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ANALYSIS

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

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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

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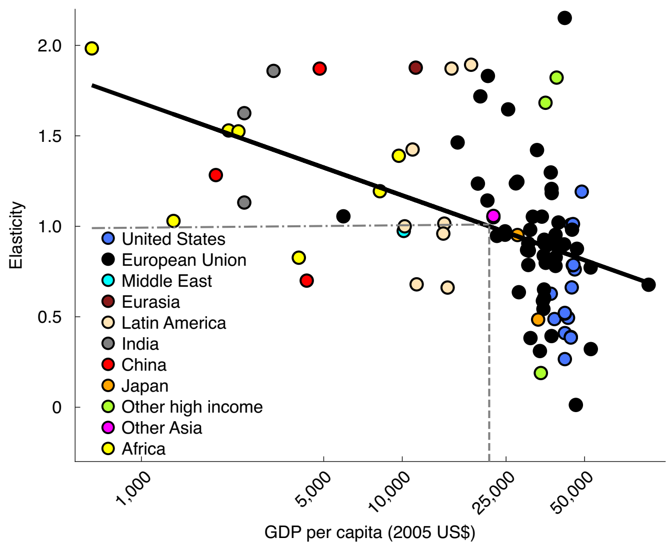

Fig. 1 | Estimates from the literature on the distribution of the initial burden of a carbon or gasoline tax and the resulting relationship with per capita GDP. This relationship (black line) is used to estimate the consumption elasticity of the initial burden before any possible redistribution as a 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.

(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

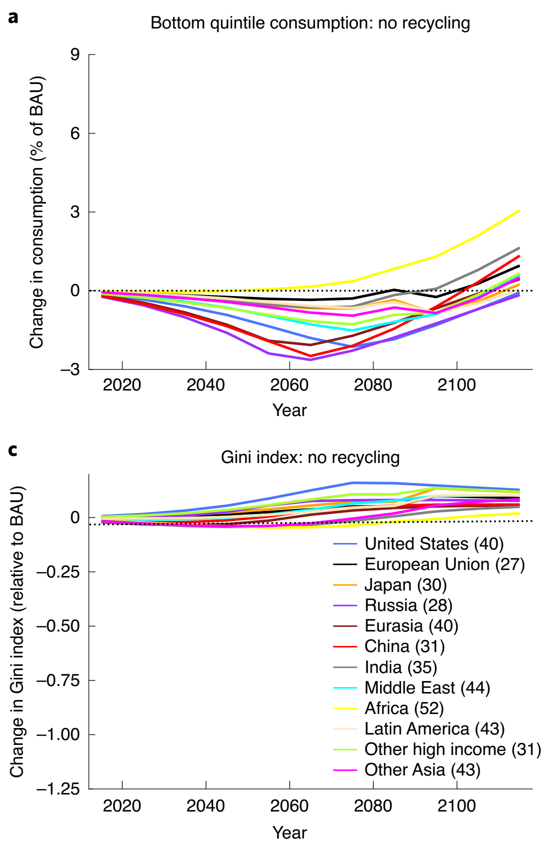

Fig. 2 | Trade-offs between climate action, poverty alleviation and inequality turn into synergies with an equal per capita carbon dividend. a,**b**, For a 2 °C mitigation pathway, the change in per capita consumption of the bottom quintile in each region is shown, without (**a**) and with (**b**) equal 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).

