HHS Public Access
Author manuscript
Nat Clim Chang. Author manuscript; available in PMC 2024 July 12.

Published in final edited form as:
Nat Clim Chang. 2021 December ; 11(12): 1111–1116. doi:10.1038/s41558-021-01217-0.

Climate action with revenue recycling has benefits for poverty, inequality and well-being

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Code availability
All model code used to generate results and create figures for this article is archived[53] and freely available at https://github.com/Environment-Research/revenue_recycling.

Competing interests
The authors declare no competing interests.

Additional information
Supplementary information The online version contains supplementary material available at https://doi.org/10.1038/s41558-021-01217-0.

Peer review information *Nature Climate Change* thanks Allen Fawcett and the other, anonymous, reviewer(s) for their contribution to the peer review of this work.

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Abstract

Existing estimates of optimal climate policy ignore the possibility that carbon tax revenues could be used in a progressive way; model results therefore typically imply that near-term climate action comes at some cost to the poor. Using the Nested Inequalities Climate Economy (NICE) model, we show that an equal per capita refund of carbon tax revenues implies that achieving a 2°C target can pay large and immediate dividends for improving well-being, reducing inequality and alleviating poverty. In an optimal policy calculation that weighs the benefits against the costs of mitigation, the recommended policy is characterized by aggressive near-term climate action followed by a slower climb towards full decarbonization; this pattern—which is driven by a carbon revenue Laffer curve—prevents runaway warming while also preserving tax revenues for redistribution. Accounting for these dynamics corrects a long-standing bias against strong immediate climate action in the optimal policy literature.

A familiar theme from research on climate policy and economic development is that there is an important trade-off between climate action and near-term poverty reduction; this literature is based in part on results from existing cost–benefit climate policy models[1–5], which assume that the burden of a nation's climate mitigation must fall to some extent on the poor. If this assumption were correct, some trade-off between climate action and poverty alleviation would be inevitable. The key question would then be to what extent benefitting the future poor through avoiding future climate damages can justify (from a development or equity perspective) reduced near-term development for the current poor[6,7].

However, these models ignore the possibility that the revenues from a carbon tax could be used in a progressive way that generates immediate net benefits for the current poor. A large literature has now investigated the implications of these 'revenue recycling' opportunities and identified an equal per capita refund of the revenues as a salient option[8–18]. The evidence indicates that an equal per capita refund typically makes immediate net beneficiaries out of most citizens and is often more progressive and potentially more feasible than other salient options for using revenues[19–21].

Findings from studies of revenue recycling have not been incorporated into optimal policy analyses at the global level, including to model possible synergies with other development goals, for example sustainable development goals (SDGs)[22–24]. This is an important oversight, as many of the arguments that there are trade-offs between climate action and poverty alleviation or other SDGs depend on the premise that climate action must harm the current poor[25,26]. Indeed, because the possibility of progressive revenue recycling is not taken into account in existing optimal climate policy calculations, these models have a built-in bias against mitigation, since they imply that mitigation must entail costs for the poorest citizens within regions in the coming decades and, more generally, imply an intergenerational trade-off in well-being[27,28].

Modelling progressive revenue recycling

In the climate economics literature, the 'initial burden' of a carbon tax—the distribution of tax payments and mitigation costs before any possible redistribution of revenues—is generally found to subtract from all income groups (and thus would increase poverty in the absence of redistribution) but in a way that is progressive in poorer countries and regressive in richer countries; in poorer countries fossil fuels are disproportionately consumed (relative to income) by richer citizens, whereas in rich countries fossil fuels are disproportionately consumed by poorer citizens[18,29,30]. Therefore, as poorer countries get richer and consumption patterns change, this regionally differentiated driver of the initial burden of carbon taxes will probably evolve

To confirm this relationship and quantify these dynamics, we conducted a review of the literature on the initial burden of a carbon or gasoline tax (Supplementary Section 1). We included studies from around the world to capture estimates for regions with different levels of wealth. Figure 1 displays the results, reporting the relationship between gross domestic product (GDP) per capita and the distribution of the initial burden before redistribution of revenues (the consumption elasticity of the initial burden, where an elasticity of ϵ means that if a person's consumption increases by 1%, that person's initial burden increases by ϵ%). An elasticity <1 means the initial burden of the carbon tax falls disproportionately on the poor (the tax is regressive before redistribution of revenues), whereas a value >1 indicates that the tax burden falls disproportionately on the rich (the tax is progressive before redistribution of revenues). We use this relationship as an estimate of the distributional implications of carbon taxation, assuming that the initial burden is distributed within a region on the basis of the consumption elasticity estimated by the best-fit line in Fig. 1. As a region grows richer over time, the elasticity used to estimate the distribution of its initial burden declines.

To investigate the impact of an equal per capita refund of tax revenues on well-being, poverty and inequality, we modify the Nested Inequalities Climate Economy (NICE), a 12-region global climate policy model that represents inequality within regions by grouping the population into five equally populous quintiles, ranked from poorest to richest. We modify NICE to implement two distinct policy scenarios. In the first scenario, the 'no recycling' scenario, mitigation costs affect consumption but tax payments do not. This is the standard assumption in this type of model and is implemented by returning tax revenues in proportion to the initial burden. In the second scenario, the 'recycling' scenario, the tax revenue in each region is redistributed on an equal per capita basis. As a result, some quintiles are net beneficiaries in the recycling scenario if the refund is greater than the initial burden; this is in contrast to the no recycling scenario where all quintiles bear a net cost from the climate policy. (See Methods and in particular equation (4), for a detailed description of the two scenarios.)

