A global just transition through carbon taxation and revenue recycling

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A global just transition through carbon taxation and revenue recycling

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Carbon taxation is regarded as an essential tool for curbing carbon emissions but can be regressive and increase poverty, and moreover lacks universal acceptance among the public and policymakers. Recycling the tax revenue raised to vulnerable households is one promising solution to this issue. However, little is known about the best strategy for designing such a policy at the global level. This paper investigates the effectiveness of various carbon taxation methods and revenue recycling mechanisms in reducing poverty and inequality between and within countries. We find that the policy mix with the highest poverty reduction potential is implementing a consumption tax with higher tax rates on luxury goods and recycling revenue through expanded social assistance systems, in line with the expansion during the COVID-19 pandemic. While differentiating tax rates across goods within countries is advantageous, the average tax level across countries is best kept uniform since it potentially offers governments in low- and middle-income countries more financial capacity to support the poor. Furthermore, collecting a global climate fund from developed countries and redistributing it to developing countries based on poverty headcounts can further significantly reduce poverty and inequality within and between countries. However, substantial improvements in social assistance systems are urgently needed to further unlock the poverty-reduction potential of revenue recycling, particularly in Sub-Saharan African countries. Also, recycling carbon tax revenues to combat poverty and inequality will inhibit the emission reduction effect of carbon taxation in the short term, necessitating additional mitigation efforts in other areas.

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Global carbon emissions are expected to reach a new high in 2022[1]. If current trends continue, the increase in CO_2 concentration will warm the Earth to 1.5°C above pre-industrial levels in less than a decade[1]. The 1.5/2°C global warming target will be nearly impossible unless we take aggressive mitigation actions. Carbon taxation is regarded as an effective and necessary tool for reducing carbon emissions[2,3]. However, achieving a just transition and balancing the conflicts between carbon taxation and its potentially negative side effects on other SDGs, particularly poverty eradication (SDG 1) and inequality reduction (SDG 10), is a challenge[4,5].

Numerous studies report adverse effects of carbon taxation on poverty and inequality. First, carbon taxation tends to burden poor households the most and exacerbate poverty[6,7]. This is due to poor households consuming proportionally more necessities such as food, energy and manufacturing goods that tend to be carbon intensive, even though in absolute terms the consumption of high-income households contributes the dominant share of carbon emissions[8–10]. A wealth of empirical evidence suggests that carbon taxation is typically regressive in high-income countries and progressive in low- and middle-income countries, implying that carbon taxation has varying side effects with respect to economic inequality[11–17].

The concerns surrounding vulnerable populations and worsening inequality are a critical factor that undermines the public's willingness to support carbon tax policies[18]. Designing a tax revenue recycling mechanism to offset the negative impact of carbon taxation and even further help to improve other social goals may make it (more) politically feasible[19,20]. The performance of several mechanisms, such as a universal lump-sum transfer[21–25] or redistributing the tax revenue to specific low-income households (e.g., the poorest 40%)[17,22,26], as well as international revenue recycling through a global climate fund[21,23,25,27] have started to be investigated. The idea of a global climate fund aligns with the fact that many developed countries have committed to providing official development assistance (ODA) to developing countries[28]. Also, the global partnership for sustainable development is emphasised by SDG 17 (Partnerships for the Goals). All these studies and policy documents have demonstrated the considerable potential of tax revenue recycling in alleviating poverty.

However, existing research is still unclear on some critical issues, particularly regarding the most effective taxation design and revenue-recycling strategies to households. Potential approaches to a carbon tax include a production tax that targets companies, much like in the cap-and-trade schemes, or in contrast, a tax on consumption based on the carbon footprint of products. There are also some notable variants of these two methods, such as introducing heterogeneity into carbon pricing across countries as tested by Bauer et al.[27] or a tax on luxury consumption proposed by Oswald et al.[17], which assigns a higher tax rate to luxury goods relative to necessity goods. For domestic revenue recycling, previous studies tend to lack consideration of countries' implementation capacity. For example, the social assistance system in some countries may be unable to fully redistribute the tax revenue to the poorest 40% population; recent evidence shows that around half of the global population is not covered by social protection[29]. Also, numerous options for international revenue recycling exist, such as transferring a certain share of carbon tax revenue from rich nations to poor nations[23], pooling global tax revenue and distributing equal per capita across the globe[25]. These raises a number of interesting questions: What are the poverty and inequality consequences of various taxation and revenue recycling strategies? Which is the best policy mix on the global scale? How would such policies affect global carbon emissions? The answers to these questions could shed light on how to strike a balance between climate action and other social goals.

In this paper, we test a large variety of possible carbon taxation designs and revenue recycling mechanisms and study their impacts across 168 countries. We start by designing six carbon taxation scenarios with different taxation principles, five domestic revenue recycling mechanisms based on country-specific social assistance capacity, and six international revenue recycling mechanisms based on global justice principles. Then, we examine the poverty, inequality, and emission effects of various policy scenario combinations using an environmentally extended global multiregional input-output approach based on the Global Trade Analysis Project[30], a highly detailed expenditure database[31,32] and data on coverage of social assistance programs. Finally, we identify the best policy mix based on poverty reduction effect and explore its regional performance.

Carbon taxation design determines burden among expenditure groups

We consider six carbon taxation scenarios (*Extended Data Table 1*). The differences in taxation methods are determined by three factors: whether the tax is a production or consumption tax, whether the tax level differs between countries (national heterogeneity), and whether it differentiates sectors (sectoral heterogeneity). A production tax is based on the carbon emissions from production activities. In contrast, a consumption tax refers to a tax based on the carbon footprint of products. The tax level under a nation-differentiated production tax is determined by territorial CO_2 emissions and development level based on the World Bank's income classification (low, lower-middle, upper-middle, and high), while the nation-differentiated tax level of a consumption tax is determined by consumption-based CO_2 emissions and development level. A product-specific consumption tax is determined by sectoral expenditure elasticities of households[17]. In economics, an expenditure elasticity above one means the product is a luxury good, a product or service households demand more of as their expenditure increases. In contrast, an expenditure elasticity below one refers to necessities – a good that poorer households demand, but it occupies a lower share in the consumption basket as people become wealthier. See the *Method* section for details in the carbon taxation scenarios setting. We set the global average carbon tax level for all scenarios at US$50/t$CO_2$, which is considered the lower boundary for achieving the 1.5 °C Goal recommended by the World Bank[33].

For the global uniform production tax scenario (T1) and global uniform consumption tax scenario (T3), the tax level for all countries is the same. The tax revenue of the former depends on production-based emissions, while the tax revenue for the latter depends on consumption-based emissions. However, since the tax levels for all products and all countries are completely uniform, both scenarios will generate the same carbon tax burden for consumers. The uniform carbon tax between countries can discourage carbon leakage[34]. Implementing production taxes relies on monitoring companies' emissions, such as the practice in Norway and Switzerland[35]. Implementing consumption taxes relies on the carbon footprint accounting of products, such as the carbon border adjustment mechanism (CBAM) in the European Union, which will be implemented end of 2023[36].

For the nation-differentiated production tax scenario (T2) and nation-differentiated consumption tax scenario (T4), the tax level varies between countries at different income levels, while the global average tax level weighted with countries' carbon emissions is kept at US$50/t$CO_2$. The national tax level under the production tax scenario (T2) is based upon production-based emissions, while the national tax level under the consumption tax scenario (T4) is based on consumption-based emissions. This difference is in line with the debate on producer and consumer responsibility[37]. A differentiated carbon tax across countries considers the ability of different countries to implement such tax under the principle of common but differentiated responsibilities (CBDR) and is, therefore, more likely to win international consensus[27]. Still, both scenarios maintain a uniform tax level across sectors.

For the design of the luxury tax scenarios (T5) and (T6), we follow Oswald et al.[17], who set a lower tax level on necessity goods and a higher tax level on luxury goods based on expenditure elasticities but maintain the average carbon tax across goods at a certain level. (T6) combines the luxury consumption tax scenario (T5) and the nation-differentiated consumption tax scenario (T4), incorporating both country and sectoral heterogeneity.

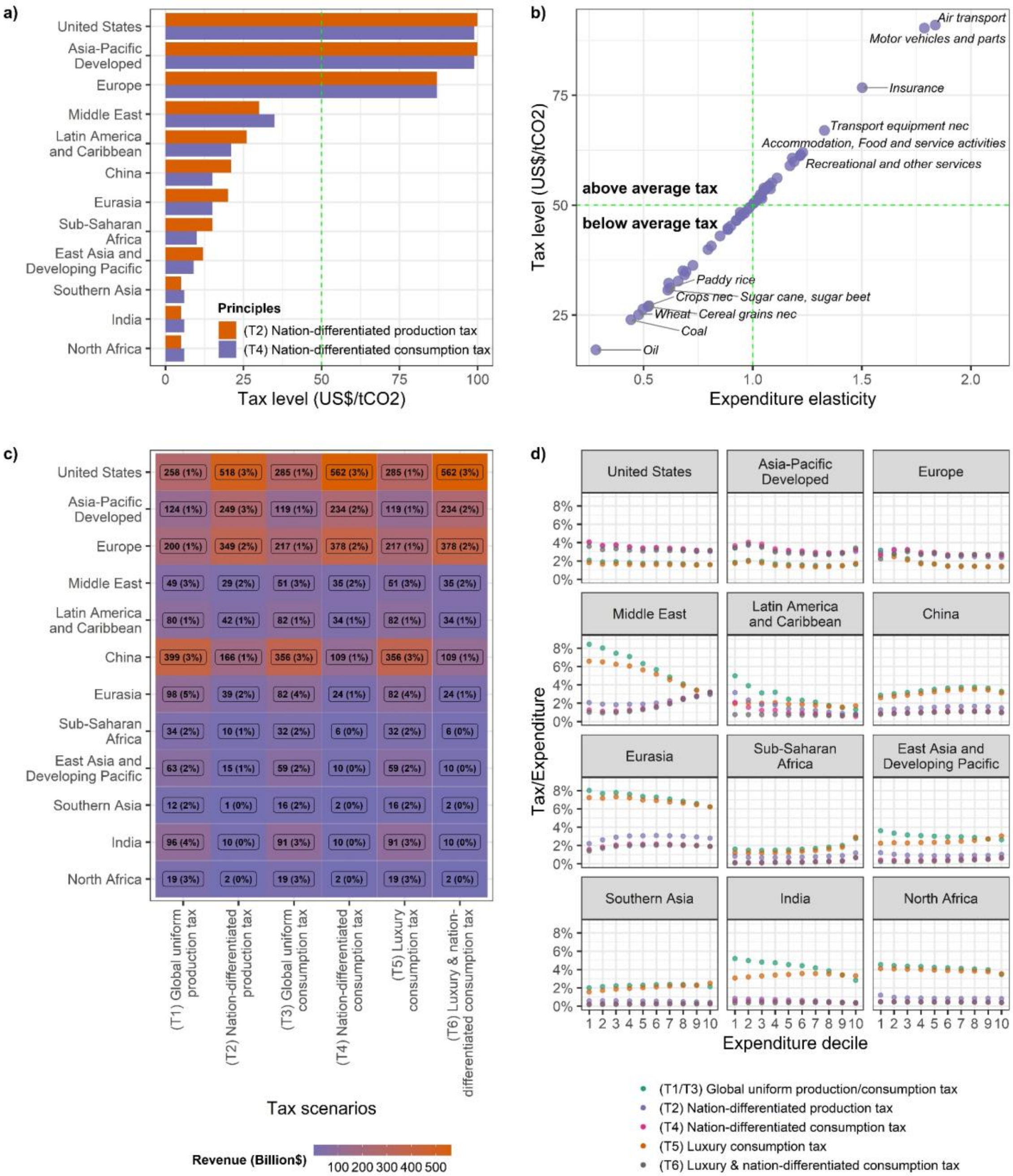

Fig. 1 | Tax revenue and burden for different expenditure groups under six carbon taxation scenarios. a, Regional tax levels under nation-differentiated tax scenarios. 168 countries are grouped into 12 regions by slightly modifying intermediate-level regional grouping in IPCC's Sixth Assessment Report (*Extended Data Fig. 1*). Both the national production and consumption tax scenarios remain at a tax level of US\$ 50/tCO_2 at the global level. See *Supplementary Table S4* for tax levels in each country. **b,** Sectoral expenditure elasticity and tax level under luxury consumption tax scenarios. The tax level for each sector presented here is the global average level. See *Supplementary Table S3* and *Supplementary Table S5* for details at the country-sector level. **c,** The carbon tax revenue by regions under six carbon taxation scenarios. The percentages show the ratio of carbon tax revenue to GDP. *Supplementary Table S6* shows the tax revenue in each country. **d,** The ratio of the carbon tax to expenditure by expenditure deciles. People have the same tax burden under global uniform production tax scenarios and global uniform consumption scenarios.

