; Rogelj et al., 2018; Tavoni et al., 2015), efficiency is often understood as ‘cost-effective’ or ‘the lowest possible cost’. Article 3.3 of the UNFCCC clearly stated that “policies and measures to deal with climate change should be cost-effective so as to ensure global benefits at the lowest possible cost”.

Equity and efficiency may interact with each other (Bertsimas et al., 2012; Manne and Stephan, 2005). In the field of energy and environment research, some studies have used different representations of equity and efficiency to examine the equity–efficiency interaction. For example, Levy et al. (2007) developed a framework that considered both efficiency and equity to identify the optimal air pollution control strategy for power plants in the United States, where efficiency and equity were measured using public health benefits and an Atkinson index, respectively. Böhringer et al. (2012) used simulations from a multi-region-sector computable general equilibrium model to study the equity–efficiency trade-offs in carbon leakage reductions, where equity and efficiency were measured using an inequality–aversion parameter and global cost-effectiveness, respectively. Hu et al. (2016) considered equity and efficiency as objectives and established a multi-objective programming to manage regional water allocation, where equity and efficiency were measured by a Gini coefficient and economic benefits, respectively. Wang et al. (2019) applied a multi-region-market equilibrium model to explore the equity–efficiency trade-offs in potential renewable energy certificate trading in China, where equity was represented by a Gini coefficient and efficiency was represented by average cost of electricity supply.

Regarding climate change mitigation or the distribution of global carbon budgets, previous studies have typically dealt with equity and efficiency separately, with a large part of them focusing on distributive equity (or fairness or justice) claims applying ethical, moral arguments (e.g., Höhne et al., 2014; Okereke and Coventry, 2016; Robiou du Pont et al., 2017; Winkler et al., 2018). The discussion of efficiency is comparatively less and is often related to market mechanisms, instruments and cooperation. In exercises of integrated assessment models (IAMs), efficiency is often assumed to be independent of equity and is represented as the implementation of mitigation under globally uniform carbon prices (Tavoni et al., 2015). Several studies have considered equity or efficiency trade-offs with other aspects. For example, Tavoni et al. (2012) provided a numerical framework to consider the safety and equity in allocating carbon budgets between developed and developing countries, where safety was measured using global cumulative emissions and equity was measured using cumulative per capita emissions. They found that the safety–equity trade-offs were formidable, but that global trading in future cumulative emissions budgets could help attenuate the trade-offs. Luderer et al. (2013) investigated the trade-offs between efficiency (represented as aggregate abatement costs) and temperature rise at the global scale through an IAM modelling. They found that the temperature–

efficiency trade-off curve was highly convex, indicating that abatement costs would increase disproportionately with the stringency of temperature targets. By assessing alternative carbon-pricing assumptions, Bauer et al. (2020) quantified the efficiency (also represented as aggregate abatement costs)–sovereignty trade-offs in allocating global carbon budgets. They found a strongly non-linear trade-off curve between cost efficiency and sovereignty at the global scale.

Scientific analysis on the equity and efficiency in the distribution of carbon budgets can be influential on the UNFCCC processes (Bauer et al., 2020; Dooley et al., 2021; Meinshausen et al., 2015; Robiou du Pont et al., 2017). Existing studies have mainly understood the distribution of global carbon budgets or mitigation from the perspective of equity or efficiency. There is an important literature gap in understanding the equity–efficiency interaction in the context of the Paris Agreement goals. The lack of such information might be detrimental to international cooperation to share Paris-aligned mitigation efforts if decision-makers feel that trade-offs have to always be made. This study therefore extends the literature through a ‘mixed’ allocation ‘big-data’ (here means substantially more allocations than previous studies) framework to explore how equity and efficiency might interact each other in the distribution of global carbon budgets. It is expected to provide the international community with some useful information to further coordinate mitigation effort-sharing and cooperation toward achieving the stringent Paris climate goals.

## 2. Methods

### 2.1. Equity and efficiency metrics

Although equity is fundamental to climate policy research and emphasized as a key component for global agreements (Klinsky et al., 2017), the UNFCCC has not determined the specific implementation of equity. We followed Teng et al. (2011) and Pan et al. (2014a) and applied a carbon Gini coefficient, defined by cumulative per capita emissions, as an aggregate equity metric to reflect how carbon budgets are dispersed across countries at a global scale. Over the past decade, cumulative per capita emissions have been widely invoked in climate equity discussion and used as a meaningful argument for equity (e.g., BASIC Experts, 2011; Fyson et al., 2020; Pan et al., 2014b; Raupach et al., 2014). The carbon Gini coefficient is an extension of the well-known Gini coefficient, which has been widely accepted as the recognized standard for defining the equity of income distribution. The rationale for this carbon Gini coefficient originally lies in the moral sense that all humans shall have equal rights to global commons such as emissions space (Baer et al., 2000; den Elzen and Lucas, 2005), and is reinforced by the strong near–linear relationship between carbon budgets and long-term anthropogenic temperature change (Riahi et al., 2022). With reference to the calculation of the income Gini coefficient, the carbon Gini coefficient is calculated through creating a so-called carbon Lorenz curve (Groot, 2010) which