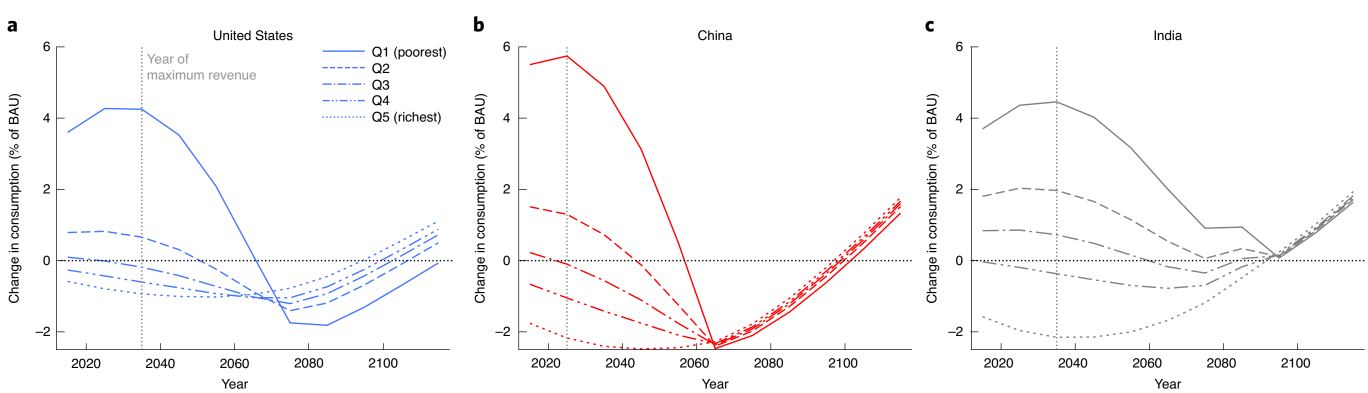

Fig. 3 | Change in consumption of all quintiles in the 2 °C mitigation pathway with the equal per capita recycling compared with the BAU case with no climate policy. a–**c**, Change in consumption as a percentage of BAU over time for the United States (**a**), China (**b**) and India (**c**). The vertical dotted line in each panel identifies the year of maximum carbon tax revenue as a percentage of regional consumption. Q, income quintile of population.

(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) decarbonization and tax revenue. Total revenue is highest in the 55–75% decarbonization range and decreases thereafter until full decarbonization ultimately implies that no revenue is generated (under full decarbonization there are no industrial emission to be taxed).

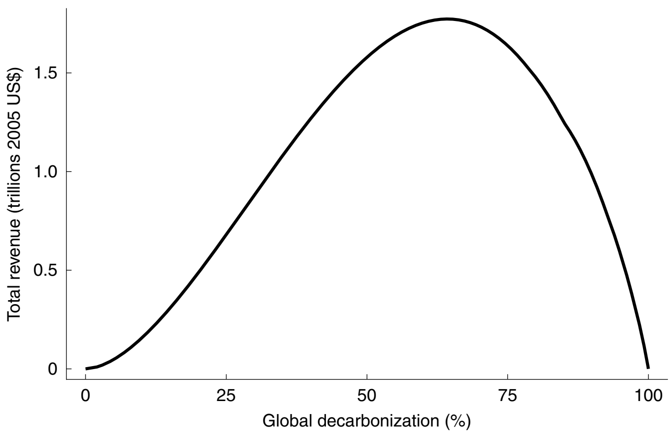

Fig. 4 | The carbon Laffer curve. The curve is illustrated by plotting near-term decarbonization versus global revenue generated (here for 2025). Global decarbonization is the percentage reduction in carbon emissions compared with a BAU scenario with no climate policy.