Fig. 1a shows the tax level under the nation-differentiated production and consumption tax. In both scenarios, low and middle-income countries have low carbon tax levels, and high-income countries have high carbon tax levels to keep the global average carbon tax level at US$50/t$CO_2$. Under the production tax scenario, the tax levels for low-income, lower-middle-income, upper-middle-income, and high-income countries are US$1.98/t$CO_2$, US$5.40/tCO_2, US$20.78/t$CO_2$, and US$100.46/tCO_2, respectively. Under the consumption tax scenario, the tax levels for these four types of countries are US$2.16/t$CO_2$, US$5.51/tCO_2, US$15.33/t$CO_2$, and US$98.56/tCO_2, respectively.

For the luxury consumption tax, the relationship between sectoral expenditure elasticity and the sectoral tax level is shown in *Fig. 1b.* Sectors with expenditure elasticity above one will be taxed at rates higher than the average. Under an average tax level of US$50/t$CO_2$, air transport, motor vehicles and parts, accommodation, food, and service activities will be taxed at US$91/t$CO_2$, US$90/tCO_2, and US$62/t$CO_2$, respectively. In contrast, sectors with lower expenditure elasticity will be taxed at lower levels, mainly including basic energy and food expenses.

Comparing the tax revenue across different taxation methods, low and middle-income countries can gather higher tax revenue under the scenarios with a globally uniform tax, including the global uniform production/consumption tax (T1 & T3) and the luxury consumption tax (T5) (*Fig. 1c*). Taking China as an example, since the tax level setting for China under the nation-differentiated production tax (T2) is much lower than the global uniform production tax (T1), the tax revenue from a globally uniform production tax (T1) is 1.4 times higher than that from a nation-differentiated production tax (T2). In addition, the tax revenue under the global uniform consumption tax scenario (T3) and the luxury consumption tax scenario (T5) will be the same because countries have same tax level in both scenarios, as does the tax revenue under the nation-differentiated consumption tax scenario (T4) and the luxury & nation-differentiated consumption tax (T6).

The uneven tax burden among expenditure groups under each tax scenario is presented in *Fig. 1d*. The carbon tax tends to be progressive in low- and middle-income countries/regions and regressive in high-income countries/regions. For example, under the global uniform production/consumption tax (T1 & T3), in Sub-Saharan Africa, the tax incidence for the top 10% is 70% higher than that for the bottom 10%, while in the United States, the tax incidence for the bottom 10% is 30% higher than that for the top 10%. This is in line with the finding of Dorband et al.[13], Feindt et al.[14], and Oswald et al.[17]. The reason is that rich individuals in low and middle-income countries and poor individuals in high-income countries tend to consume proportionally more carbon-intensive goods.

Designing a luxury consumption tax can effectively reduce the burden on the poor. In *Fig. 1d*, the yellow dots (T5) for low-income groups are lower than the green dots (T1 & T3) in all countries and regions. In East Asia and Developing Pacific, Southern Asia, and India, the luxury tax can even convert a regressive carbon tax into a progressive one.

Tax revenue recycling mechanisms

Carbon tax revenues can be recycled at two levels, nationally or internationally. In this paper, domestic recycling mechanisms are implemented through social assistance programs, and international recycling mechanisms are implemented through a global climate fund (*Extended Data Table 2*).

We consider five social assistance-based internal tax revenue recycling mechanisms, including a universal transfer scenario (S1), a scenario based on current cash transfer programs (S2), a scenario based on current social assistance programs (S3), a scenario based on an expansion of social assistance based on the experience of the COVID-19 pandemic (S4), and a hypothetical ideal scenario based on proxy means test (PMT) (S5). The universal scenario (S1) is usually also referred to as a "climate dividend". All citizens will get the same benefit from tax revenue recycling. This is similar to the experience in Switzerland and Canada, as well as many current proposals. In the current cash transfer programs scenario (S2), the beneficiaries are the population currently enrolled in targeted cash transfer programs, usually low-income people. The revenue will only be redistributed to a small number of people and should go to those who need it the most. However, in many countries, these programs suffer from very high exclusion errors, meaning many people in poverty are not reached. This is particularly evident in the Sub-Saharan African countries (see *Fig. 2a*). This scenario gives a lower bound of the redistributive capacity of countries as it considers just cash-based programs. The current social assistance scenario (S3), conversely, considers all social assistance programs with a higher coverage rate, especially among the poorest. The social assistance during the COVID-19 scenario (S4) is based on the expansion of social assistance during the COVID-19 pandemic, with a significantly higher coverage rate. Lastly, we also consider a hypothetical PMT scenario (S5) which uses the PMT method to determine the targeted population. PMT is the most common way of targeting vulnerable people and is used here as a reference scenario of a well-executed and progressive targeting mechanism, nonetheless still presenting exclusion errors.

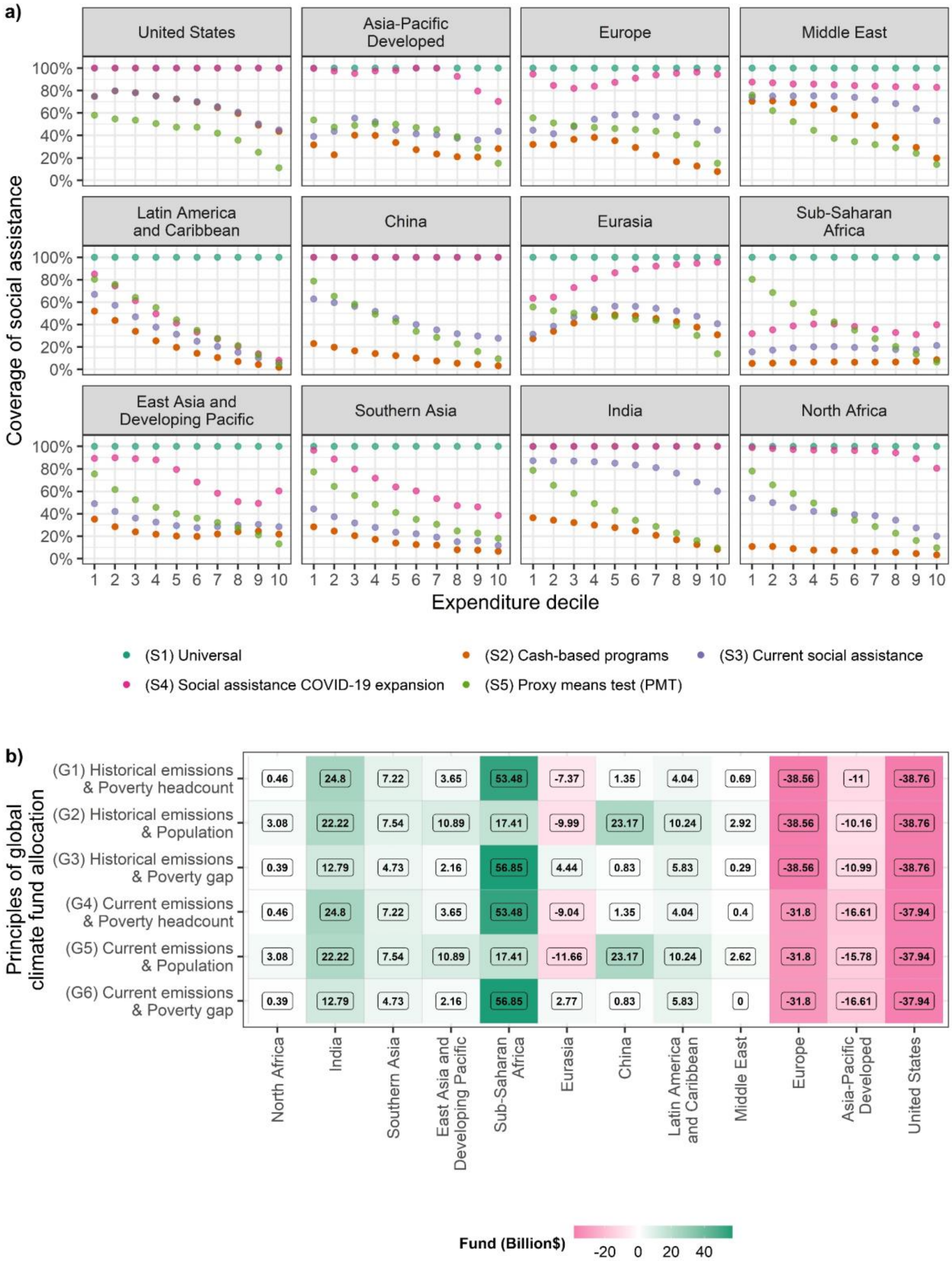

Fig. 2 | Revenue recycling mechanisms. a, The coverage rate of social assistance by expenditure deciles under five social assistance scenarios. The coverage rate is the share of the population registered in social assistance programs. **b,** The flow of funds under six global climate fund scenarios. In all scenarios, a fund for US$100 billion is gathered in developed countries and redistributed to developing countries. When talking about the climate fund, we use the developing vs developed countries categorisation (and not income groups) following the UNFCCC groupings and names. See *Supplementary Table S7* for the fund distribution between countries.

Regarding feasibility, the current cash transfer (S2) and social assistance (S3) scenarios would be the easiest to implement; they rely on existing programs and would require channelling new resources into existing architectures. Similarly, the COVID-19 scenario (S4) is a scenario that models a feasible expansion as it is based on the extended coverage achieved in response to the COVID-19 pandemic. On the other hand, the universal scenario (S1), while mostly feasible in richer countries, is more difficult in lower-income countries, where it is difficult to reach the most vulnerable. Similarly, the PMT scenario (S5) is considered an ideal benchmark.