graphically illustrates how emissions are distributed across countries, as shown in [Appendix A](#). The value of the carbon Gini coefficient ranges from 0 to 1, which can be interpreted as the proportion of global carbon budgets that are unequally allocated across countries ([Teng et al., 2011](#)). It is important to note that the carbon Gini coefficient here does not necessarily determine equity by all definitions. In our opinion, it is a transparent and practical communication metric ([Zimm and Nakicenovic, 2020](#)) from the dimension representing the ‘distributive performance’ of global carbon budgets across countries, and does not preclude the application of other metrics designed from other dimensions in future work.

This study considers the efficiency of implementing mitigation as synonymous with ‘cost-effective’ and uses aggregate global abatement costs over time as an efficiency metric. Cost-effectiveness has also been invoked as one basis for sharing mitigation in the first commitment period of the Kyoto Protocol within the European Union ([Groenenberg et al., 2004](#)). Similar to previous studies (e.g., [den Elzen and Lucas, 2005](#); [Hof et al., 2017](#); [Wang et al., 2018](#)), this study estimates abatement costs through the area under marginal abatement cost curves (MACCs). MACCs have been widely adopted to illustrate the relationship between an additional unit of emissions reduction and the associated costs. The MACCs used in this analysis are obtained from the fourth version of the Global Change Assessment Model (GCAM), an IAM that examines global energy–economy–climate long-term changes ([Kim and Wise, 2006](#)). The calculation of aggregate global abatement costs can be found in [Appendix A](#). Although mitigation could generate some ancillary benefits, such as improved air quality, energy security, and human health, these benefits are not included in the cost assessment for this analysis, which accommodates the political reality that most decision-makers currently consider only the direct costs associated with mitigation, rather than potential benefits or avoided impacts in the future.

## 2.2. Allocation framework

As mentioned earlier, previous studies (e.g., [BASIC Experts, 2011](#); [den Elzen et al., 2006](#); [Höhne et al., 2006](#); [Pan et al., 2014b](#); [Raupach et al., 2014](#); [Winkler et al., 2013](#)) from both developed and developing countries have proposed different allocations of global carbon budgets or mitigation. The Intergovernmental Panel on Climate Change (IPCC) Fifth Assessment Report (AR5) ([Clarke et al., 2014](#); [Höhne et al., 2014](#)) grouped existing allocations into seven categories: responsibility (RES), which allocates global mitigation according to national historical responsibility for warming; capability (CAP), which relates national emissions allowances to the ability to pay; equality (EQU), which takes into account equal emissions rights for all humans, regardless of where they live; responsibility–capability–need (RCN), which combines responsibility, capability, and sometimes sustainability needs to allocate global mitigation; equal cumulative per capita emissions (ECPC), which considers equal cumulative emissions rights for all humans over a certain period of time; staged

approaches (STA), which differentiates mitigation processes of developing countries into several stages; and global uniform costs (GUC), where allocations emerge from the least-cost implementation of global mitigation.

The basic allocation framework assessed in this study is built on an investigation of the existing allocation literature, as shown in [Table 1](#). Of course, other theoretical approaches to allocating carbon budgets exist. For example, [Giménez-Gómez et al. \(2016\)](#) applied the bankruptcy division rule and [Park et al. \(2012\)](#) used the Boltzmann distribution to allocate budgets. However, these additional approaches have not been applied by government experts, climate negotiators, or non-governmental organizations (e.g., the IPCC reports, the Climate Action Tracker (<https://climateactiontracker.org/>), the Paris Equity Check (<http://paris-equity-check.org/multi-equity-map.html>)) as a benchmark for allocating carbon budgets or assessing national mitigation aligned with the Paris climate goals. Therefore, the allocation framework here is intended to cover the allocations endorsed in the IPCC reports, rather than including all the theoretical allocations presented in the literature. The implementation of the allocation framework in a large part follows [Pan et al. \(2017\)](#), and the main sources of these allocations are also provided in [Table 1](#). For transparency, the allocation parameterization is provided in [Appendix C](#).