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

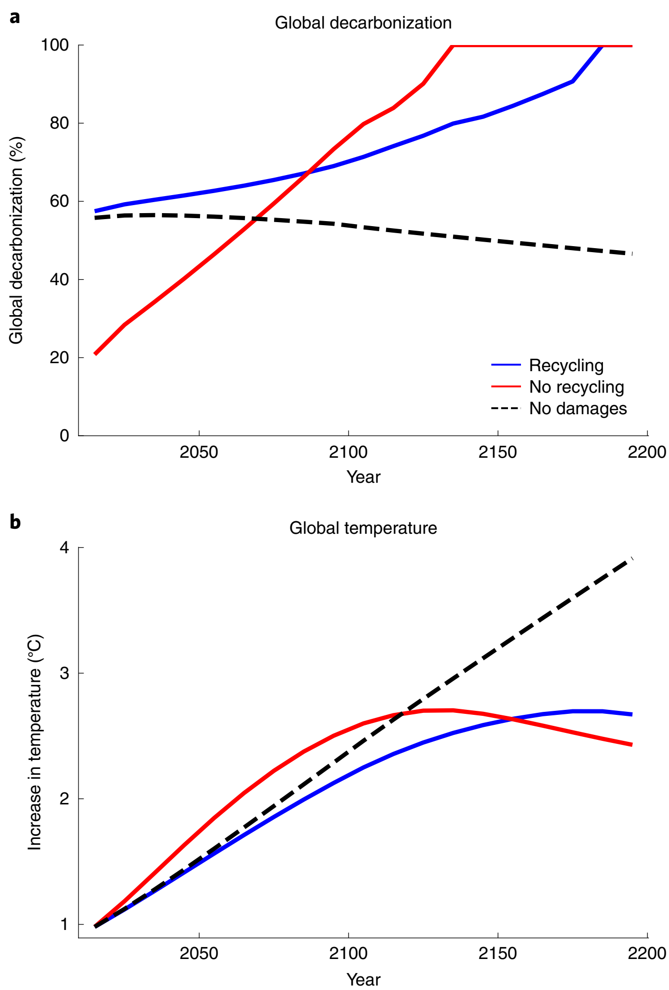

Fig. 5 | Optimal mitigation with and without equal per capita carbon dividend. a,b, Optimal decarbonization (**a**) and temperature (**b**) with and without revenue recycling, and a comparison case that assumes no climate damages; the latter shows how much mitigation is driven by progressive redistribution 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.

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.

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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

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

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

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

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 $\hat{\omega}_{it} = \hat{\alpha} + \hat{\beta} y_{it}$ according to the regression above for the model GDP per capita, y_{it}, of region j in period t.

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.

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.

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Author contributions

M.B., F.D., F.E., U.K., K.K. and N.S. are co-lead authors and contributed equally to the study. M.B., F.D., D.K., F.E., M. Ferranna, U.K., K.K., A.M., N.S. and S.Z. designed the research. M.B., F.D., S.F., M. Ferranna, D.K., U.K., K.K., A.M. and S.Z. conducted the literature review on the distributional impact of a carbon tax. F.D., F.E. and K.K. conducted the modelling. F.D., K.K., S.F., M. Ferranna, M. Fleurbaey, D.K., U.K., A.M. and S.Z. led the social welfare and tax analysis. M.B. and N.S. wrote the first draft of the manuscript with contributions from U.K. and K.K. All authors interpreted the results and edited the manuscript.

Competing interests

The authors declare no competing interests.

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Supplementary information

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

In the format provided by the authors and unedited

SUPPLEMENTARY INFORMATION

Climate action with revenue recycling has benefits for poverty, inequality, and wellbeing

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1. Literature review on the distributional impact of a carbon or gasoline tax

We conducted a review of the literature on the distributional consequences of carbon or gasoline taxes. As a starting point, we considered all studies included in the systematic review and meta-analysis by Ohlendorf et al. (2020)[1], which screened literature published between 1991 and 2017 on the distributional impacts of market-based climate policies. We added additional studies that (i) were published after the cut-off date in Ohlendorf et al., (ii) reported fuel expenditures or the carbon content of consumption, and/or (iii) analyzed sector-specific taxation that included household gasoline expenditure. A total of 97 estimates from 63 studies, cited by region in Supplementary Table 1, met the requirements to be included in the final analysis. The requirements for inclusion were the following. First, the distributional impact is reported for a policy *without* explicit recycling of revenues raised. Second, the impact is reported as the share of the initial burden relative to income (expenditure) by income (expenditure) quintile, where we also allow for a finer level of disaggregation. The initial burden is the sum of tax payments and mitigation costs as analyzed in the study. Third, the policy implemented is either a carbon or gasoline tax (with the exception of the studies that reported fuel expenditure or carbon content of consumption). Fourth, studies were published after 1999. Lastly, one study was excluded from the list as it reported costs from the policy for some income groups and gains for others, which a constant consumption elasticity of the distribution of the initial burden cannot represent. As can be seen from Table S1 and Figure 1 of the main text, the resulting list is geographically diverse and covers a wide range of development levels as measured by GDP per capita, but still disproportionately from the US and Europe.