2 °C benefits for poverty, inequality and well-being

As a first demonstration of the potential impact of revenue recycling, we model the difference in consumption of the poorest quintile in all NICE regions under a 2 C scenario relative to business-as-usual (BAU), both with equal per capita revenue recycling (the recycling scenario) and without it (the no recycling scenario) (Fig. 2a,b). There is a similar pattern in all regions: without progressive revenue recycling, climate action does indeed involve a substantial trade-off where the poorest lose from climate policy in the short-to-medium term as they shoulder their share of mitigation costs without compensation. In contrast, with the equal per capita dividend, climate action involves a synergy with poverty alleviation. Yet even in the recycling scenario, consumption falls below BAU for several regions later in the century. This occurs because it is after the point where there are substantial revenues to be distributed (see section on the carbon Laffer curve) but before the point where the benefits of climate action are large. Nevertheless, consumption in the recycling scenario is always above the no recycling scenario in the early periods due to the benefits of redistribution. After the year 2100, both cases produce increasing benefits from avoided climate damage. Note that once carbon revenues disappear in the future, people will also be much wealthier than their counterparts today.

Focusing on inequality—measured by the Gini index (Fig. 2b,d)—also demonstrates the benefits of progressive redistribution. Equal per capita recycling generates a reduction in inequality in all regions while revenues are available for redistribution. Once full decarbonization occurs and revenues disappear, mitigation has a regressive impact compared with BAU due to the relationship reported in Fig. 1 combined with the continued cost of decarbonization even after there are zero net emissions. The impacts on inequality without recycling, which are determined by the elasticity estimated in Fig. 1, are small overall and switch from progressive to regressive once a region's GDP per capita surpasses ~US$21,500 (Fig. 1).

Examining the impact of the equal per capita refund on all quintiles in the United States, China and India—chosen to represent countries at different levels of wealth—reveals that in all three countries, more than half the population (namely, those in the lower part of the distribution) benefits in the near term, particularly those in the bottom quintile (Fig. 3). In India, the poorest 40% never experience a loss relative to BAU over the full time horizon. This redistribution towards the lower quintiles has a positive effect on poverty alleviation by reducing the percentage of the population below the poverty line (Supplementary Tables 2–4).

Furthermore, the progressive equal per capita dividend increases aggregate well-being in every region relative to the BAU over the next decades and in the far future (Supplementary Fig. 3). The intergenerational trade-off between costs of reducing emissions now and benefits in the future is weakened over the entire time horizon: aggregate well-being over time is higher with the equal per capita dividend than without it in all regions and both are better overall than BAU.

All results presented above assume that revenues raised in a given region are distributed only within that region. However, there are well-being- and justice-based arguments for redistributing total global revenues on an equal per capita basis globally[21,31,32]. Under this redistribution framework, more dramatic improvements occur for inequality and consumption in the poorest regions of the world (Supplementary Fig. 4).

The carbon Laffer curve

The stringent 2 C constraint means that the world will rapidly decarbonize and so there will be less and less revenue from carbon taxation to recycle. This highlights an important caveat to our storyline: the positive effect of the carbon tax through progressive redistribution is initially strong but diminishes once the economy decarbonizes enough for revenues to decline. In short, there is a ‘carbon Laffer curve’. Conceptually, the Laffer curve is the widely recognized fact that tax revenue does not monotonically increase with the tax rate—in the case of sufficiently large taxes, market transactions (for example, fossil fuel use) reduce to the point where there is little taxable activity to generate revenue[33]. As a quantitative illustration of the carbon Laffer curve in NICE, Fig. 4 shows this nonlinear relationship between global near-term (2025) decarbonisation and tax revenue. Total revenue is highest in the 55–75% decarbonisation range and decreases thereafter until full decarbonisation ultimately implies that no revenue is generated (under full decarbonisation there are no industrial emission to be taxed).

This relationship implies that an optimal climate policy with an equal per capita carbon dividend must balance the value to society of (1) lower CO_2 emissions—and thus reduced climate change—that will result from high carbon taxes and (2) some level of continuing emissions, which enables the progressive redistribution that tax revenues can fund. Note that unlike income tax where going beyond the peak of the Laffer curve is inefficient, in the case of climate we ought to go beyond that point to curb climate change.

Strong action now and steady action later

To investigate the trade-off between the benefits of lowering emissions and the benefits of continued carbon tax revenue, we perform an optimal policy calculation; optimal policy refers to the policy that maximizes (discounted) net benefits through time and does not feature a temperature constraint as in the results above. With revenue recycling, the model recommends high decarbonization initially—there are dual benefits of redistributable revenue and lower future temperatures—but postpones full decarbonization for many decades as redistribution continues (Fig. 5). Without the equal per capita revenue recycling, the model at first recommends more moderate ambition, to protect the current poor from high mitigation costs, followed by a rapid increase in decarbonization to avoid extreme warming. Despite this different temporal pattern of mitigation, the maximum temperature rise is similar in both scenarios, although it peaks later with revenue recycling, a potentially valuable delay if it reduces the rate of temperature change and enables more time for adaptation[34]. The carbon tax and carbon dividend trajectories corresponding to the decarbonization paths are reported in Supplementary Figs. 7 and 8. (Unless otherwise stated, results assume standard discounting parameters from the Regional Integrated Climate Economy (RICE) model: pure time preference = 1.5% per year; consumption elasticity of marginal utility = 1.5 (representing the diminishing marginal utility of consumption) and distribution of climate damages proportional to consumption.)