On top of this existing allocation framework, this study further constructs a series of ‘mixed’ allocations that combine multiple ‘pure’ allocations using weighting factors to represent possible political compromises between ‘pure’ allocations ([Pozo et al., 2020](#); [Raupach et al., 2014](#); [Robiou du Pont et al., 2017](#)). For example, if 50% of decision-makers and negotiators vote for PCC1 and the remaining 50% vote for GF1, then a weight of 0.50 for both PCC1 and GF1 might provide a possible compromise to reconcile debates. The ‘mixed’ framework will expand the allocation space to ‘big-data’ to facilitate exploration of the equity–efficiency interaction. This study constructs ‘mixed’ allocations through random choices on the existing ‘pure’ allocations in [Table 1](#). The selected ‘pure’ allocations are then linearly aggregated using randomly generated weighting factors (linear aggregation ensures consistency with global emissions pathways). To provide a numerical illustration, this study produces 1000 allocations mixed by two existing ‘pure’ allocations and another 1000 mixed by three under each temperature target (2 °C or 1.5 °C), and then calculates the carbon Gini coefficient and aggregate global abatement costs under each allocation.

## 2.3. Scenario and assumption

This study focuses on fossil fuel and industrial CO<sub>2</sub>, the main contributor to anthropogenic warming, and considers historical emissions since 1850 ([Pan et al., 2014a](#); [Pozo et al., 2020](#); [van den Berg et al., 2020](#)). An annual discount of 1.5% ([Robiou du Pont et al., 2017](#)) is applied to historical emissions to reflect autonomous energy efficiency improvements ([BASIC Experts, 2011](#); [den Elzen et al., 2013](#)). 1.5% is in the middle of the range of historical emissions discount rates

Table 1  
The existing 'pure' allocation framework.

Allocation	Characteristic and implementation	IPCC category
Ability to pay (AP)	National emissions allowances are calculated in a bottom-up manner based on the ability to pay. Implementation mainly follows <a href="#">Jacoby et al. (1999)</a>	CAP
Billion high emitters (BHE)	Individuals reduce their luxurious emissions above a universal cap. Implementation mainly follows <a href="#">Chakravarty et al. (2009)</a>	EQU
Carbon budget approach (CB)	Global carbon budgets are shared to achieve equal cumulative emissions rights per person in each country by the end of the century. The resulting national budgets are assigned to individual years following <a href="#">Raupach et al. (2014)</a>	ECPC
Common but differentiated convergence (CDC)	National per capita emissions converge to a common level within a certain time period, but the starting year of convergence may vary across countries. Implementation mainly follows <a href="#">Höhne et al. (2006)</a>	STA
Emissions intensity targets (EIT)	National emissions allowances are calculated in a bottom-up manner based on emissions intensity improvements. Implementation mainly follows <a href="#">den Elzen and Lucas (2005)</a>	CAP
Equal marginal abatement costs (EMC)	Allocations come from global uniform carbon prices. Implementation uses the MACCs exogenous from GCAM	GUC
Grandfathering (GF)	National emissions allowances are allocated in proportion to the emissions status-quo. This analysis considers an immediate constant ratio (GF1) and a gradual participation (GF2)	STA
Greenhouse development rights (GDR)	A framework combines responsibility and capacity to share mitigation. Implementation mainly follows <a href="#">Baer et al. (2009)</a>	RCN
Historical responsibility (HR)	Mitigation is shared among participating countries based on historical responsibility for warming. Responsibility is assumed in proportion to cumulative emissions	RES
Multi-criteria (MC)	National emissions allowances are allocated based on weighing per capita GDP, per capita emissions, and emissions intensity. Implementation mainly follows <a href="#">Ringius et al. (1998)</a>	STA
Multi-stage (MS)	Developing countries follow three stages (business as usual, improved emissions intensity, and absolute reductions) to reduce emissions. Implementation mainly follows <a href="#">den Elzen et al. (2006)</a>	STA
Per capita convergence (PCC)	National per capita emissions converge to the same level in a common year. This study considers immediately equal per capita emissions (PCC1), and linear convergence by 2050 (PCC2) and 2100 (PCC3), respectively	EQU
South-African approach (SAA)	Similar to GDR, but capacity is adjusted using human development index to incorporate development needs. Implementation mainly follows <a href="#">Winkler et al. (2013)</a>	RCN
Two-convergence (TC)	Similar to CB, but allocations also achieve equal per capita emissions for each country in a common year. This study considers reaching equal per capita emissions in 2050 (TC1) and 2100 (TC2), respectively. Implementation mainly follows <a href="#">Pan et al. (2014b)</a>	ECPC