Although not explicitly part of the elasticity estimates in Figure 1, the progressive impact of climate policy in low-income countries mirrors the distributional impact of removing fossil fuel subsidies. Instead of introducing a positive carbon price, removing a subsidy increases the price on emissions from negative to zero, which often has a progressive impact in developing countries.

Supplementary Table 1. Studies identified in the literature review and included in Figure 1 of the main text.

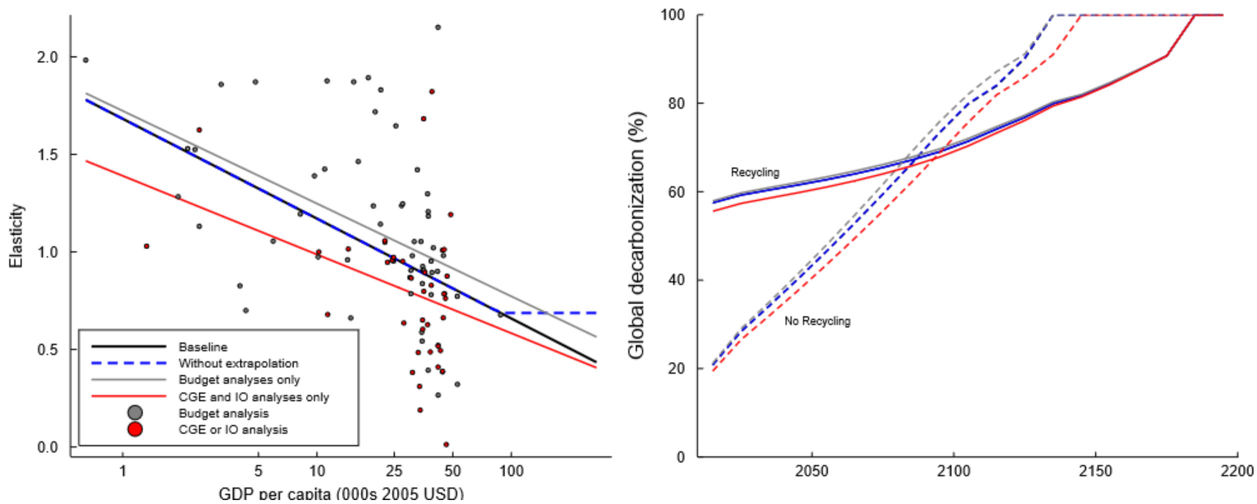
NICE Region	Studies included
USA	USA[2-17]
European Union	Austria[18], Belgium[18], Cyprus[19], Czech Republic[18,20,21], Denmark[19,22], Estonia[18], Finland[18], France[18,19,23-27], Germany[18,26,28], Greece[18], Hungary[18], Ireland[18,29,30], Italy[18,23,31], Luxembourg[18], Netherlands[18,32], Poland[18], Slovak Republic[18], Slovenia[18], Spain[18,20,23,26,33], Sweden[20,26], Switzerland[18,34], Turkey[18], UK[18,20,23,26,35-37]
Japan	Japan[23,38]
China	China[39-41]
India	India[42-44]
Russia	-
Eurasia	Serbia[26]
North Africa & Middle East	Iran[45]
Sub-Saharan Africa	Ethiopia[46], Ghana[47], Kenya[48], Mali[49], Nigeria[50], South Africa[51,52]
Latin America	Brazil[53,54], Chile[18,55], Costa Rica[56], Mexico[57-59]
Other Asia	Taiwan[60,61]
Other High Income	Australia[62,63], Canada[64]