The optimal decarbonization pathway is not exclusively driven by the motive to redistribute. To demonstrate this, the ‘no damages’ scenario depicts the optimal carbon tax with revenue recycling but where climate damages are artificially set to zero regardless of warming (Fig. 5, black line). In this case, the only benefit of a carbon tax is the redistribution it allows. Global decarbonization that is optimal purely from this motive is substantial and ranges between ~50 and 60%, as this ensures maximum redistribution to the poor. Still, this is much lower than the case where climate benefits exist alongside redistributional benefits, demonstrating that substantial incentive to decarbonize further remains even at such high levels of decarbonization.

An equal per capita global redistribution leads to similar decarbonization trajectories to those reported in Fig. 5 (which assume within-region redistribution only), a result driven largely by the carbon Laffer curve (Supplementary Fig. 5). However, it would lead to far greater improvements in global well-being, particularly for Africa, India and Other Asia (Supplementary Fig. 6 and associated text).

Discussion and sensitivity analyses

We have shown that an equal per capita refund of carbon tax revenues improves the well-being of individuals toward the bottom of the income distribution and reduces poverty and inequality. The implication is that adopting strong climate policy need not entail a trade-off where the people of today (and the poor in particular) must sacrifice for the benefit of future generations.

This finding contributes to the debate over whether there should be a gradual ramp up to aggressive policy (for example, as advocated by Nordhaus[27]) or a large-scale push toward immediate maximum feasible reductions (for example, as advocated by Stern[28]). Even with the relatively high discounting parameters preferred by Nordhaus, progressive revenue recycling leads to high levels of decarbonization immediately—comparable in the initial decades to strict climate target pathways (for example, 1.5 or 2 C)—followed by less decarbonization in later periods (Fig. 5). With lower carbon emitted in the atmosphere early on, and anticipating the carbon Laffer curve, the initial period of high decarbonization is followed by a gradual long-term increase toward full decarbonization to keep peak warming at a moderate level and preserve revenue for redistribution.

The temporal difference in optimal decarbonization pathways between scenarios with and without revenue recycling (the crossing pattern seen in Fig. 5a) appears robust to several key uncertainties. While our main results assume background inequality remains constant in all regions, Supplementary Fig. 9 shows that the crossing pattern persists in several scenarios involving narrowing or widening background inequality. The crossing is repeated in all scenarios but is less extreme with more reductions in background inequality. When background inequality is lower, initial decarbonization is again much higher with the progressive recycling but, unlike in the other scenarios, it then remains relatively high through time. This occurs because a greater decrease in background inequality reduces the incentive to delay decarbonization to preserve tax revenues for redistribution, thus bringing forward the optimal date of full decarbonization to avoid more climate harms.

Our qualitative results are also robust to choices about key discounting parameters, namely the rate of pure time preference and the consumption elasticity of marginal utility. As explained in the Methods, normative and descriptive disagreements exist about the appropriate value of these parameters[27]. Under a range of discounting parameter combinations typically considered in the literature, revenue recycling always induces stronger short-term emission reductions and a slower transition to full decarbonization (Supplementary Fig. 10).

Our findings raise important questions about feasibility. One is whether it is technically feasible to decarbonize as quickly in the early periods as the model recommends. This question is beyond the scope of this paper; however, we note that the initial decades of the optimal trajectory reported here are comparable to many IPCC 1.5–2 C pathways[35]. Another question relates to negative emissions, both whether they are needed and how they would be funded if all carbon dividends are redistributed. Consistent with some IPCC scenarios, our trajectories do not require negative emissions (Supplementary Fig. 11). Nevertheless, even if a substantial fraction of revenues was diverted to subsidize negative emission technologies, the benefits of redistributing the remaining dividends remains strong (Supplementary Fig. 12). However, we acknowledge that negative emission technologies would have unprecedented and currently poorly understood implications.

A second dimension of feasibility concerns public opinion and political will. An emerging literature indicates that communicating the co-benefits of climate action may increase policy support, in particular for co-benefits that lead to economic development and more compassionate communities[36,37]. Similarly, bundling climate policy with social and economic programmes, a feature of widely discussed strategies across the political spectrum from the Climate Leadership Council to the Green New Deal, may also increase support for action[38]. Overall, the literature suggests that progressive redistribution may have relatively broad appeal, at least given effective communication of the benefits, although this may be tempered by evidence from Pigouvian taxation studies which indicates that people may be resistant to policies that start with high tax rates[19,21,39–42].

A third feasibility concern is whether governments would actually have the capacity to perform progressive transfers, even if there was political will to do so. In Supplementary Fig. 13, we report optimal policy results under imperfect recycling programmes, including that the bottom quintile does not receive any transfers or if a large proportion of the revenue was lost in policy implementation cost; in both cases the pattern of high initial decarbonization followed by the gradual progression to full decarbonization remains intact, although is somewhat muted. Supplementary Fig. 13 also reports results for a scenario that is more progressive than an equal per capita redistribution.

One potential limitation of our study is that NICE does not include the full suite of policy levers available to alleviate distributional concerns. Within countries, for example, one might consider changes to income taxation. We model synergies between carbon taxation and inequality reduction under the assumption that, apart from the distribution of mitigation costs and the distribution of the tax revenue, inequality is not otherwise affected by economic incentive effects of the policy (Supplementary Information Section 9 gives details about the relation with optimal taxation theory). Complementary work could use subregional agent-based or microsimulation models to estimate how such incentive effects and other interaction effects may influence inequality levels and optimal policy with revenue recycling.