(0–3%) chosen by experts interviewed by [van den Berg et al. \(2020\)](#). Global CO<sub>2</sub> pathways aligned with 2 °C and 1.5 °C in future years are assumed to follow the Representative Concentration Pathway (RCP) 2.6 ([van Vuuren et al., 2011](#)) and the median of the 1.5 °C pathways in [Rogelj et al. \(2015\)](#), respectively. This study allocates from 2011 (the base year of the two global emissions pathways and GCAM we applied is 2010) to 2050. Any allocations meet the selected global pathways at every point in time. Therefore, the discounted historical emissions for the period 1850–2010 and the allocated emissions allowances for the period 2011–2050 are used to calculate the carbon Gini coefficient. Historical CO<sub>2</sub>, GDP and population are obtained from the Potsdam Real-time Integrated Model for the probabilistic Assessment of emission Paths (PRIMAP) (<https://doi.org/10.5880/PIK.2017.001>), the World Bank (<https://data.worldbank.org>) and the United Nations World Population Prospects (<https://esa.un.org/unpd/wpp>), respectively. National GDP and population to 2050 are assumed to follow the Shared Socioeconomic Pathway 2 (SSP2) (<https://tntcat.iiasa.ac.at/SspDb>). Since most future baseline emissions scenarios in the literature lie between RCP6.0 and RCP8.5 ([Clarke et al., 2014](#)), this study uses the average trajectory of RCP6.0 and RCP8.5 (<https://tntcat.iiasa.ac.at:8787/RcpDb>) as the baseline scenario and downscales

([van Vuuren et al., 2007](#)) using SSP2 to obtain national baseline emissions to 2050. Under these assumptions, the global 2011–2050 carbon budgets for 2 °C and 1.5 °C are 1000 and 750 Gt CO<sub>2</sub>, respectively, approximately 45% and 60% lower than cumulative baseline emissions, respectively. Abatement costs correspond to achieving the global pathways from the baseline emissions scenario.

### 3. Results

#### 3.1. Allocations from the existing 'pure' framework

Carbon budget allocations, especially under the 2 °C threshold, have been extensively analyzed (e.g., [Höhne et al., 2014](#); [Pan et al., 2015](#); [van den Berg et al., 2020](#)). After the adoption of the Paris Agreement, these allocations have also been used as a benchmark to compare the Nationally Determined Contributions (NDCs) ambitions (e.g., [Pan et al., 2017](#); [Robiou du Pont et al., 2017](#); [Holz et al., 2018](#); [Winkler et al., 2018](#)). Under our scenario assumptions, the trajectories of emissions allowances by regions resulting from the existing 'pure' allocation framework in [Table 1](#) are shown and



compared in Fig. 1. Emissions allowances for all regions are remarkably smaller under 1.5 °C than under 2 °C, in line with the smaller global carbon budgets to stay below 1.5 °C. As might be expected, the required mitigation (as reductions from 2010 emissions) is overall greater in developed regions than in developing regions. Emissions allowances for the Organization for Economic Cooperation and Development countries, while varying by allocation, show a rapid decline from 2010 onwards, particularly under allocations that emphasize responsibility. Their emissions allowances in alignment with 1.5 °C would reach net-zero by mid-century or even earlier. Emissions allowances for developing regions such as Asia, Latin America, the Middle East and Africa typically show a peaking- or plateauing-then-declining trajectory. In particular, almost all of the allocations analyzed here feature the need for developed regions to achieve more stringent mitigation than globally cost-optimal outcomes ('EMC' in Fig. 1), while domestic economic mitigation potentials typically exceed the required mitigation in developing regions, reflecting the prospect of multilateral cooperation to reduce emissions under the Paris Agreement.

### 3.2. Equity–efficiency frontier

Fig. 1 indicates that existing 'pure' allocations would lead to very different distributions of carbon mitigation burdens and abatement costs. Here, as mentioned earlier, we calculated the carbon Gini coefficient as an equity metric and overall abatement costs as an efficiency metric to infer the interaction between equity and efficiency on a global scale. We showed in Fig. 2 the equity–efficiency combinations calculated from all

'pure' and 'mixed' allocations when countries meet their allocated emissions allowances individually. Under the metric assumptions, Fig. 2 clearly reflects an equity–efficiency frontier for 2 °C or 1.5 °C, indicating that it is possible to reduce global abatement costs without sacrificing global 'distributive performance' (and vice versa), or even improve both, compared to existing allocations. For example, despite similar carbon Gini coefficients, mobilizing GDR tends to be more expensive globally than mobilizing the allocation on the frontier mixed by TC2 (weight 0.35), EMC (weight 0.63) and MS (weight 0.02) under 2 °C, and mixed by PPC1 (weight 0.12) and PCC2 (weight 0.88) under 1.5 °C. This suggests a perspective for tuning the complexity of equity debates: we can explore the possibility of co-improvements of equity and efficiency.