The included studies differ in policy type and magnitude considered, but all include an estimate of the distribution of the initial burden by income or expenditure quintile (or finer level of disaggregation). For each study, we extracted the distribution of the initial burden, and matched it to the GDP per capita and consumption distributions of the study period. The GDP per capita data are based on the World Bank's World Development Indicators and measured in 2005 international dollars (the units of the NICE model). The distributions are extracted from the World Income Inequality Database[65] (WIID UNU-WIDER) and converted to consumption distributions by the method outlined below in Section 6 of this SI.

For each study, the share of the initial burden to each quintile was regressed against the consumption share of each quintile in the country to estimate the elasticities, which are then used as the y-axis values in Figure 1 (and Supplementary Figure 1, presented and described below).

The studies fall into one of three broad categories: direct budget analyses, in which the expenditure on fuel or the carbon content of consumption is calculated for each income group; input-output (IO), in which the impact of a carbon price on the expenditure of income groups is captured via input-output tables possibly including demand and supply side responses; and computational general equilibrium (CGE), in which behavioral adjustments and indirect effects via labor and capital income are captured. Ideally, we would base our analysis exclusively on CGE and to some extent IO studies, as these provide a more complete account of the effects that the initial burden should encompass. Unfortunately, only a few such studies exist and from a more limited geographic area, so we performed our primary analysis on the entire set of 97 estimates. However, we also performed sensitivity analyses to this approach by dividing the estimates by study type, pooling the 59 direct budget analyses (Supplementary Figure 1 grey line) and pooling the 23 IO and 15 CGE analyses (Supplementary Figure 1 red line). To allay concerns that the log-linear relationship between elasticity and income may not hold extrapolating beyond the range of observed GDP per capita, we also include a piecewise linear estimate that interrupts the downward sloping relationship at the highest observed GDP per capita (Supplementary Figure 1 blue line); this implies that the elasticities in the richest regions remain essentially unchanged, but that the elasticities in developing countries decrease until they reach that higher level of GDP. The CGE and IO studies are concentrated at higher levels of income, so the best fit line is overall lower. The slope (dependence on income) is not meaningfully changed.

Supplementary Figure 1 (right panel) shows that the main qualitative implications of the model remain the same for all four specifications.