In addition, some NICE regions consist of multiple countries. Therefore, our main results implicitly assume some level of international transfers between countries within these multicountry regions. This could be important for multicountry regions with heterogeneous levels of development and differing capacities. Nevertheless, NICE represents several key countries as individual regions (United States, China, India, Russia and Japan) and avoids transfers across regions in the main results.

Further studies could investigate the role of the distribution of carbon tax revenues when regions apply different carbon taxes. In the absence of international transfers such as those modelled in Supplementary Fig. 6, the assumption of a global carbon price is certainly a constraint to the alleviation of distributional concerns, since it requires a high policy burden from poor countries. In models allowing for differential carbon prices by region, all high emitters are required to mitigate at least as much as under the global carbon price assumption[43–45]. Our results here with a global carbon price could thus be seen as a price floor for high emitters, as recently proposed by the International Monetary Fund[45].

We also do not consider the question of horizontal inequality—that is the heterogeneous effects of a carbon tax on households with the same income level but different consumption patterns—which recent evidence suggests may be important[46–48]. Including horizontal inequality would be a worthwhile extension of our work.

Recent research also indicates that the damage functions used in cost–benefit models, such as NICE, may underestimate future climate impacts[49]. We test this possibility in two ways. First, we keep the total damages the same but assume that they disproportionately harm the poor (thus having a greater well-being impact). Second, we double the total size of the damages. Both cases display the characteristic crossing pattern of Fig. 5, although full decarbonization occurs earlier (Supplementary Fig. 14). The crossing pattern is also evident when we replace the NICE climate module with the FAIR climate model (Supplementary Fig. 15), as recommended in a recent report by the National Academies[50].

Conclusions

Estimates of optimal climate policy have ignored the possibility that revenues from a carbon tax could be used in a progressive way that generates immediate net benefits for the current poor. As a consequence, they mistakenly imply that climate action must come at some cost to overall well-being and especially to the poor. We have shown that this storyline of the climate, development and inequality nexus reverses when progressive revenue recycling is taken into account. Our approach corrects a long-standing bias against strong immediate climate action. We find that with progressive revenue recycling, aggressive climate action can pay large dividends for improving well-being, reducing inequality and alleviating poverty. In an optimal policy calculation, the recommended policy is characterized by aggressive near-term climate action followed by a slower climb towards full decarbonization; this pattern prevents runaway warming while also preserving tax revenues for redistribution. The benefits from progressive use of carbon revenues are most pronounced in the early decades, when the revenues are largest and the needs of the poor are most urgent.

Online content

Any methods, additional references, Nature Research reporting summaries, source data, extended data, supplementary information, acknowledgements, peer review information; details of author contributions and competing interests; and statements of data and code availability are available at https://doi.org/10.1038/s41558–021-01217–0.

Methods

All model code and data used to generate results for this article are archived[53] and a running version is available at https://github.com/Environment-Research/revenue_recycling.

The NICE model[52] used here is a modification of the RICE model[3,54], which was developed by W. Nordhaus. RICE is the regional counterpart to the global dynamic integrated climate–economy (DICE) model, which is one of three leading cost–benefit models used by researchers and governments for regulatory analysis, including to estimate the social cost of carbon[55]. RICE[3,54] and NICE[51,52] have been described in great detail elsewhere. Since their basic architecture is the same, we first describe this RICE architecture and then explain the model developments that make RICE into NICE, noting from the outset that all models of this class are reduced-form representations of reality with associated strengths and limitations[56,57].

RICE is a regionally disaggregated optimization model that includes an economic component and a geophysical (climate) component that are linked. RICE divides the world into 12 regions, some of which are single countries while others are groups of countries. Each region has a distinct endowment of economic inputs including capital, labour and technology, which together produce that region's gross output via a Cobb–Douglas production function. Carbon emissions are a function of gross output and an exogenously determined, region-specific, carbon intensity pathway. These carbon emissions can be abated (mitigating climate change) at a cost to gross output via regional control policies that are selected so that in every period the marginal cost of abatement—or carbon price—is the same for all regions. The climate module determines how unabated carbon emissions affect global temperature and, ultimately, the future economy through climate-related damages. Region-specific damage functions capture this relationship between increased temperature and economic damage, with poorer regions generally more vulnerable as a proportion of income.

The original RICE model is solved by choosing decarbonization and savings rates in all regions and periods to maximize an objective function which sums, over periods and regions, a concave utility function of regional per capita consumption with a discount factor applied to future values. To simplify the optimization, the solution concept implemented in this study takes the savings rates as given—rather than solving for their optimal values—and maximizes only over the control rates (decarbonization). In the default implementation of RICE, Negishi weights are added to the objective function to ensure that the marginal cost of reducing emissions by a ton (the carbon price) is the same for all regions, period by period. NICE achieves equality of carbon prices without using Negishi weights[52].

The NICE model extends RICE by disaggregating regional consumption into five socioeconomic groups with consumption levels reflecting the current distribution of consumption within the regions[58]. So as not to affect any of the aggregate economic variables (investment, capital, output and so on), this is done by splitting average regional consumption into five units (or quintiles) after aggregate savings have been determined. The background consumption distribution and the distributions of damage and mitigation cost are determined in the way described below.