While implying 'Pareto'-improvements of 'pure' allocations, the frontier also highlights strong trade-offs between further equity and efficiency improvements if national allocations are to be achieved individually. Along the frontier, equity matters to efficiency under strict definitions of both, and further improvements in the 'distributive performance' of global carbon budgets compromise overall cost efficiency (and vice versa). According to the PRIMAP, cumulative per capita CO<sub>2</sub> emissions in developed countries were 5.5 times (with an annual discount of 1.5% to historical emissions; this number was 7.1 without discount) higher than in developing countries between 1850 and 2010. Thus, achieving a smaller carbon Gini coefficient, as defined here, would increase mitigation burdens of developed countries toward mid-century. The inverse proportional shape of the frontier is consistent with the fact that marginal abatement costs are higher in developed

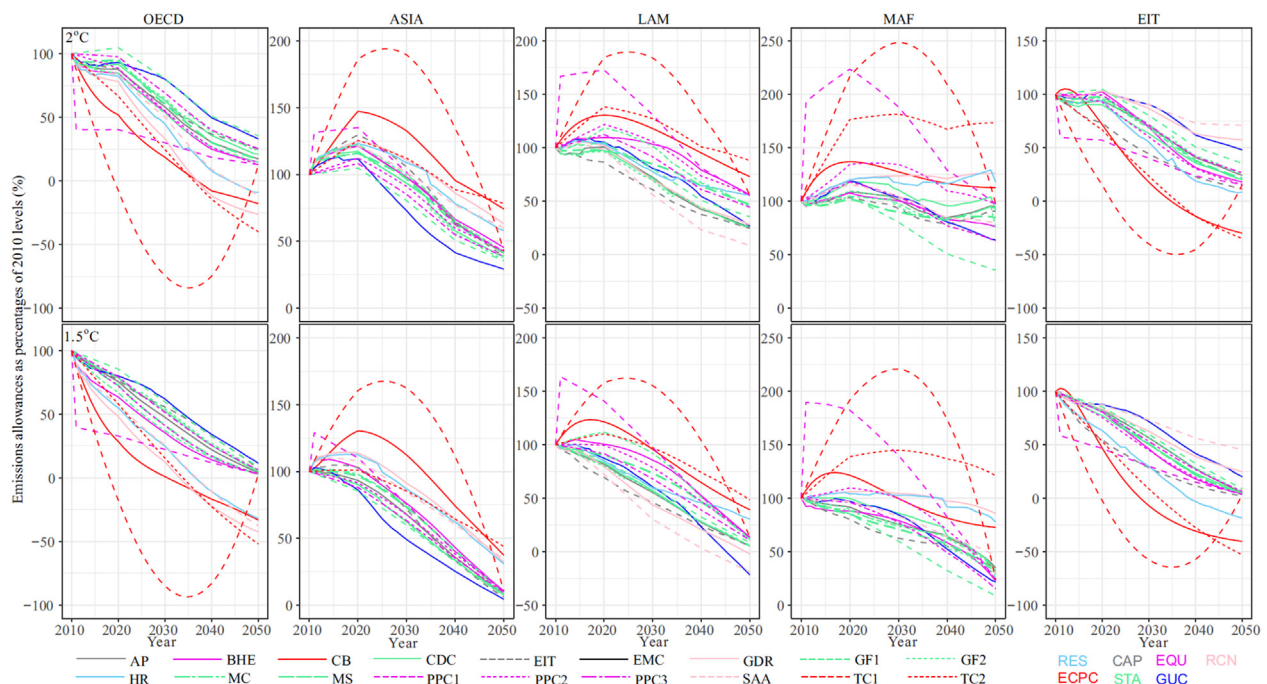


Fig. 1. Allocations resulting from the existing 'pure' allocation framework (OECD—the Organization for Economic Cooperation and Development, LAM—Latin America, MAF—Middle East and Africa, EIT—Economies in Transition. Colors of the lines correspond to the IPCC categories).