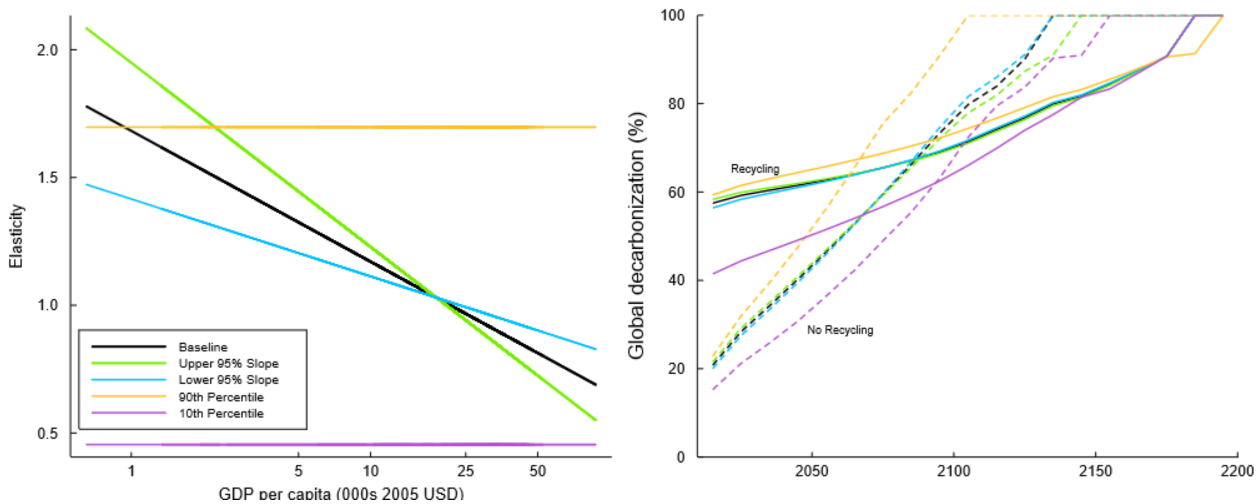
Supplementary Figure 1. The initial burden of a carbon or gasoline tax: sensitivity to study type. The left panel reports several different potential regression lines fit to studies on the distribution of the initial burden of a carbon/gasoline tax. The black "Baseline" line corresponds to the best fit line in Figure 1 of the main text, estimating the relationship between per capita GDP and the consumption elasticity of the distribution of the initial burden across all 97 estimates from the 63 studies selected from the literature review. The gray line is the best fit through only the 59 direct budget analyses. The red line is the best fit through only the 38 computational general equilibrium (CGE) and input-output (IO) analyses. The dashed blue line is a piecewise linear relationship that corresponds identically to the black line until the highest GDP per capita level found in any of the empirical studies and extends as a flat line beyond that point. The right panel reports corresponding optimal climate policy with these alternative calibrations of the initial burden of a carbon tax. (Baseline solutions in black, which reproduce the results presented in Figure 5 of the main text, are hardly visible as they are almost identical to the solutions in blue).

Figure 1 (and Supplementary Figure 1) has limitations. The empirical estimates behind each point mostly assume low to moderately ambitious climate policy. However, both the 2˚C cases and our central results of optimal mitigation entail deep decarbonization. Unfortunately, there are very few studies that estimate the distributional implications of such strong emission reduction scenarios.[66] For example, how the costs needed to decarbonize the last fraction of industrial and agricultural emissions will be distributed across the population is unknown. We thus perform a set of additional sensitivity analyses to test the robustness of our results to changes in the Figure 1 regression line.

First, we test uncertainty about the relationship between the consumption elasticity and the logarithm of income fitted in Figure 1 by calculating the 95% confidence interval of the regression line and constructing the flattest and steepest straight line that fits within that interval, depicted in Supplementary Figure 2 (left panel, green and blue lines). These two lines represent our first set of sensitivity runs. Both keep the negative relationship between income and consumption elasticity that we identified in Figure 1. However, one line models a scenario in which a carbon tax is even more progressive at lower income levels and then shows a steeper increase in regressivity with higher national income. The other line models a scenario in which the elasticity is less sensitive to the income levels of countries.

Second, we reject the relationship identified in Figure 1 altogether and assume that the distribution of the initial burden of the carbon tax is either always progressive or always regressive. The value of the elasticity for both of these scenarios is calculated as the 10th and 90th percentile of the distribution of estimates in Figure 1. The yellow and purple lines in Supplementary Figure 2 (left panel) show that these values are roughly 0.4 and 1.7, respectively. The two scenarios represent rather extreme cases that aim to test the validity of our results when we hardly know anything about how a carbon tax will affect different parts of the population. The distribution of the initial burden might be progressive because stranded assets under high carbon prices put the largest burden on capital owners that tend to be rich. On the other hand, deep decarbonization could increase the prices of necessity goods such as food and energy to such high levels that the carbon tax is highly regressive prior to redistributing the revenues.