For international revenue recycling, we consider six scenarios distinguished by various principles for collecting and redistributing the global climate fund. In all scenarios, the fund will be collected from developed countries and then redistributed to developing countries. This reflects the "common but differentiated responsibilities and respective capabilities" principle from the Rio Declaration on Environment and Development (and restated in the Paris Agreement). As there are no clear rules on how to implement and respect this principle, different interpretations are used, including burden sharing based on historical and current responsibility, capability, and equality[38]. Among these, we choose our two principles for collecting funds to be based on historical carbon emissions since 1850 or the current carbon emissions, which corresponds to the debate between historical and current responsibility[39]. Moreover, we select three principles for redistributing the fund, based on the number of people in poverty, population, or poverty gap. The poverty headcount and poverty gap are measured under the extreme poverty line ($2.15 per person per day based on 2017 PPPs) proposed by the World Bank[40]. Here, the poverty gap is defined as the fund needed to lift people out of extreme poverty. It is difficult to know in advance which redistribution approach will have better poverty reduction effects, which depends on whether countries' social assistance systems are effectively targeted to the poor.

We explore the impact of implementing a global climate fund of US$100 billion per year, which is the amount of fund developed countries committed in the 15th Conference of Parties (COP15) of the UNFCCC to support climate action in developing countries[41]. *Fig. 2b* demonstrates the regional distribution of fund contributors and receivers under the six global climate fund scenarios. In all scenarios, the United States, Asia-Pacific Developed countries, and European countries are the main contributors to the fund, while Sub-Saharan African countries and India are the main recipients of the fund. Because of the high poverty rates, Sub-Saharan African countries will receive more funds under the poverty headcount and poverty gap principles than under the population principle. In contrast, China, which has a large population but a low poverty rate, will receive more funds under the population-based distribution mechanism rather than the other two poverty-based distribution mechanisms.

The best domestic policy mix

In this section, we examine the poverty, inequality, and emission effect of all combinations of tax and social assistance scenarios to determine the best domestic policy mix (*Fig. 3*). In addition to the five social assistance scenarios mentioned above, we also consider a no-recycling scenario to show what would happen if without recycling and a universal transfer scenario with only 30% of revenue redistributed to test the impacts of partially recycling.

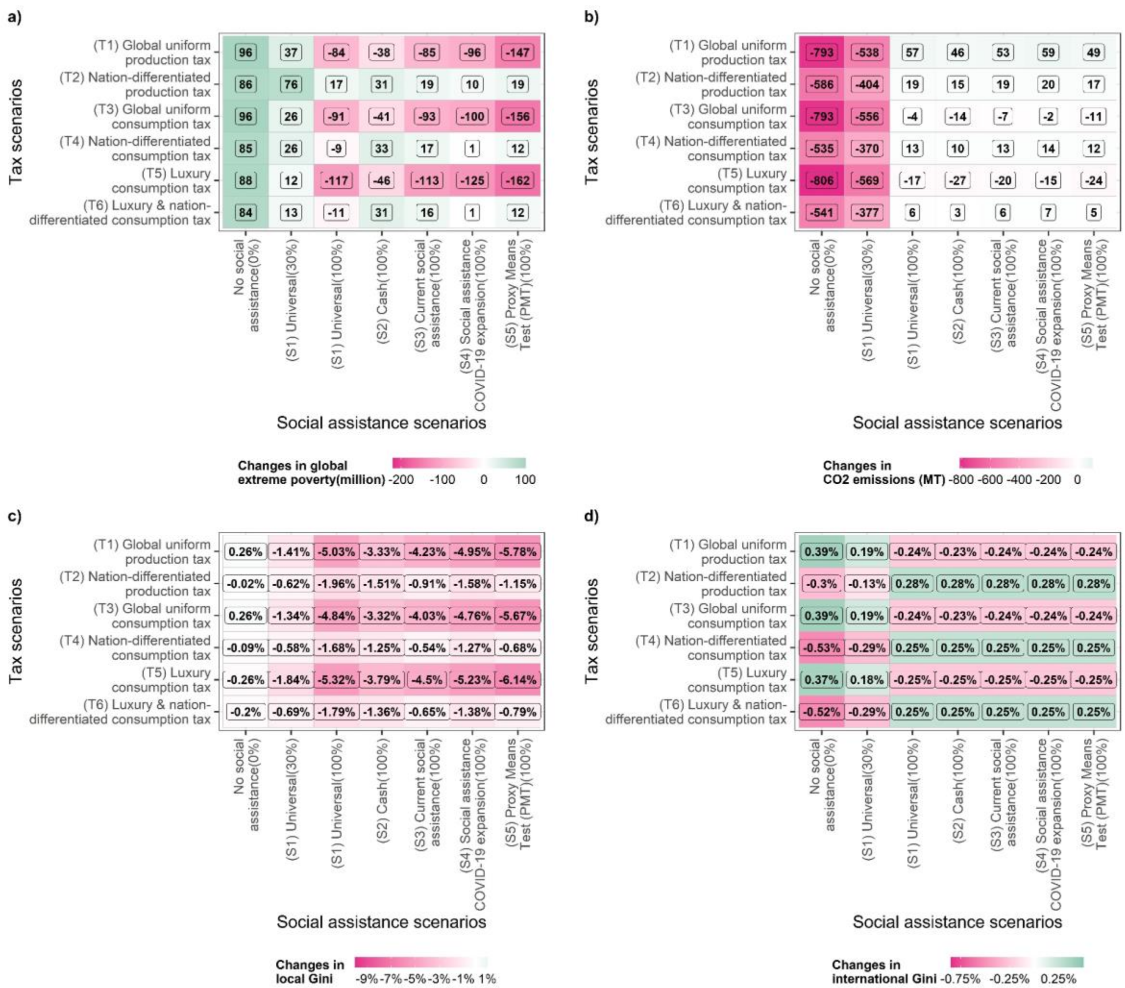

Fig. 3 | The poverty, emission, and inequality effect of combinations of various carbon taxation and social assistance scenarios. Here, poverty is measured by the extreme poverty headcount. The emission effects only come from the consumption adjustment caused by carbon taxation and revenue recycling. Inequality effects are measured by the change rate of Gini coefficient. All values shown in the figure are based on the comparison to the pre-tax status. The percentage in the horizontal axis indicates the share of tax revenue redistributed. **a,** effects on global extreme poverty. **b,** effects on global carbon emissions. **c,** effects on the local Gini coefficient. The local Gini coefficient reflects the inequality between expenditure bins within the country and is the weighted mean (use the population as the weight) of the countries' Gini coefficient. **d,** effects on the international Gini coefficient. The international Gini coefficient is calculated as the Gini coefficient based on the mean expenditure in each country, reflecting the inequality between countries.

Without revenue recycling, the carbon tax can push 84-96 million people into extreme poverty, depending on the tax scenarios. The number of people pushed into poverty in the luxury consumption tax scenario (T5) is 8 million lower than in the global uniform consumption tax scenario (T3). Recycling carbon tax revenues can effectively mitigate the poverty-increasing effects of carbon taxes. For example, in most tax scenarios, recycling 30% of the tax revenue through a universal dividend could largely offset the poverty headcount caused by carbon taxation, which is similar to the findings of Vogt-Schilb et al.[22].

For the impact of 100% revenue recycling, among the combinations of six tax scenarios and four feasible social assistance scenarios (S1-S4), the worst choice is the nation-differentiated consumption tax (T4) combined with the current cash programs scenarios (S2), which will push 33 million people into extreme poverty compared with the pre-tax status; this is because of the high exclusion errors of cash transfers and the low revenues of such tax design in poorer countries. The best choice is the luxury consumption tax (T5) combined with expanded social assistance as in the COVID-19 pandemic (S4), which will bring 125 million people out of poverty after offsetting the negative poverty effect caused by carbon taxation. However, the poverty reduction effect of the best feasible solution (luxury consumption tax + social assistance during COVID-19) is 37 million lower than the scenario simulating a perfectly executed PMT (S5), which means that the current social assistance system has enormous space for improvement. What should be noted is at the national level, the best internal revenue recycling mechanism would vary between countries (see *Extended Data Fig. 2*). Social assistance during COVID-19 (S4) is the best option for 73 out of 168 countries. A universal dividend (S1) is the best option for more countries, accounting for 84 out of 168 countries, particularly in most Sub-Saharan African countries where the social assistance programs cannot reach the poor population effectively. Also, there are 26 countries with multiple best options.

An interesting phenomenon is that without the recycling mechanism, the global uniform tax is worse than the nation-differentiated tax in terms of the poverty effect. For example, the population in poverty caused by the nation-differentiated production tax (T2) is 10 million lower than the global uniform production tax (T1). However, after recycling, the global uniform tax is always better than the nation-differentiated tax. The reason is that the global poverty population is mainly located in low and middle-income countries. In these countries, the global uniform tax can generate more tax revenue than the nation-differentiated tax, which means the governments have more financial capacity to support the poor.

In terms of the carbon emission effect, when a carbon tax is implemented without recycling, a higher price tends to lower the real income of households and thus suppress demand, resulting in significant emission reductions. The luxury consumption tax (T5) has the greatest impact on reducing carbon emissions because it applies a very high tax level to price-sensitive carbon-intensive products[17]. However, recycling the carbon tax revenue would cancel out the tax's emissions reductions. The reason is that when a carbon tax is combined with a revenue recycling mechanism, it acts more like an indirect income redistribution policy, transferring money from the rich to the poor. As highlighted by previous research[8,31], eradicating poverty would increase the required mitigation efforts, even if just minimally, for meeting global climate goals. However, it is important to note that the near-zero emissions impacts observed in this paper only consider the changes in carbon emissions caused by consumption adjustments through estimated elasticities. In fact, the carbon tax will also incentivise producers to develop green technologies, thereby reducing emissions, which is, in the long run, the principal goal of any carbon pricing mechanism. Accordingly, this paper does not address the appropriate carbon tax rate to achieve the global climate goal. Here, our goal is to show how revenue recycling can hinder efforts to reduce emissions in the short term and highlight the tension between poverty/inequality reduction and climate mitigation. We, therefore, execute an incidence analysis looking at the short term, which in terms of poverty and inequality is what affects the most social acceptability of carbon pricing.

In terms of the impacts on inequality within countries, without the revenue recycling, the global uniform production/consumption tax scenarios (T1 & T3) will bring slight adverse impacts on the average Gini coefficient (+0.26% & +0.26%, measured as a percentage change of population-weighted national Gini coefficients), meaning an increasing inequality, while other scenarios will cause slight positive impacts (ranging from -0.02% to -0.26%). Recycling the revenue can bring remarkable positive impacts on inequality within countries (ranging from -0.54% to -5.78%). The best feasible combination is the luxury consumption tax (T5) with the universal climate dividend (S1), which can lower the local Gini coefficient by 5.32% on average across countries. The luxury consumption tax (T5) combined with the COVID-19 social assistance expansion (S4), the best solution for the poverty effect, is the second-best choice regarding inequality. Similarly, the hypothetical ideal social assistance scenario (S5) can bring more inequality reduction.

For the impacts on international inequality, without the revenue recycling, since the global uniform tax will bring greater shock to the household in low and middle-income countries, the global uniform tax scenarios (T1, T3 & T5) will worsen the inequality between countries. In contrast, the nation-differentiated tax scenarios (T2, T4 & T6) will improve it. Nevertheless, this situation is offset by revenue recycling, and overall the impacts remain marginal.

Poverty eradication is the first of the SDGs; and is also a prerequisite for guaranteeing people's basic physiological needs, including ending hunger (SDG 2). Also, physiological needs are a foundational aspect of maintaining human well-being and social stability. With this in mind, we consider the scenario with the largest poverty reduction effect to be "the best" domestic policy mix: the luxury consumption tax (T5) combined with social assistance during COVID-19 (S4).