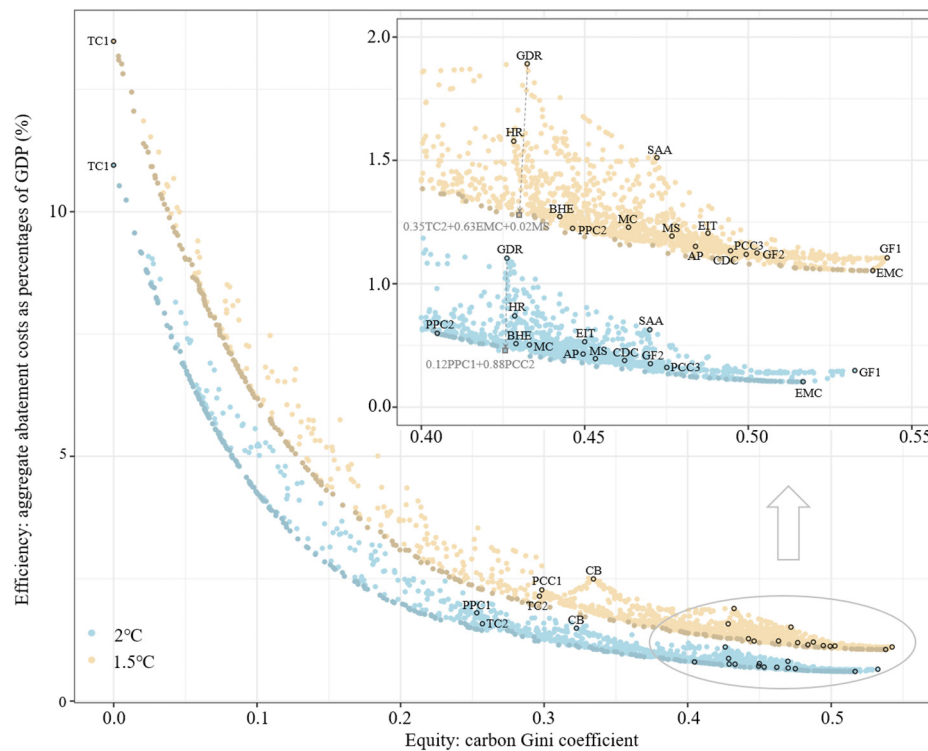


Fig. 2. The equity–efficiency interaction calculated from ‘pure’ and ‘mixed’ allocations (The dark hollow dots mark the frontier of these allocations).

countries than in developing countries (Clarke et al., 2014; Rogelj et al., 2018).

### 3.3. Improvement of equity–efficiency synergies

By showing a wide range of equity–efficiency outcomes, Fig. 2 also implies that some allocations seem practically impossible to achieve with domestic mitigation alone. For example, to achieve a carbon Gini coefficient of less than 0.10 which requires developed countries to achieve negative budgets, aggregate global abatement costs for the period 2011–2050 could exceed 5% or even 10% of GDP, according to estimations using MACCs. Carbon markets are considered to have the potential to facilitate the implementation of equitable allocations in practice (Leimbach and Giannousakis, 2019; Manne and Stephan, 2005; Wang et al., 2018), where countries can minimize their abatement costs to meet allocations through a flexible combination of domestic mitigation and internationally traded mitigation outcomes (Robiou du Pont et al., 2016; Tavoni et al., 2015). Guided by Article 6 of the Paris Agreement, climate change negotiations in the Conference of Parties to the UNFCCC in Madrid and Glasgow had targeted on the establishment of a global carbon market to link national mitigation efforts and the NDCs within an organized framework, which is expected to have tremendous implications for the equity–efficiency interaction in the distribution of global carbon budgets. Here, we derived those implications by assuming different trading-constrained carbon markets using different maximum buying rates (T0%, T10%, T20%, T30%, T40%, T50% and T100%). For example, T10%

indicates that for each country and region, up to one-tenth of national mitigation burdens could be achieved through off-setting from carbon markets (in other words, at least nine-tenths of mitigation burdens must still be achieved through domestic actions); and T100% (T0%) indicates that emissions trading is completely open (prohibited) across the world, representing a fully connected (unconnected) carbon market. Note that these assumptions affect abatement costs, but not carbon Gini coefficients, which are determined by initial allocations.

Our results in Fig. 3a clearly show that relaxing buying constrains levels frontiers off, demonstrating the crucial role of an integrated global emissions trading scheme in attenuating the equity–efficiency trade-offs and promoting synergies. For example, to achieve a carbon Gini coefficient of 0.20 (the threshold for the income Gini coefficient representing ‘absolute equality’ in income distribution) by mid-century, a well-connected carbon market has the potential to avoid global efficiency losses of at least 70% under 2 °C and 65% under 1.5 °C. In T100% which assumes that national mitigation actions and potentials are fully connected, aggregate global abatement costs will become minimum (0.60% of GDP under 2 °C and 1.05% under 1.5 °C in our scenarios) regardless of the allocation, because mitigation can flexibly occur wherever the cheapest. Aware of this, we recommended accelerating the negotiation and launch of transnational carbon markets or equivalent cooperation mechanisms that link countries' NDCs and carbon neutrality visions; otherwise, the trade-offs between equity and efficiency will likely be unavoidable.