We denote regions by index i, quintiles by j and periods by t. Quantities without a j index are regional aggregates and are identical to the quantities in the more aggregated RICE model. Net output Y_{it} is given by

$$Y_{it} = \frac{1 - \lambda_{it}}{1 + D_{it}} Q_{it} \tag{1}$$

where Q_{it} denotes gross output, λ_{it} mitigation cost (opportunity costs of reducing CO_2 emissions as a share of GDP) and D_{it} climate damages. The basic trade-off of the RICE model—mitigation costs in the present for the reduction of climate damages in the future—is embodied in this equation. As mentioned above, in each period the regional mitigation costs are chosen so that they are consistent with a globally uniform carbon price, which is implemented as a local tax, tax_t, in each region.

Defining the aggregate savings rate, s_{it}, and population, L_{it}, the average regional consumption is

$$\bar{c}_{it} = \frac{1 - s_{it}}{L_{it}} Y_{it} \tag{2}$$

while the average gross consumption (predamage and premitigation cost) is

$$\bar{c}_{it}^{\text{pre}} = \frac{1 - s_{it}}{L_{it}} Q_{it} = \frac{1 + D_{it}}{1 - \lambda_{it}} \bar{c}_{it} \tag{3}$$

We assume that gross consumption is distributed across population quintiles according to a baseline distribution, yielding gross consumptions for each quintile. Under the no recycling scenario, final consumption of each quintile is computed by subtracting climate damages and mitigation costs from gross consumption according to distributions that reflect different exposures and vulnerabilities of consumption groups to these impacts. Under the recycling scenario, carbon taxes are raised according to the same distribution as mitigation costs and redistributed as equal per capita payments within regions.

The baseline distribution is given by quintile weights, q_{ijt}, that denote the ratio between quintile consumption and average consumption. If for quintile j in region i and period t, $q_{ijt} > 1$, its consumption is greater than average regional consumption in that period; if $q_{ijt} < 1$, its consumption is less than the average. Since the five quintiles comprise equal proportions of the population, $\sum_j q_{ijt} = 5$ in all regions and periods. In the base implementation these quintile weights are fixed across time and estimated to the current distribution of consumption in the region by aggregating country level distributional data from the World Income Inequality Database[58] to regional distributions. The aggregation is described in detail in Section 6 of the Supplementary Information.

The initial burden of the carbon tax is the sum of the mitigation costs and tax payments. Within a region, the initial burden is distributed across quintiles according to the weights, τ_{ijt}. The substantive assumption of our analysis is that the two components of the initial burden —the mitigation cost and the tax payment— are distributed according to the same weights, τ_{ijt}, which are calculated on the basis of Fig. 1, as described in more detail below.

We denote by d_{ijt} the weights of the distribution of damage to consumption in region i and period t, which we also describe in more detail below.

With this notation the consumption of quintile j in region i and period t is given by

$$c_{ijt} = \underbrace{\bar{c}_{it}^{\text{pre}} q_{ijt}}_{\text{Gross consumption}} - \underbrace{\bar{c}_{it} D_{it} d_{ijt}}_{\text{Damage cost}} - \overbrace{\left(\underbrace{\bar{c}_{it}^{\text{pre}} \lambda_{it} \tau_{ijt}}_{\text{Mitigation cost}} + \underbrace{\frac{E_{it}}{L_{it}} tax_t \tau_{ijt}}_{\text{Tax ayments}} \right)}^{\text{Initial burden}} + \underbrace{\frac{E_{it}}{L_{it}} tax_t \delta_{ijt}}_{\text{Refund}} \tag{4}$$

The value of the parameter δ_{ijt} in the expression for the refund distinguishes our two policy scenarios: no recycling and recycling. In the no recycling scenario, carbon tax revenues are refunded within each region according to the distribution of the initial burden, so that $\delta_{ijt} = \tau_{ijt}$. From equation (4) we can see that this implies that tax payments and the refund cancel each other out. Hence the carbon tax components disappear, leaving the mitigation cost as the only impact of the climate policy, as is standard in cost–benefit Integrated Assessment Models (IAMs). That is the reason we call this the no recycling scenario. Under this implementation, all quintiles bear some cost from climate policy.

In the recycling scenario, carbon tax revenues are refunded equally per capita within each region, so that $\delta_{ijt} = 1$. As a hypothetical example to illustrate the distributional impact of this scenario, if $\tau_{ijt} = 1$ for all quintiles, the tax would be raised equally per capita and cancelled out with the equal per capita dividend, resulting in the same situation as in the no recycling scenario. But in all of our model runs $\tau_{ijt} > 1$ for the top quintile and <1 for the bottom quintile, so that the recycling scenario always yields a more equal distribution than the no recycling scenario when the same (positive) tax is applied.

The essential ingredients for the process of downscaling regional consumption to subregional consumption quintiles are the distributional weights q_{ijt}, d_{ijt} and τ_{ijt}. As described in the Supplementary Information, the q_{ijt} for the first model period are estimated from current regional consumption distributions. Under our baseline assumption these remain constant over time and in Supplementary Fig. 9 we consider alternative projections.

For the distributional weights of damage and of the initial burden (d_{ijt} and τ_{ijt}) we assume a constant elasticity relationship to the consumption distribution:

$$d_{ijt} = 5\frac{q_{ijt}^{\xi}}{\sum_k q_{ikt}^{\xi}}$$

and

$$\tau_{ijt} = 5\frac{q_{ijt}^{\omega_{it}}}{\sum_k q_{ikt}^{\omega_{it}}}$$

In the main results of the paper we take the damage elasticity of consumption, ξ, to be equal to 1 in all periods and in all regions. In Supplementary Fig. 14 we consider alternative values of this parameter. Previous applications of the NICE model study the importance of this parameter to optimal carbon prices[51,52].