The best international recycling mechanism

Having found the best domestic policy mix, we further test the impacts of international revenue recycling mechanisms (*Table 1*).

Table 1 | The poverty, emission, and inequality effect of international tax revenue recycling.

	(T5) Luxury consumption tax + (S4) Social assistance expansion as during COVID-19				**(T5) Luxury consumption tax + (S5) Proxy Means Test (PMT)**			
	Extreme poverty (million)	CO_2 (MT)	Local Gini	International Gini	Extreme poverty (million)	CO_2 (MT)	Local Gini	International Gini
(G1) Historical emissions & poverty headcount	-238	22	-5.81%	-0.79%	-336	11	-8.50%	-0.79%
(G2) Historical emissions & population	-176	29	-6.04%	-0.53%	-214	19	-7.62%	-0.53%
(G3) Historical emissions & poverty gap	-210	42	-5.54%	-0.77%	-336	31	-8.07%	-0.77%
(G4) Current emissions & poverty headcount	-238	22	-5.81%	-0.79%	-336	10	-8.50%	-0.79%
(G5) Current emissions & population	-176	29	-6.04%	-0.53%	-214	18	-7.62%	-0.53%
(G6) Current emissions & poverty gap	-210	41	-5.54%	-0.78%	-336	30	-8.07%	-0.78%

Here, the effects of international tax revenue recycling scenarios are simulated on the basis of both the best and ideal domestic policy mix. The poverty effect is the changes in global extreme poverty headcount compared to pre-tax status. The emission effect is the changes in global carbon emissions caused by the consumption adjustment. The local Gini effects measure the change rates of inequality within countries. At the regional level, the local Gini coefficient is the weighted mean (use the population as the weight) of countries' Gini coefficient. The international Gini effects measure the change rates of inequality between countries. The international Gini coefficient is calculated as the unweighted Gini coefficient based on the mean expenditure in each country.

For the collection of the fund, the historical and current emission principles have similar effects on poverty, emissions, and inequality. For the redistribution of the fund, allocating the fund by poverty headcount (G1 & G4) has the biggest poverty reduction effect, lifting 238 million people out of extreme poverty. Compared with the best purely domestic policy mix (luxury consumption tax (T5) + social assistance during the COVID-19 pandemic (S4)), a US$100 billion per year global climate fund can further reduce global extreme poverty headcount by 113 million. However, compared with the combination with the best targeted domestic policy (luxury consumption tax (T5) + PMT (S5)), there is a difference of 98 million people but since this policy is likely not executable in the near-term, international revenue recycling grants large additional benefit compared to purely domestic strategies.

Comparing the results in *Table 1* and *Fig. 3*, the climate fund will slightly increase global carbon emissions because more demand will shift from developed to developing countries, where carbon intensity is higher than that in developed countries[42]. Also, under the best combination (T5 + S4 + G1/G4), globally, the local and international Gini coefficients will decrease by 5.81% and 0.79%, respectively, which is more significant than the best domestic policy mix (T5 + S4).

Further, *Fig. 4* shows the regional poverty and inequality outcome of the best policy mix judged by the poverty reduction effect (luxury consumption tax (T5) + social assistance during the COVID-19 pandemic (S4) + historical/current emissions & poverty headcount (G1 & G4)).

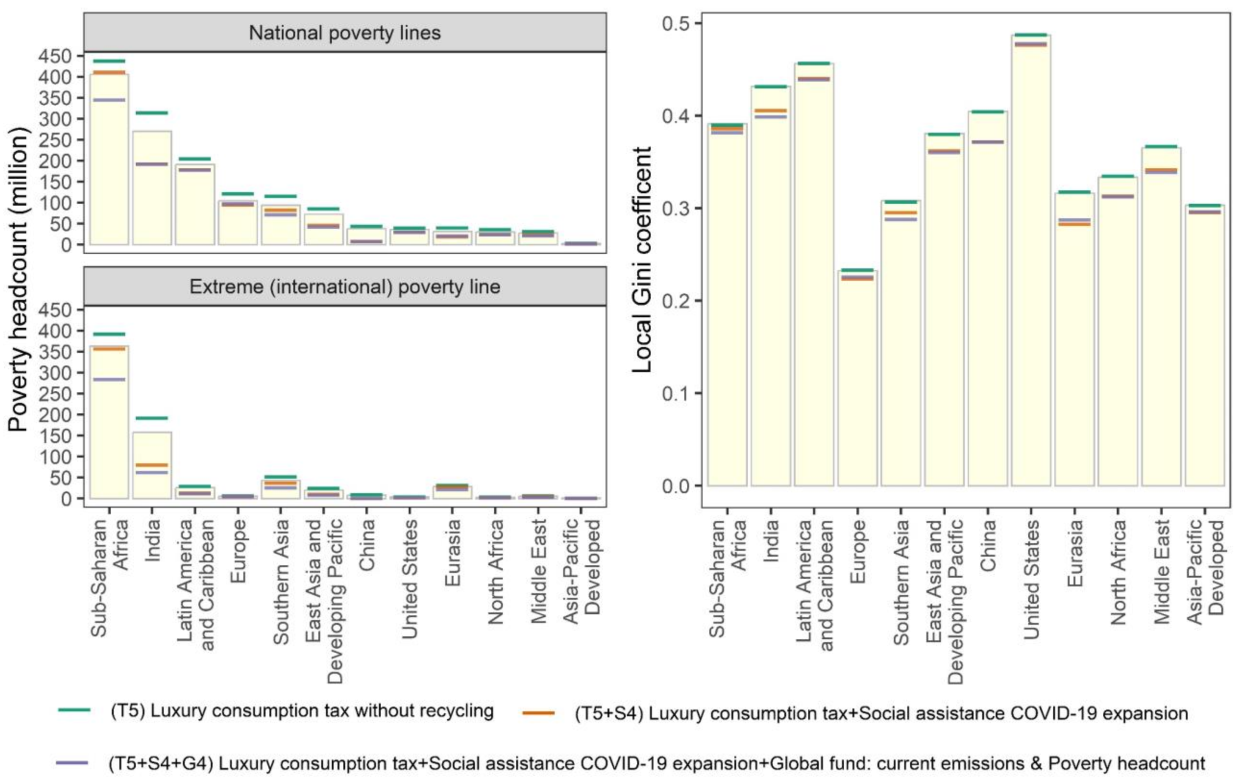

Fig. 4 | The regional poverty and inequality outcome under the best policy mix (T5 + S4 + G4). The left panel shows the poverty headcount at the regional level. The poverty headcount is considered both under the national and the national (extreme) poverty lines. The yellow bar in the background shows the poverty headcount/Gini coefficient in the pre-tax status. The right panel shows the within-countries inequality measured by the local Gini coefficient. The local Gini coefficient for a region is the weighted mean (use the population as the weight) of the national Gini coefficient. *Extended Data Fig. 3-5* shows the results at the national level.

For estimating the effect of poverty, in previous sections, we only consider international (extreme) poverty, which refers to severe poverty where people cannot meet their basic survival needs. International poverty is often the target of international poverty reduction efforts. Here, we also consider the national poverty lines. National poverty lines differ by country and depend on national considerations of poverty, which is important in policymaking at the national level. Under the best policy mix, some countries/regions would witness a considerable decline in their poverty headcount. Like the case in China, the best policy mix would decrease the poverty headcount under the national poverty line by 79% (from 38 million to 8 million). Also, the poverty headcount under the international poverty line would decrease by 90% (from 8 million to 0.8 million). The largest poverty headcount reduction would happen in India and Sub-Saharan Africa. Under the best policy mix, the poverty headcount of India and Sub-Saharan Africa would decrease by respectively 79 and 60 million under the national poverty line and 95 and 79 million under the international poverty line.

All regions will witness a significant decrease in the Gini coefficient. The effects are highest in China. Compared to the pre-tax status, China's Gini coefficient would decrease by 9% (from 0.40 to 0.37) (*Fig. 4*). The reason is that China is the world's largest emitter, China can gather US$356 billion revenue for redistribution under the luxury consumption tax scenario (3% of its GDP, see *Fig 1c*). Meanwhile, China's social assistance system can target low-income households effectively (see *Fig 2a*).

Finally, we further test the poverty reduction potential of different levels of the global climate fund (*Fig. 5*). The global climate fund exhibits diminishing returns. In other words, its marginal poverty reduction effect decreases. Without the global climate fund, the best domestic policy mix can achieve a 19% reduction in global extreme poverty headcount. A US$100 billion fund achieves a 36% reduction, while the extreme poverty reduction will stop at about 56% for funds over US$700 billion. This is mainly because even if a larger fund is pooled, the internal recycling mechanisms (social assistance) within the countries cannot effectively reach 44% of the population living in extreme poverty.

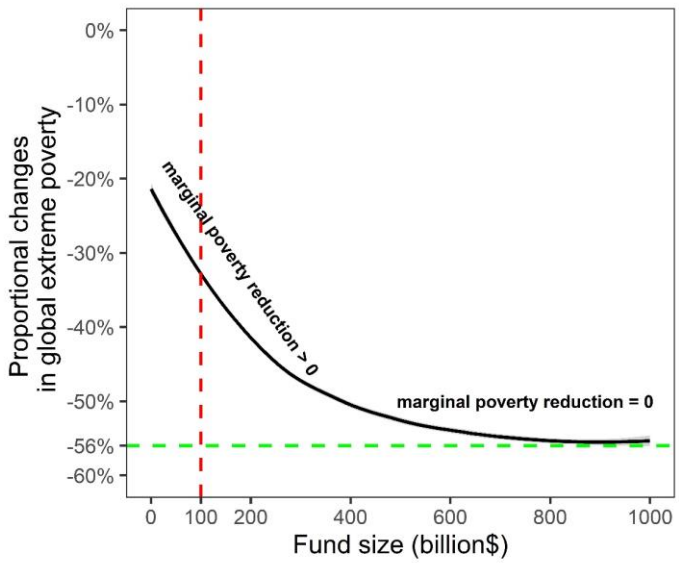

Fig. 5 | The relationship between the size of the global climate fund and poverty reduction. The marginal poverty reduction means the extra poverty reduction induced by unit additional fund. The horizontal green dash line denotes that the marginal poverty reduction effect is equal to 0. The vertical red dash line denotes the effect of a US$100 billion fund.

Discussion and policy implications

The debate on just transitions highlighted the challenges in coordinating climate actions (SDG 13), poverty eradication (SDG 1), and inequality reduction (SDG 10). Designing a carbon tax combined with a revenue recycling mechanism has long been considered to be an effective path out of this dilemma. However, prior to this study, the design of carbon tax mechanisms and their revenue allocation remained largely unexplored at a global scale. Our results suggest that, globally, the best domestic policy mix is implementing a carbon-based luxury consumption tax and recycling tax revenue through expanded social assistance programs as during the COVID-19 pandemic. At a global average tax level of US50$/t$CO_2$, the best combination can lift 125 million people out of extreme poverty. Meanwhile, inequality between the within and between countries will decrease by 5.23% and 0.25%, respectively. For the global climate fund's design, the best way of redistributing the fund to developing countries is based on their poverty headcount. Combining the best domestic policy mix with a US$100 billion global climate fund, the global extreme poverty headcount can be further reduced by 113 million. However, using carbon tax revenue to combat poverty and inequality will withdraw some of the emission reduction effects of carbon taxation, necessitating additional mitigation efforts in other areas.

Based on our results, there exist several systemic solutions for the trade-off between climate and social goals.