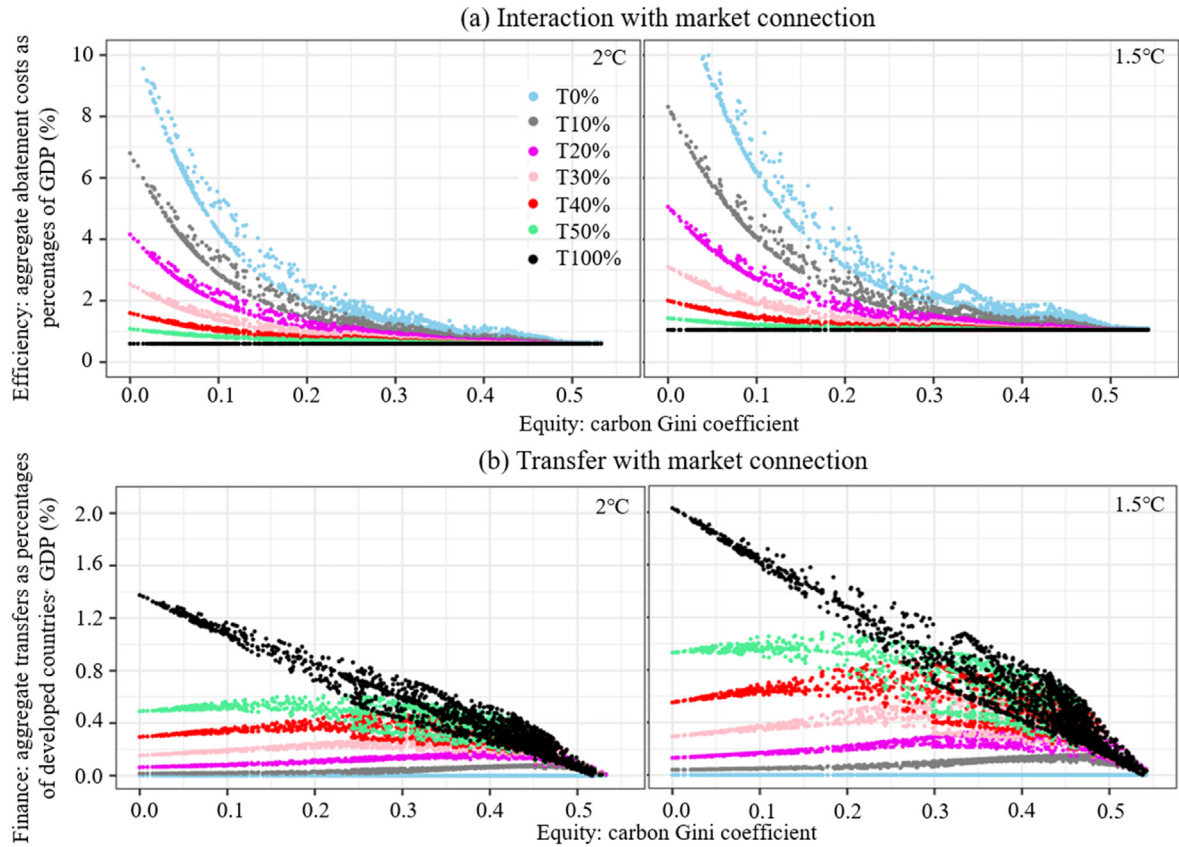


Fig. 3. The equity–efficiency interaction and aggregate financial transfers from developed to developing countries at different levels of global carbon market connection. The same legend is used for both subplots. Note that if zero-cost hot airs (i.e., emissions allowances in excess of baseline emissions) meet all market demand, a zero carbon price is assumed.

Under the assumed carbon markets, aggregate trading financial transfers from developed to developing countries over the 2011–2050 period are shown in Fig. 3b. These transfers, calculated as net trading volumes of developed countries multiplied by carbon prices, result from the comprehensiveness of market connection and the extent to which allocations differ from global cost-effective outcomes. In many allocations, we found that the average annual financial transfers mobilized from developed to developing countries by mid-century are of an order of hundreds of billions of dollars. Financial transfers are highest in T100%. To achieve a zero carbon Gini coefficient, the aggregate financial transfers in T100% reach even 1.40% and 2.05% of developed countries' GDP under 2 °C and 1.5 °C, respectively. Until a broad carbon market is put in practice, developed countries could scale up their ambition to provide climate finance to fund cheaper mitigation outcomes elsewhere as a way to help offset their efficiency in meeting allocations, especially under 1.5 °C. As mentioned earlier, developing countries typically have higher economic mitigation potentials than their allocated mitigation. In light of national circumstances and international support, they could pursue maximum mitigation efforts on top of meeting their allocations, which is important not only to improve global cost efficiency in closing the NDC emissions gap, but also to pave the way for their own carbon neutrality visions.

### 3.4. Marginal Gini-improvement cost curves

Following the definitions of equity and efficiency metrics, the slope of the frontier in Fig. 3a can be considered to constitute marginal 'Gini-improvement' cost curves (MGCCs) on a global scale, which illustrate the relationship between an additional unit improvement in the carbon Gini coefficient and the minimal abatement costs required by the world to do so. Fig. 4a provides the Paris-aligned global MGCCs in our scenarios (no additional costs globally in T100%). Limiting warming below 1.5 °C would require more expensive mitigation options than well below 2 °C (Pan et al., 2022; Riahi et al., 2022). The carbon prices (Fig. 4b) in T100%, which increase somewhat linearly over time, are 1.4 times higher under 1.5 °C in 2030 than under 2 °C and 1.7 times higher in 2050. Consistent with more limited carbon budgets and higher carbon prices, it is more difficult to resolve the equity–efficiency conundrum in a 1.5 °C future than in a 2 °C future when mitigation efforts and the NDCs are fragmented. For example, with a carbon Gini coefficient of 0.20 in T0%, global marginal 'Gini-improvement' costs of staying below 1.5 °C are 1.5 times those of staying well below 2 °C. Under both 2 °C and 1.5 °C, the smaller the carbon Gini coefficient, the higher marginal 'Gini-improvement' costs. MGCCs are only manageable if the carbon market is sufficiently connected (e.g., a buying rate over 50%), confirming the importance of