Because the distributional weights, τ_{ijt}, of the initial burden are central to our policy analysis and because there is substantial evidence that the consumption elasticity of the initial burden, ω_{it}, decreases with a region's per capita GDP, we estimate a relationship between this elasticity and GDP per capita with a simple ordinary least squares regression of the estimates from the literature on the distributional impact of carbon and fuel taxes, summarized in Fig. 1. For each study, k, we estimated the elasticity, ω_k, as the slope of the regression of log initial burden reported in the study with respect to log consumption level of the population quintile. In Fig. 1 (and Supplementary Fig. 1) these estimated elasticities are plotted against the (log) GDP per capita of the country-year on which the study is based,y_k.

The result is an estimated relationship between the consumption elasticity of the initial burden, ω_k, and the log of GDP per capita, $\log y_k : \omega_k = \hat{\alpha} + \hat{\beta} \log y_k$.

The analysis is described in more detail in Section 1 of the Supplementary Information.

To project elasticities, ω_{it}, for each region and period in the model, we compute the predicted elasticities $\widehat{\omega}_{it} = \widehat{\alpha} + \widehat{\beta} y_{it}$ according to the regression above for the model GDP per capita, y_{it}, of region j in period t.

Supplementary Material

Refer to Web version on PubMed Central for supplementary material.

Acknowledgements

This article has received funding from the NAVIGATE project of the European Union's Horizon 2020 research and innovation programme under grant no. 821124 (S.F., M. Fleurbaey, U.K., A.M., F.W. and S.Z.) and the NIEHS-funded HERCULES Center P30ES019776 (N.S.). We thank C. Burnham and the Climate Futures Initiative at Princeton University for support.

Data availability

All data used in our version of the model are archived[53] and freely available at https://github.com/Environment-Research/revenue_recycling.

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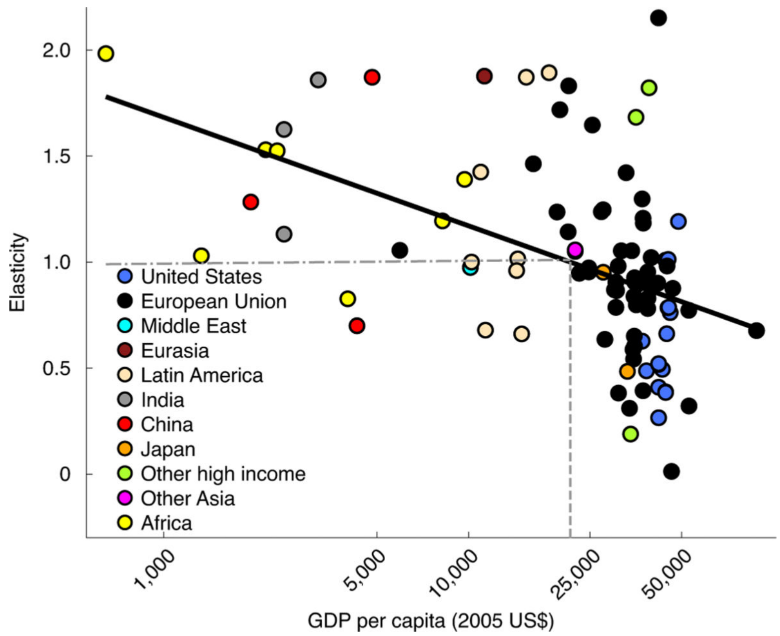

Fig. 1 |. Estimates from the literature on the distribution of the initial burden of a carbon or gasoline tax and the resulting relationship with per capita gDP.

This relationship (black line) is used to estimate the consumption elasticity of the initial burden before any possible redistribution as a function of regional per capita GDP in each NICE model region at each point in time. Section 1 of the Supplementary Information describes the Methods of the literature review; Supplementary Table 1 cites all included studies, and Supplementary Figs. 1 and 2 detail multiple sensitivity tests.