First, recycling carbon tax revenue can leverage social and political acceptability toward carbon pricing. Without recycling, a global average US$50/$tCO_2$ tax would push 84-96 million people into extreme poverty, depending on the taxation method. In high-income countries, the poor population will suffer more than the rich, and thus the carbon tax worsens inequality. These adverse effects are the main barriers to implementing carbon tax policies. Framing carbon taxation as a combined climate and social policy might be a decisive step toward acceptability. Essentially, a carbon tax combined with revenue recycling transfers income from the rich to the poor, and this, therefore also always a redistribution policy. Compared to other climate policies, such as emissions regulatory instruments, carbon tax policies augment the government's ability not only to regulate the climate but also to tackle income inequalities and assist the most vulnerable households.

Second, implementing a carbon-based luxury consumption tax versus a flat tax can improve the initial distributive impacts of carbon taxation. The carbon-based luxury consumption tax exerts higher tax rates on luxury goods and keeps the tax rates for necessities relatively low so that it can relieve the pressure on low-income people to some extent from the outset. However, we need to acknowledge that there are substantial technical challenges. Implementing a consumption tax relies on the carbon footprint assessment of products under an internationally comparable, systematic, and transparent carbon accounting standard. Fortunately, the CBAM proposed by the European Union has provided an excellent pioneering example of applying a tax based on products' carbon footprint. Also, numerous research has made significant progress in the methodologies of carbon footprint accounting[43], and carbon labelling is more and more widespread in business practice[44]. Moreover, measuring expenditure elasticity for a myriad of products also suffers from data constraints. Implementing a global uniform production tax will be a sub-optimal choice if the luxury consumption tax is not feasible. When combined with a revenue recycling mechanism, a global uniform production tax could still lead to appealing poverty and inequality reduction, although less potent than a luxury tax.

Third, improving social assistance systems in low- and middle-income countries is urgently needed. Even though the expansion of social assistance during the COVID-19 pandemic has (temporarily) increased the coverage of the poor and improved the poverty reduction effect of redistributing carbon tax revenue through social assistance systems, it is not enough. The social assistance, and social protection programs as a whole, still do not cover about 44% of the global extreme poor. Especially in the Sub-Saharan Africa region, where extreme poverty is prevalent, the low coverage rate of social assistance limits the potential of using carbon tax revenue to address poverty. Thus, low- and middle-income countries still have a long way to go in reforming their social assistance systems. In this regard, China has set an example. The social assistance system in China, which is improved under the Targeted Poverty Alleviation Strategies, can effectively cover low-income groups[45]. In addition, also at the international level, including the G7 and the UN Secretary-General's initiative for a "Global Accelerator on Jobs and Social Protection for Just Transition", underline the need for universal social protection.

Fourth, setting up another complementary global climate fund can bring massive poverty reduction effects. Some countries, especially in Sub-Saharan Africa, can only raise limited carbon tax revenue from their low emissions. Without global aid, carbon taxation and domestic revenue recycling have limited effects on poverty reduction. In addition to directly assisting them in reducing poverty, international aid can be used to incentivise these countries to improve their social assistance systems, thereby releasing the fund's poverty-reduction potential. For example, setting the reform of the fiscal system as a prerequisite for aid disbursement. However, we must be aware that setting another US$100 million would face some international political barriers. In the past, even though the developed countries have committed at the COP15 and reiterated at the COP21 to collect US$100 billion per year by 2025 to address the need of developing countries, the available fund is still much lower than the commitment[46]. Yet, we should remain optimistic. At COP27, countries achieved a historic new deal on creating a "loss and damage fund" to compensate vulnerable countries suffering from climate impacts[47], which is seen as an important success for the global climate justice movement.

One important point is to put the global fund into perspective; this amount (US$100 million) in fact is small compared to the level of other financial flows regarding lower-income countries. It has been estimated that around US$2 trillion leave the global south for the global north (net of inflows), comprising debt payments and, for the majority, capital flight and illicit flows[48]. Trade misinvoicing was, for example, close to US$1 trillion in 2017. A similar amount (US$2 trillion) has been estimated using the concept of unequal exchange[49]; and it is also the amount that low and middle-income countries (excluding China) need annually to mitigate and address the effects of climate change[50]. Therefore, global structural reforms could provide much more needed finance for poverty and inequality reduction in lower-income countries. The recent minimum global tax agreement can be a good starting point, but it is also critical to address the debt of low and middle-income countries that are nearing US$9 trillion.

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Methods

Environmental-extended multiregional input-output model

The environmentally extended multiregional input-output model (EEMRIO) is the most popular approach for country-sector level carbon footprint accounting[8,51,52], which is also widely used in analysing other environmental impacts of consumption and trade[53–57]. The advantage of the EEMRIO approach is that it can trace the carbon emissions that emerge in the whole supply chain by the Leontief inverse matrix. This paper uses the EEMRIO approach to measure the carbon footprint of final products produced in each country. Later, the carbon footprints by sectors would be used to calculate household carbon tax burden and consumption-based emissions for countries/regions.

Suppose there are g countries, and each country/region has n sectors. The basic formula for sectoral carbon footprint (c) accounting under the MRIO framework can be written as follows:

$$c = f(I - A)^{-1} + d \tag{1}$$

Here, A is the direct requirement coefficient matrix ($gn \times gn$), representing the production technologies in each sector of each country/region. For example, the element A_{rs}^{ij} is the amount of intermediate input in sector i of country r required by producing 1$ final goods in sector j of country s. Setting I as an identity matrix ($gn \times gn$), $(I - A)^{-1}$ is the complete requirement coefficient matrix ($gn \times gn$), also known as the Leontief inverse matrix. Essentially, the Leontief inverse matrix is the accumulated sum of all direct and indirect intersectoral linkages (equal to $I + A + A^2 + A^3 + \cdots$). f is the sectoral emission coefficient vector ($gn \times 1$), which is the carbon emissions emitted from producing 1$ products in each sector. d is the sectoral household direct emission vector ($gn \times 1$), reflecting the carbon emissions from the final consumption of products, such as gas and coal used by residents.

The data we employed for carbon footprint accounting is the latest global MRIO table for 2017 and the associated carbon emissions satellite account developed by the Global Trade Analysis Project (GTAP-v11)[30,58,59]. GTAP-v11 contains information for 65 sectors and 141 regions, including 121 individual countries and 20 aggregated regions (see *Supplementary Table S2* for sectoral classification in GTAP-v11), and has been used in several publications[32,60–63].

Household expenditure data

The discussion of unequal carbon tax burden between income groups relies on the information on household expenditure. The household expenditure dataset used in this paper is primarily based on the global expenditure survey from the World Bank Global Consumption Database (WBGCD), supplemented by the Household Budget Survey (HBS) for European countries provided by Eurostat and the Family Income and Expenditure Survey (FIES) for Japan provided by Statistics Bureau of Japan. The WBGCD provides expenditure data for 33 sectors for 201 expenditure bins in 113 countries. Our previous studies have derived a unified dataset for the share of consumption in each sector and the population by expenditure bins[31,32,64]. The HBS provides expenditure data for 12 sectors for 5 quintiles in 32 European countries, and the FIES provides data expenditure data for 23 sectors for 10 deciles in Japan.

The reference year for WBGCD, HBS, and FIES is 2011, 2015, and 2017 respectively, while the GTAP MRIO table derived from GTAP-v11 is for 2017. To coordinate the data from different sources, first, following Bruckner et al.[31], we construct a bridging matrix that links the 33 sectors in WBGCD to the 65 sectors in GTAP MRIO table based on the sector definition (one sector in WBGCD would match several sectors in GTAP MRIO table). Then, we use the bridging matrix to get the share of consumption in each sector by expenditure bins for 65 sectors in GTAP MRIO table. Further, considering WBGCD has the broadest geographical coverage, we take the consumption share of each sector by expenditure bins in WBGCD as the basis and update them by HBS and FIES. Consequently, the new expenditure dataset covers 65 sectors, 201 bins, and 119 countries. Finally, we take the share of consumption in each sector by expenditure bins to disaggregate the national-level household consumption in GTAP MRIO table. Since we only use the consumption share information from the household expenditure survey data, we do not need to deal with the price differences. Also, the total household expenditure in each country would be in line with household consumption in the GTAP MRIO table. Furthermore, we update the population data for 2011 in the WBGCD dataset to 2017 based on the population statistics from World Development Indicators, World Bank. The population distribution between expenditure bins remains the same as the original dataset.

The carbon footprint per capita for the s^{th} expenditure bin in country *r* can be obtained by multiplying the expenditure per capita of the s^{th} expenditure bin in country *r* and the carbon footprint by sectors.

$$CF_r^s = c' h_r^s / p_r^s \quad (2)$$

where c' $(1 \times gn)$ is the carbon footprint by sectors obtained from formula (1), h_r^s is the expenditure vector of the s^{th} expenditure bin $(gn \times 1)$, which is the disaggregated household consumption in the GTAP MRIO table. p_r^s is the population of the s^{th} expenditure bin in country *r*. The results from formula (2) will be used to calculate the carbon tax burden for various expenditure bins in each country.

National and international poverty lines

The poverty headcount ratio at national poverty lines reported by the Poverty and Inequality Platform, World Bank is the most accurate poverty statistic at the national level. It serves as the foundation for drawing national and international poverty lines. Experts from World Bank estimated the national and international poverty lines in 2017 PPP$[40]. The international poverty line was recently updated to $2.15 per day. The national poverty line varies by country, depending on the country's specific situation.

However, the national/international poverty lines in Jolliffe & Prydz[40] are not comparable with the household consumption in the GTAP. The national poverty lines in Jolliffe & Prydz[40] are constructed based on household and consumer survey data, while the household consumption in the GTAP MRIO table is based on the macro statistic data. Even though they have similar terminology, they have different scopes. For example, the expenditure on real estate is a part of consumption in consumption survey data. However, it belongs to the household investment in the System of National Accounts (SNA), which is used in GTAP. Thus, directly using the national/international poverty lines in Jolliffe & Prydz[40] would bring bias for counting the poverty population. In addition, there is the issue of underreporting in household surveys.

Given that poverty is the central concern of this paper, we need to ensure that our poverty headcount and poverty ratio data align with the World Bank data. So, in this paper, whether the population in a bin is under the international/national poverty line is decided by the population distribution across bins and the poverty headcount ratio at national/international poverty lines (%

of population). This way, the baseline national/international poverty headcount ratios in this paper will be the same as that reported by World Bank. The World Bank has reported the poverty headcount ratios under national/international poverty lines for 168 countries. For most countries, data is available for 2017. For countries with missing data, we use data from the nearest year, which is also the treatment in Jolliffe & Prydz[40].

Data integration

There are 168 countries in the poverty data, 121 in the GTAP MRIO table, and 119 in the expenditure data. We tried to make the most of the available data to extend the analysis to the 168 countries with poverty statistics because the countries missing from the expenditure data and the GTAP MRIO table are mainly small, less developed countries with high poverty rates.

For countries aggregated into regions in the GTAP MRIO table, we disaggregate them from the aggregated regions. The final demand by sectors for a missing country is derived from the share of its GDP in the region and the region's final demand. Similarly, the carbon emissions by sectors for a missing country are derived from the share of its carbon emission share in the region and the region's total carbon emissions. The national-level GDP and carbon emissions data are obtained from the World Development Indicators, World Bank.