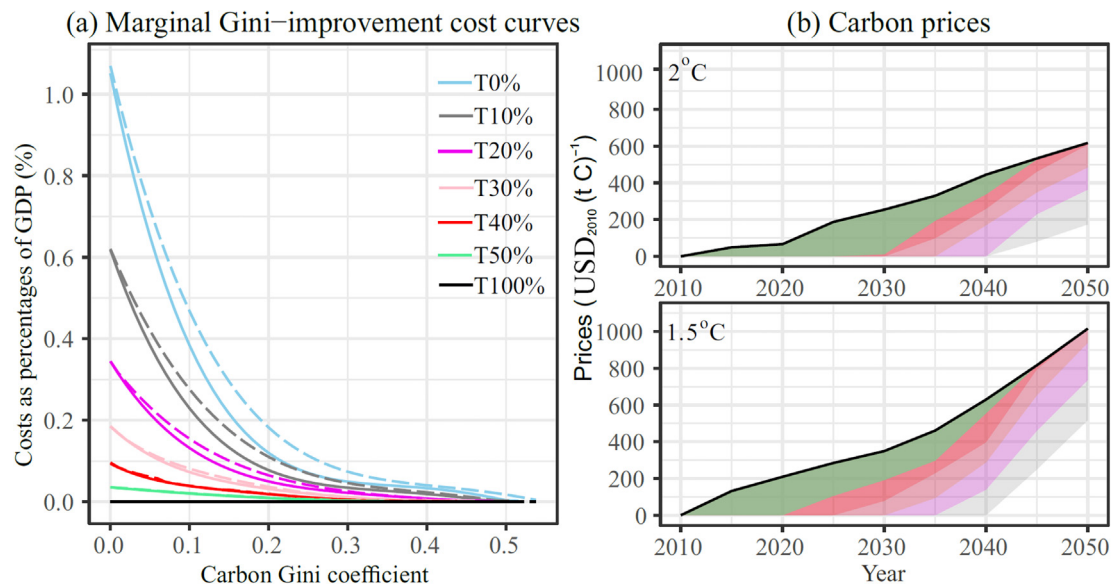


Fig. 4. Global marginal ‘Gini-improvement’ cost curves and carbon prices along the equity–efficiency frontier (The same legend is used for both subplots. In (a), the solid and dashed lines correspond to 2 °C and 1.5 °C, respectively. In (b), T0% is not included because there is no trade; and the T100% line also provides the ceiling prices of all the other five scenarios).

international cooperate if equity is to be pursued without sacrificing overall efficiency.

#### 4. Conclusions

This study expanded the knowledge on the distribution of global carbon budgets in two ways. First, we developed a ‘mixed’ allocation ‘big-data’ framework based on existing ‘pure’ allocations in the literature and the IPCC AR5. ‘Mixed’ allocations are a natural extension of ‘pure’ allocations and provide a new perspective for exploring the interaction between equity and efficiency. Using the carbon Gini coefficient as a metric of ‘distributive performance’ of carbon budgets and global abatement costs as an efficiency metric, this framework reveals an equity–efficient frontier that suggests the potential to co-improve equity and efficiency from existing allocations. However, when national allocations are met individually, the frontier also reflects strong trade-offs for further equity and efficiency improvements. Second, we emphasized that a global carbon market linking transnational mitigation efforts and potentials, or an equivalent cooperative or financing mechanism, would be key to further attenuating the equity–efficiency trade-offs and promoting synergies. In many assessed allocations, hundreds of billions of dollars are expected to be transferred annually from developed to developing countries by 2050 to support efficient achievement of the Paris temperature and equity goals. Our analysis strongly supports Article 6 of the Paris Agreement as a window for voluntary cooperation among Parties to reduce abatement costs, and reinforces that only through broad cooperation might equitable mitigation aligned with 2 °C or 1.5 °C practically be implemented without compromising overall efficiency.

This study intends to stimulate some discussion on the equity–efficiency interaction in the context of climate change mitigation. However, there are limitations and weaknesses. For example, while the carbon Gini coefficient has also been used as an aggregate metric to quantify inequality of carbon emissions in many other studies (e.g., Teng et al., 2011; Golley and Meng, 2012; Wiedenhofer et al., 2017; Zimm and Nakicenovic, 2020), it only narrates equity from the view of the physical ‘distributive performance’ of global carbon budgets across countries. Future equity–efficiency research could investigate the distributional effects of carbon budgets on adaptation, vulnerability, and broader socioeconomic dimensions.

#### Declaration of competing interest

The authors declare no conflict of interest.

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#### Appendix A. Supplementary materials

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