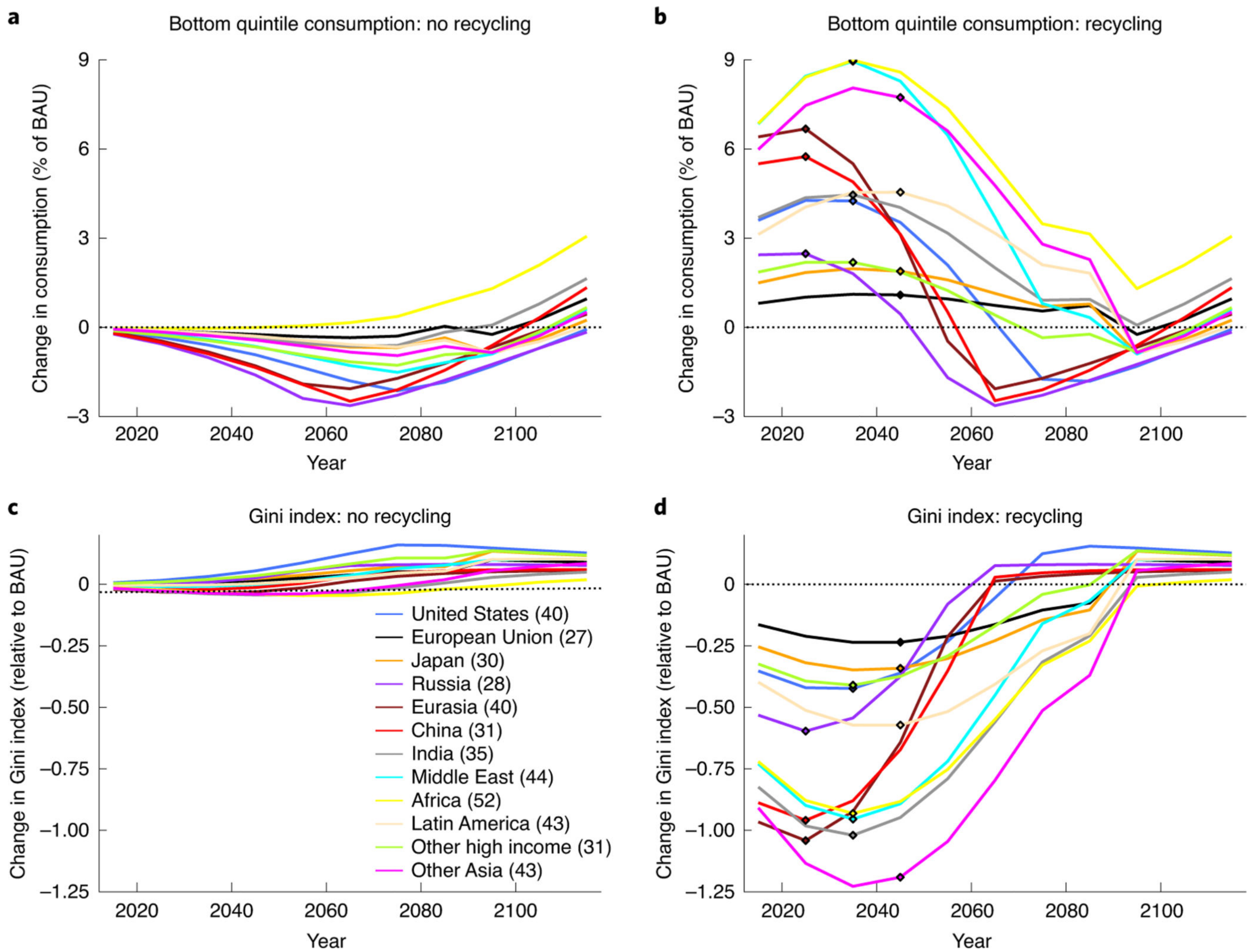

Fig. 2 |. Trade-offs between climate action, poverty alleviation and inequality turn into synergies with an equal per capita carbon dividend.

a,**b**, For a 2°C mitigation pathway, the change in per capita consumption of the bottom quintile in each region is shown, without (**a**) and with (**b**) equal per capita recycling, compared with the BAU case with no climate policy. **c**,**d**, The change in the Gini index, without (**c**) and with (**d**) equal per capita recycling, where a higher value indicates more inequality. The numbers in the legend are the initial Gini values. Diamond symbols identify the year of maximum carbon tax revenue as a percentage of regional consumption. (Results assume that each region's aggregate climate damages are distributed to quintiles in proportion to consumption, an assumption that makes the welfare impact of damages essentially equivalent to what they would be in more aggregated cost–benefit models including DICE, RICE, PAGE and FUND[51,52]. Further below and in Supplementary Fig. 14 we discuss results that modify this important assumption, showing that our main findings hold with other damage specifications and distributions).

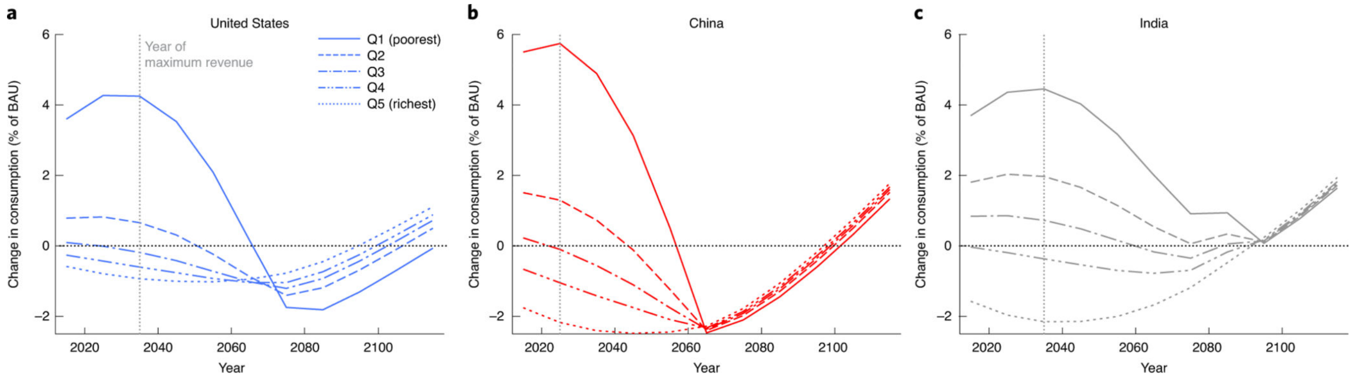

Fig. 3 |. Change in consumption of all quintiles in the 2°C mitigation pathway with the equal per capita recycling compared with the BAU case with no climate policy.

a–**c**, Change in consumption as a percentage of BAU over time for the United States (**a**), China (**b**) and India (**c**). The vertical dotted line in each panel identifies the year of maximum carbon tax revenue as a percentage of regional consumption. Q, income quintile of population.