For countries missing from the expenditure data, we use the expenditure distribution in the neighbouring country with the same development level (low-income, lower middle-income, upper middle-income, and high-income) as a proxy to get the expenditure distribution between bins. Meanwhile, the total expenditure is consistent with the statistics in the GTAP MRIO table. For countries that do not have a similar neighbouring country, we use the expenditure distribution in China and the United Kingdom as the proxy for developing countries and developed countries, respectively.

Finally, our research covers 168 countries (*Supplementary Table S1*), which account for 98% of the global population and 97% of the global GDP.

The measurement of inequality

The Gini index is employed to measure inequality within and between countries[17,52,64–66]. We use the expenditure data to measure inequality; compared to using income, inequality estimates using expenditure/consumption are lower as part of income is saved and expenditure/consumption represents the expected long-term average income ("permanent income" hypothesis). We named the Gini index calculated based on the expenditure distribution among 201 expenditure bins as the local Gini index, reflecting the inequality within countries. In contrast, the inequality between countries, named the international Gini index, is calculated based on the expenditure per capita of 168 countries.

The formula for the Gini index is

$$Gini = \left(\frac{G}{G-1}\right)\left(1 - 2\sum_{s=1}^{G} E^s p^s\right) \quad (3)$$

Here, G is the number of groups (expenditure bins in the local Gini index, countries in the international Gini index). E^s is the cumulative expenditure share of group *s*, is the population share of group *s*. What should be noted is that when calculating the international Gini index, each country is considered a person whose expenditure level is the national average. $G/(G-1)$ is used to correct the small sample bias.

Carbon taxation scenarios

Based on industry and policy experience, the literature reviewed, and consideration of the respective strengths and limitations of these information sources, the High-Level Commission on Carbon Prices from the World Bank concluded that the explicit carbon price level consistent with achieving the Paris temperature target is at least US\$50-100/tCO_2 by 2030[33]. The main text shows the results based on a global average carbon tax level of US\$50/tCO_2. In *Extended Data Fig. 6*, we also simulate the poverty and inequality impacts of the other three tax levels, US\$25/tCO_2, US\$75/tCO_2, and US\$100/tCO_2. It should be noted that the question about the appropriate tax level for achieving specific climate goals is out of the scope of this paper. Instead, our key concern is identifying the best policy design for combining carbon taxation and revenue recycling.

We have six carbon taxation scenarios (*Extended Data Table 1*), including global uniform production tax, nation-differentiated production tax, global uniform consumption tax, nation-differentiated consumption tax, luxury consumption tax, and nation-differentiated luxury consumption tax. The global uniform production/consumption tax is straightforward and applies the same tax to all carbon emissions. Here, we further explain how to design the nation-differentiated production/consumption tax and the luxury tax.

The nation-differentiated production/consumption tax differs between countries based on four income levels defined by the World Bank. Countries with the same income level have the same tax level. The nation-differentiated production tax for income group *w* (e.g., high-income countries) can be decided by

$$PT_w = k \times \frac{k \times GDP_w}{\sum_{w=1}^{4}(k \times GDP_w \times PE_w)} \quad (4)$$

where GDP_w is the GDP per capita in income group w. PE_w presents the total production-based CO_2 of income group w, which is the sum of income group w's industrial emissions and household direct emissions. k is the global average tax level (e.g., US$50/t$CO_2$). Under formula (4), the rich nations will have higher tax levels, while the less developed countries will have lower tax levels.

Similarly, the nation-differentiated consumption tax for income group *r* can be decided by

$$CT_w = k \times \frac{k \times EXP_w}{\sum_{w=1}^{4}(k \times EXP_w \times CE_w)} \quad (5)$$

Here, EXP_w is the expenditure per capita in income group w. CE_w presents the consumption-based CO_2 of income group w, which is the sum of carbon footprint of the final demand of income group w. Still, k is the global average tax level. Both formula (4) and formula (5) will remain the global average carbon tax level at *k*, but assign different tax levels to countries.

The sectoral tax level under the luxury consumption tax scenario is decided by

$$LT_{ri} = CT_r \times \frac{CT_r \times e_{ri}}{\sum_{i=1}^{n}(CT_r \times e_{ri} \times CE_{ri})} \quad (6)$$

where CE_{ri} is the consumption-based CO_2 of sector *i* in country *r*. CT_r is the average tax level in country *r*. Under the luxury consumption tax scenario, CT_r is same for all countries. Under the nation-differentiated luxury tax scenario, CT_r is equal to the tax level for country *r* in the nation-differentiated consumption tax scenario (formula 5). In addition, e_{ri} is the expenditure elasticity of sector *i* in country *r*, which is estimated by a log-log model[17],

$$\log(EXP_{ri}) = a + b \times \log(EXP_r) \quad (7)$$

Here EXP_{ri} is the expenditure per capita on sector i for 201 expenditure bins in country *r*, and EXP_r is the expenditure per capita for 201 expenditure bins in country *r*. *b* is the expenditure elasticity of sector *i* in country *r*.

Social assistance scenarios

We have five social assistance scenarios as described in the main text. as definition of social assistance we follow the World Bank which includes in social assistance the following categories: unconditional cash transfers; conditional cash transfers; social pensions (non-contributory); food and in-kind transfers; school feeding; public works, workfare and direct job creation; fee waivers and subsidies; other social assistance. Together with social insurance and labour market policies, social assistance represents overall social protection in countries.

For each scenario, the coverage in a specific decile or percentile is calculated as the share of individuals in each bin that live in a household where at least one member receives the transfer.

We estimate these five scenarios for all the 168 countries described above, prioritising cross-country comparability in the choice of data and estimations. For low- and middle-income countries, our starting point is the Atlas of Social Protection Indicators of Resilience and Equity (ASPIRE) from the World Bank, due to its coverage and comparability across countries. Within the ASPIRE categories, we use the social assistance coverage for the whole social assistance scenario (S3); for the cash transfers scenario (S2), we use the coverage of the subcategories of social assistance that relate just to cash transfers (conditional and unconditional cash transfers, social pensions and public work schemes), addressing potential double counting. We used interpolation to estimate coverage of bins as ASPIRE presents coverage for quintiles. For some countries, those with no estimates and those that are especially relevant for global poverty and present survey years that are more recent compared to ASPIRE, we used directly household surveys, such as India and China. For the countries with no ASPIRE indicator and no household survey available, other estimates from the literature, existing databases or reports are used (especially ILO data). For high-income countries, we use standardised household surveys from the Luxembourg Income Study Database (LIS). Using LIS, we replicate the same scenarios (cash transfers (S2) and social assistance (S3)) using the information in the surveys.

For the scenario on the COVID-19 expansion (S4), it is difficult to establish the real increase as the number of beneficiaries benefitting from programs implemented to address the COVID-19 pandemic as the published numbers present overlap with existing beneficiaries of previous programs. We use regional estimates on the increase in coverage from several reports, as recent surveys are not available across countries (apart from Latin America). We multiply the social assistance coverage from current programs for the proportional increase estimated during COVID-19 (limiting of course the maximum coverage to 100%).

For the PMTs scenario (S5), we use household survey data and run PMTs using different county surveys, assuming that the government is targeting the lowest 40% of the population, as it is also part of the SDGs and the World Bank. We use the same set of variables for all the PMT regressions in all countries to have comparable and standardised results. As surveys for all countries are not available and standardised, we used one or few countries for each region and use the estimates for all the other countries in the region. The results confirm that PMT, if used, can be progressive but still have exclusion errors on some of the poorest.

Global climate fund scenarios

The global climate fund is collected from developed countries and then transferred to developing countries. The classification scheme in IPCC's Sixth Assessment Report is used to distinguish developed countries and developing countries. Here, we use the developed/developing country classification rather than the World Bank's income group classification because high-income countries have a broader scope than developed countries. In past global climate finance practices, it was usually developed countries rather than high-income countries that donated funds[67]. Each developed country's contribution to the fund is determined by their historical cumulative or current emissions and supported by their carbon tax revenue. The Global Carbon Budget 2022 provides data on countries' historical cumulative emissions since 1850[1]. The data for countries' current carbon emissions comes from World Bank statistics.

The fund is delivered to developing countries based on three principles: the population, extreme poverty headcount, and poverty gap. The population and extreme poverty headcount data are obtained from World Bank statistics. The poverty gap is the amount of money needed to lift all extremely poor people out of extreme poverty, and it is calculated based on expenditure and population for each country's 201 expenditure bins.

Combining the two principles for collecting fund and the three principles for delivering fund, totally, we have six scenarios for the global climate fund.

Emissions effect of carbon taxation and revenue recycling

In this paper, we only consider the emission effect from the consumption adjustment caused by carbon taxation and revenue recycling and ignore the emission reduction from production adjustment. Essentially, the carbon taxation and revenue recycling policy proposed in this paper is a kind of indirect income redistribution mechanism that transfers the income from the rich population to the poor, from developed to developing countries.

First, we calculate the new final demand level under carbon taxation and revenue recycling for each bin and the other two types of final demand, investment demand and government expenditure. The new final demand for sector *i* in country *r* can be derived from the changes in expenditure level and expenditure elasticity[68]:

$$D_{ri} = \sum_{s=1}^{G}(1 + ExpChg_r^s \times e_{ri}) \times EXP_{ri}^s \times p_r^s \tag{8}$$

where $ExpChg_r^s$ is the percentage change rate of expenditure level of the s^{th} expenditure bin in country *r*, which is obtained by subtracting the carbon tax burden from the original expenditure and adding the recycling revenue. e_{ri} is the expenditure elasticity of sector *i* in country *r* (formula 7). EXP_{ri}^{s} is the initial per capita expenditure for sector i of the s^{th} expenditure bin in country r. p_r^s is the population for the s^{th} expenditure bin in country r. For investment demand and government expenditure, we treat them as an expenditure bin with a population size of 1.

Then, to recognise the emission effect stemming from consumption adjustment, we assume the production and trade patterns are fixed at pre-tax status. With these assumptions, we can get the new global carbon emissions by multiplying the new final demand in formula (8) with the sectoral carbon footprint in formula (1),

$$E = \sum_r^g cD_r \tag{9}$$

Finally, the carbon emissions effects for carbon taxation and revenue recycling are the difference between the new global carbon emissions and the global carbon emissions in the pre-tax status.

Limitations

We acknowledge that both the data and the modelling in our study have limitations.

GTAP-v11 only has data for 121 countries. Other countries are grouped and represented as 20 aggregated regions. The paper includes 168 countries with poverty statistics to cover as many countries as possible for the analysis. We disaggregated the aggregated regions based on GDP and carbon emissions share to facilitate the analysis of missing countries. The underlying assumption is that countries within the same aggregated regions have similar production and trade patterns. GTAP is already our best choice among existing MRIO databases. For other alternative databases, such as Eora, despite covering 188 countries, the sectors were consolidated into 26 sectors[69]. A highly integrated sectoral classification can introduce significant integration errors in the sectoral carbon footprint accounting[70,71].

For the household expenditure data, we have integrated WBGCD and HBS by Eurostat as much as possible, but still only covering 119 countries. The role of consumption data is to provide an expenditure distribution structure to disaggregate the GTAP MRIO's total household consumption. We use the expenditure distribution structure of neighbouring countries with the same level of development as a proxy for the missing countries. Under the constraints of data availability, we believe this is an appropriate treatment. Nonetheless, at the global scale, the ranking of impact magnitude for various policy scenarios should be reliable. However, we must be more cautious about the results for the missing countries at the national level.