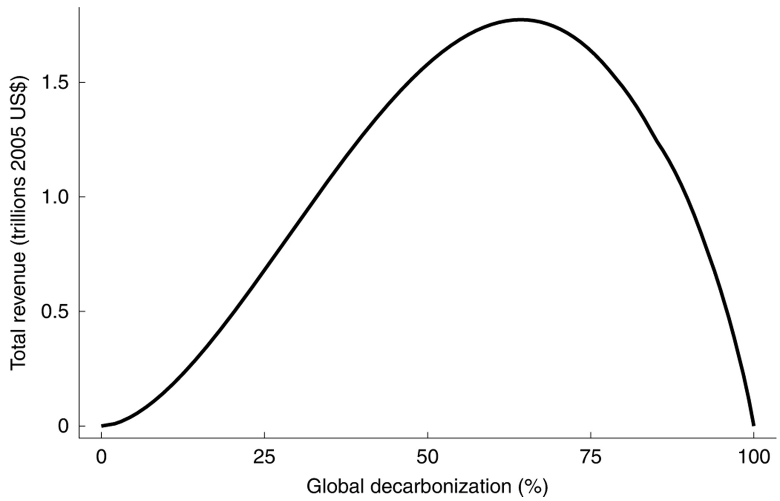

Fig. 4 |. the carbon laffer curve.

The curve is illustrated by plotting near-term decarbonization versus global revenue generated (here for 2025). Global decarbonization is the percentage reduction in carbon emissions compared with a BAU scenario with no climate policy.

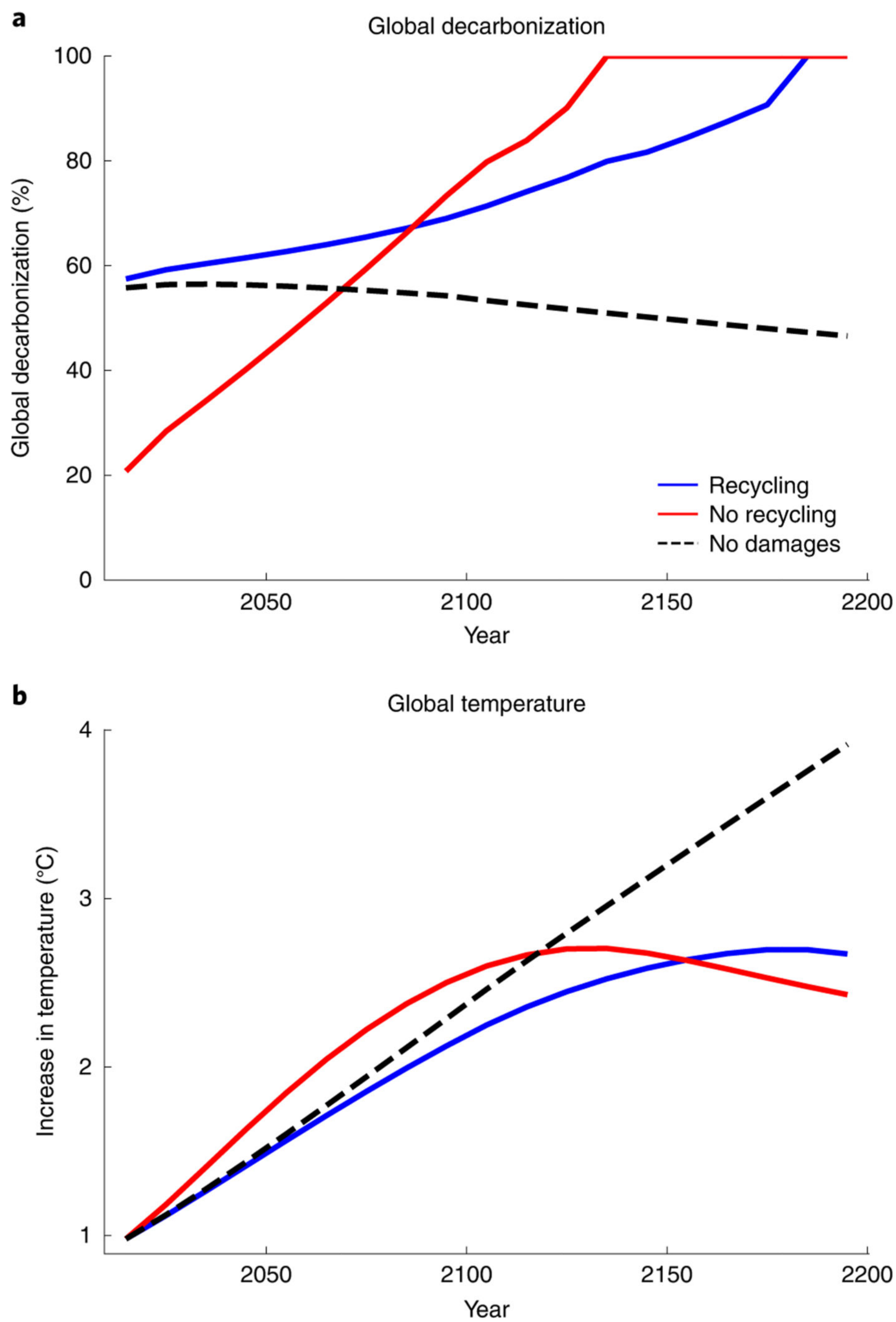

Fig. 5 |. Optimal mitigation with and without equal per capita carbon dividend.

a,**b**, Optimal decarbonization (**a**) and temperature (**b**) with and without revenue recycling, and a comparison case that assumes no climate damages; the latter shows how much mitigation is driven by progressive redistribution alone, as opposed to being driven by avoided climate damages. Global decarbonization in **a** is the percentage reduction in carbon emissions compared with a BAU scenario with no climate policy.