For social assistance coverage estimates, there are also some limitations. Underreporting of social assistance may happen because of several reasons, including the fact that not all programs are covered in surveys (and the format of the surveys changes by country); in addition, the surveys can underrepresent the part of the population covered by social assistance programs. That is why we chose to use different scenarios to give lower and upper bounds of coverage using comparable data. For the estimates related to the expansion during the COVID-19 pandemic (S4), new nationally representative household surveys with information on the social assistance coverage during COVID-19 are not available for the majority of countries; the evidence is based mainly on administrative data that may double counts beneficiaries of pre-COVID programs and beneficiaries of programs implemented/modified during COVID-19. We use estimates from such data, at the regional level; therefore, we simulate an expansion of social assistance similar to the one during the COVID-19 pandemic, to give an idea of a realistic short-term expansion, rather than using precise information on the COVID-19 social assistance coverage by country. Finally, small limitations may arise as we match data on the distribution of social assistance coverage different data sources and surveys based on both consumption and income (depending on the county), with WBGCD expenditure data.

In terms of modelling, this research is built on a static input-output model and thus has assumptions for fixed production and trade patterns. Fixed production and trade patterns imply that production and trade patterns do not change in response to changes in product prices caused by carbon taxes. Given the price rigidity and the time required for production adjustments, this assumption is reasonable for the short-term analysis[72]. Also, the short-term analysis in this paper does not account for the circular effect of emissions, tax revenue changes, and consumer response. Nonetheless, rather than providing an accurate measure of the impacts, this paper aims to obtain the right rank of different policy tools and thus shed light on the general principles we can apply to the design of just climate policies.

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Data availability

The MRIO table used in the paper is derived from the GTAP-v11 database (https://www.gtap.agecon.purdue.edu/). For household expenditure data, World Bank Global Consumption Database (WBGCD) is available at the database website (https://datatopics.worldbank.org/consumption/). The Household Budget Survey (HBS) for European countries is obtained from Eurostat (https://ec.europa.eu/eurostat/web/household-budget-surveys). The Family Income and Expenditure Survey (FIES) for Japan is provided by Statistics Bureau of Japan (https://www.stat.go.jp/english/data/sousetai/1.html). For social assistance data, Luxembourg Income Study Database (LIS) is available at https://www.lisdatacenter.org/our-data/lis-database/. The Atlas of Social Protection Indicators of Resilience and Equity (ASPIRE) is provided by World Bank (https://www.worldbank.org/en/data/datatopics/aspire). Countries' historical cumulative emissions is obtained from Friedlingstein et al.[1]. All other socioeconomic and emission data (including population, GDP, current carbon emissions, and national/international poverty headcount ratios) come from World Bank (http://data.worldbank.org/). The MRIO table based on the GTAP-v11 database and the detailed WBGCD is not publicly available. If interested, please contact the corresponding authors. The detailed results used for generating the figures and tables in the main text are available at https://github.com/XJChenUMD/Carbon-Taxation-and-Revenue-Recycling.

Code availability

The code used to simulate the poverty, inequality, and emissions effect and results visualisation are available at https://github.com/XJChenUMD/Carbon-Taxation-and-Revenue-Recycling.

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Author contributions

All authors designed the policy analysis framework together. X.C. and D.M. implemented the scenario modelling, and X.C. conducted the results visualisation. X.C. and D.M. led the analysis and writing with assistance from all authors.

Competing interests

The authors declare no competing interests.

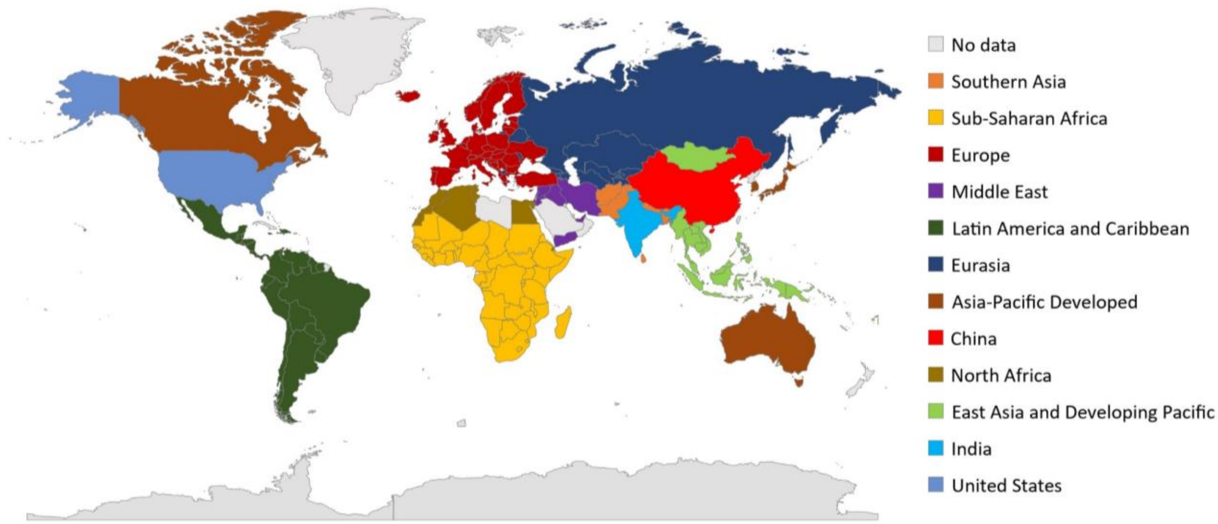
Extended Data

Extended Data Table 1 | Carbon taxation scenarios

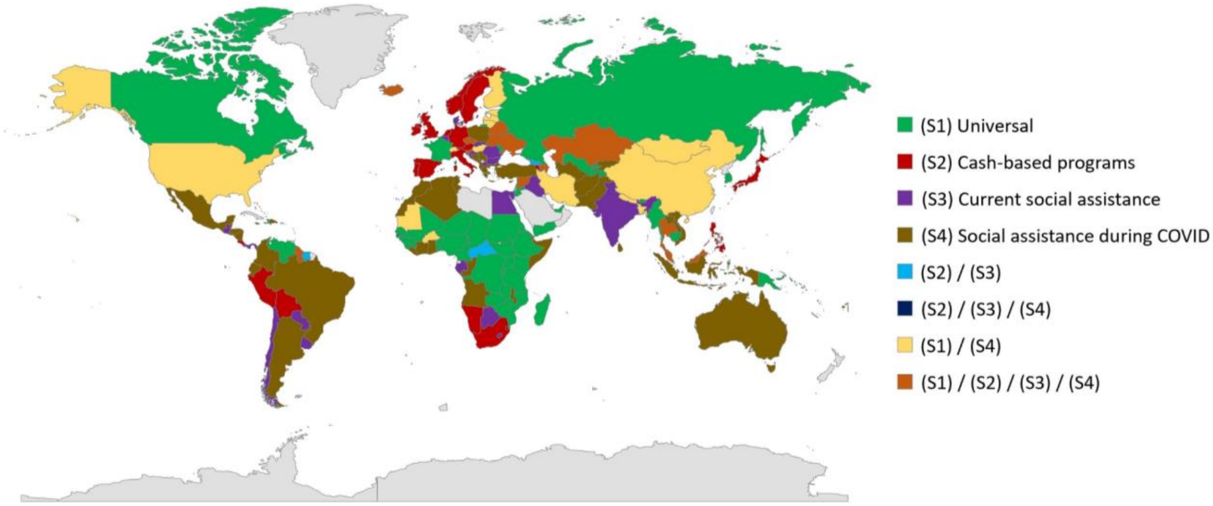
	Production/ consumption tax	**National Heterogeneity**	**Sectoral Heterogeneity**
(T1) Global uniform production tax	Production	No	No
(T2) Nation-differentiated production tax	Production	Yes	No
(T3) Global uniform consumption tax	Consumption	No	No
(T4) Nation-differentiated consumption tax	Consumption	Yes	No
(T5) Luxury consumption tax	Consumption	No	Yes
(T6) Luxury & nation-differentiated consumption tax	Consumption	Yes	Yes

Extended Data Table 2 | Domestic and international tax revenue recycling mechanisms

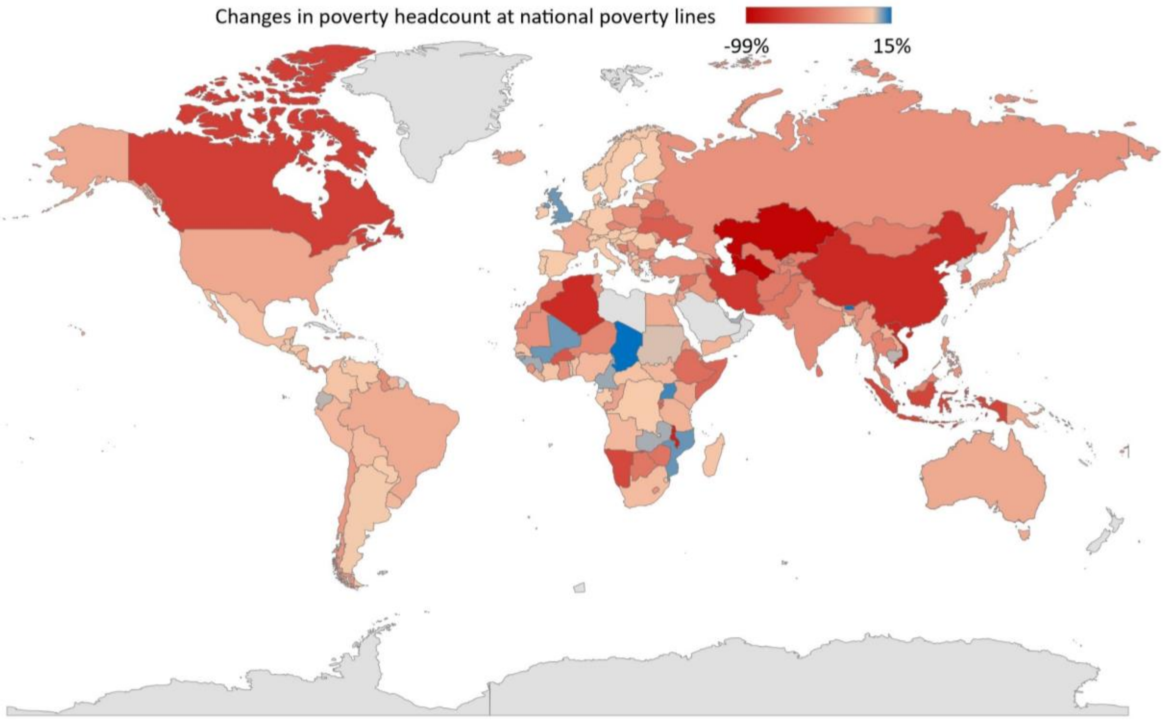
Name	**Description**
Domestic revenue recycling by social assistance programs	
(S1) Universal	Partially feasible. An untargeted lump sum transfer in which all citizens receive the same benefit.
(S2) Current cash transfer programs	Feasible. Represents a lower bound of existing social programs that target the poorest, as it considers just cash-based programs; it stimulates an increase in the transfer level of current beneficiaries.
(S3) Current social assistance	Feasible. Use all existing social assistance programs that target the poorest, stimulating an increase in the transfer level of current beneficiaries.
(S4) Social assistance during the COVID-19 period	Feasible. Based on an increased coverage of current social assistance that resembles the regional expansion rates during the COVID-19 period.
(S5) Proxy Means Test (PMT)	Hypothetical (ideal). Represents a progressive proxy means test based on household surveys, with some exclusion errors but high coverage of the poorest.
International revenue recycling by global climate fund	
(G1) Historical emissions & poverty headcount	The fund is gathered from developed countries based on their historically accumulated carbon emissions and redistributed to developing countries based on their extreme poverty headcount.
(G2) Historical emissions & population	The fund is gathered from developed countries based on their historically accumulated carbon emissions and redistributed to developing countries based on their population.
(G3) Historical emissions & poverty gap	The fund is gathered from developed countries based on their historically accumulated carbon emissions and redistributed to developing countries based on their poverty gap.
(G4) Current emissions & poverty headcount	The fund is gathered from developed countries based on their current carbon emissions and redistributed to developing countries based on their extreme poverty headcount.
(G5) Current emissions & population	The fund is gathered from developed countries based on their current carbon emissions and redistributed to developing countries based on their population.
(G6) Current emissions & poverty gap	The fund is gathered from developed countries based on their current carbon emissions and redistributed to developing countries based on their extreme poverty gap.



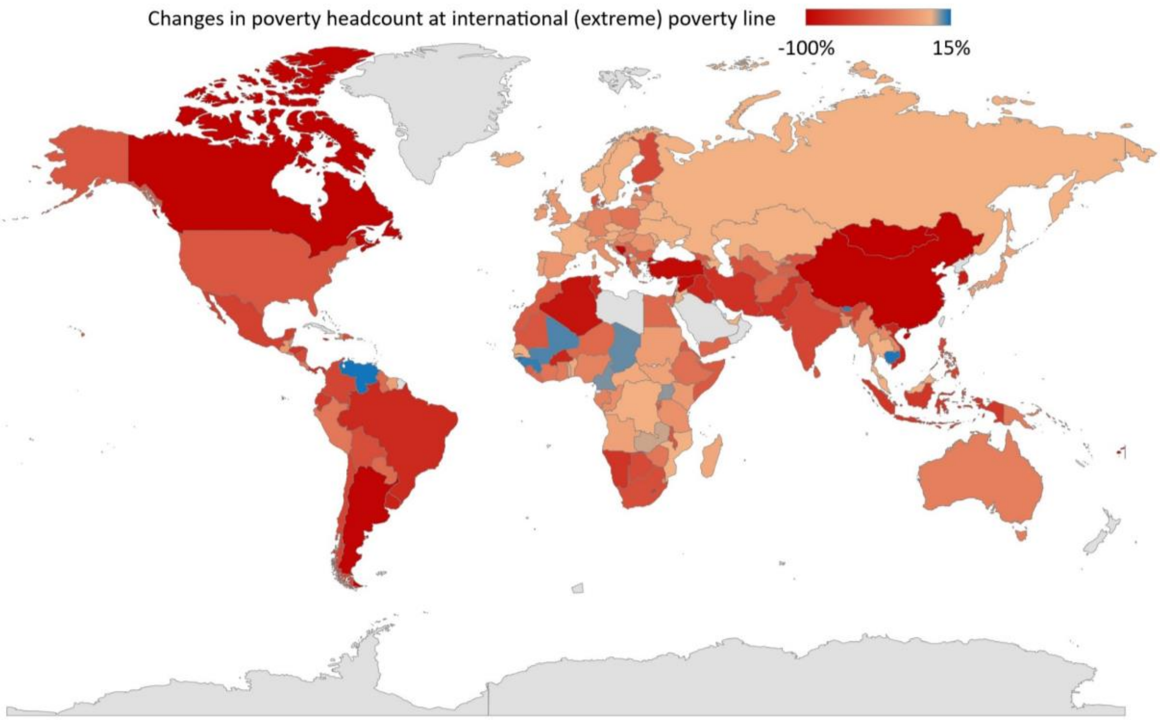
Extended Data Fig. 1 | Region classification.



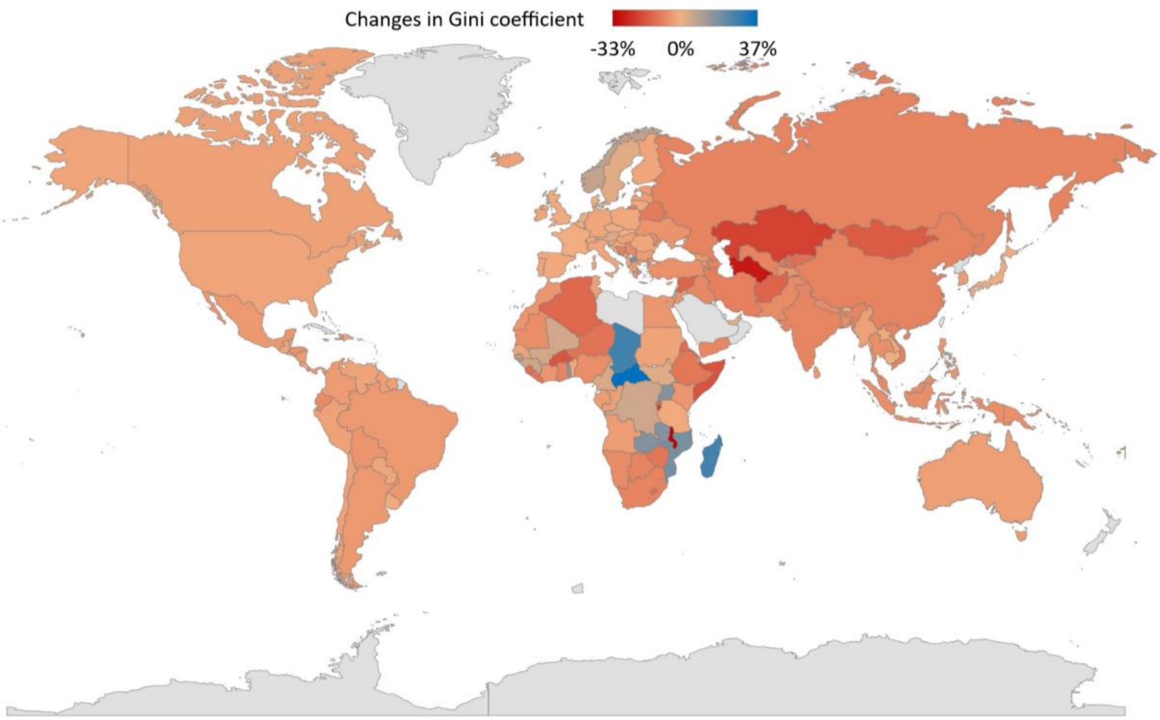
Extended Data Fig. 2 | The best internal recycling mechanism for each country judged by extreme poverty reduction effect. The potential for poverty reduction under various social assistance scenarios is compared using the average poverty reduction effect when they are combined with six carbon taxation scenarios.



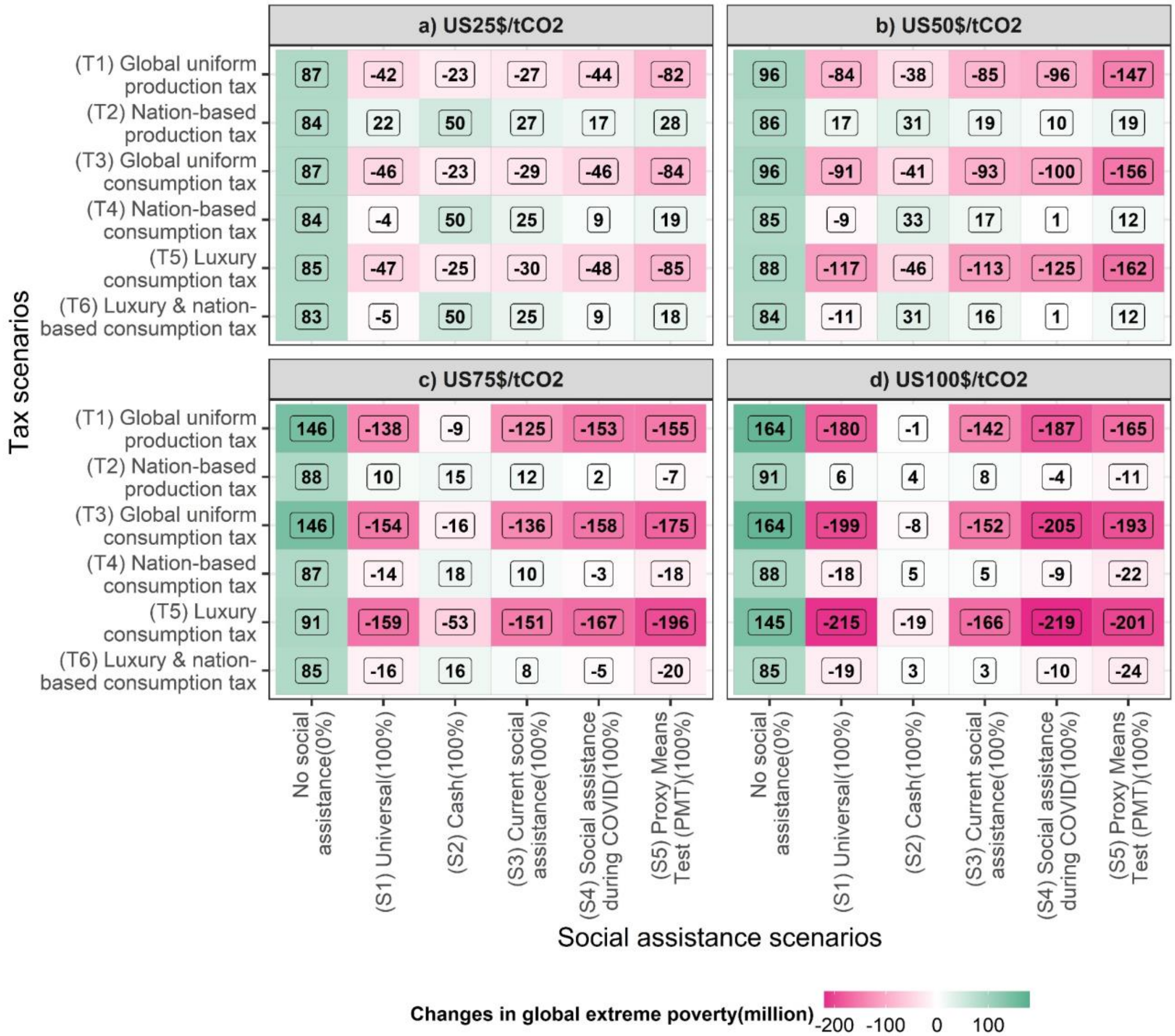
Extended Data Fig. 3 | Percentage changes of poverty headcount at national poverty lines under the best policy mix. The best policy mix is the luxury consumption tax (T5) + social assistance during the COVID-19 pandemic (S4) + current emissions & poverty headcount (G4).



Extended Data Fig. 4 | Percentage changes of poverty headcount at international (extreme) poverty line under the best policy mix. The best policy mix is the luxury consumption tax (T5) + social assistance during the COVID-19 pandemic (S4) + current emissions & poverty headcount (G4).



Extended Data Fig. 5 | Percentage changes of Gini coefficient under the best policy mix. The best policy mix is the luxury consumption tax (T5) + social assistance during the COVID-19 pandemic (S4) + current emissions & poverty headcount (G4).



Extended Data Fig. 6 | Global extreme poverty reduction under different tax levels.

Supplementary Files

This is a list of supplementary files associated with this preprint. Click to download.

- SupplementaryData.xlsx