The right panel of Supplementary Figure 2 shows optimal decarbonization corresponding to the different calibrations (left panel) and again confirms the same general pattern with and without progressive revenue recycling. Without it, decarbonization rates are low in the beginning of the time horizon and then increase towards the end of the century, with zero emissions achieved thereafter. With revenue recycling, substantial decarbonization is optimal early on and full decarbonization is delayed to sustain carbon tax revenues. Quantitatively, the results hardly change in the scenarios that retain the downward sloping relationship between the consumption elasticity of the distribution of the initial burden and income in Figure 1 (black, green, and blue curves in Supplementary Figure 2). Interestingly, we observe a shift in the quantitative behavior of optimal mitigation in the extreme scenarios with constant elasticities (yellow and purple lines); if the distribution of the initial burden from the carbon tax is always progressive, more ambitious mitigation is optimal both without and with progressive revenue recycling compared to the baseline case for almost the entire time horizon. As the carbon tax puts the largest burden on high-consumption quintiles, more aggressive climate policy enhances social welfare. The opposite is true if the distribution of the initial burden is always regressive; optimal mitigation is lower without (with) progressive revenue recycling compared to the baseline case without (with) recycling to shield low-consumption quintiles from the larger carbon tax burden that they have to carry.



Supplementary Figure 2. The initial burden of a carbon or gasoline tax: sensitivity with confidence interval on the regression line in Figure 1 and the 90th/10th percentile of studies. The green and blue lines in the left panel show the 95% confidence interval on the regression line and represent the interval around which the mean of the line could lie. The yellow and purple lines represent the 90th and 10th percentiles of all the estimates reported in Figure 1. The right panel reports corresponding optimal climate policy with these alternative calibrations. Baseline solutions in black reproduce the results presented in Figure 5 of the main text.

2. Poverty alleviation

To quantify the effect of recycling carbon tax revenues on poverty, we estimate the projected poverty rates in 2030 and 2040 for India, China, and the USA under different policy scenarios. For each of the three countries we fit a log-normal distribution through the latest available income data, and project that forward to 2030 and 2040 under the assumption that the coefficient of variation of pre-damage, pre-mitigation cost income remains constant, and that average income grows at the growth rate of GDP per capita in the model. We compute final (i.e., post damage, mitigation cost, tax, and redistribution) income by applying the assumptions of the NICE model concerning the distribution of the various costs. Damage costs are assumed to be distributed in proportion to income; mitigation costs and carbon tax payments according to the constant elasticity ω_{it}, as described in Section 1 above. For India we compute the proportion of people with incomes below $1.90 a day – the World Bank extreme poverty line – and for China we compute the proportion below $2.25 a day – roughly the PPP equivalent of the poverty line used by the Chinese administration.[67] For the USA we estimated the poverty line to be at $15,310 (in 2019 USD). This line coupled with our lognormal fit to the US income distribution results in a 2019 poverty rate of 10.5%, which was the empirical poverty rate in that year according to the household-dependent poverty thresholds used by the US Census Bureau.*

To parameterize the Indian distribution, we adopt the following procedure. We use the latest poverty headcounts for India available from the World Bank's Povcal database (up to 2011) and estimate three different logistic relationships respectively between the $1.90, the $3.20, and the $5.50 base poverty headcounts and time. This allows us to compute predicted poverty headcounts at those three levels for the year 2020.† We estimate a lognormal distribution through the three predicted headcounts (for the different poverty lines) to produce an income distribution for India in 2020 that is intended to accurately represent the very bottom of the income distribution.

For China, richer distributional estimates are available thanks to a recent research project detailing inequality in China (Piketty et al., 2019[68]). They compute centile income estimates up to the year 2015 based on nationally representative household surveys by China's Statistical Bureau. The upper tail of the Piketty et al. (2019) data is generated using a Pareto interpolation method, as it is known that top incomes do not fit a log-normal assumption well. As our focus is on poverty rates, we prioritize matching the bottom half of the distribution as closely as possible. To that end we use only the bottom 50% of earners to estimate our lognormal parameterization. The estimated 2015 distribution is projected forward to 2019 assuming that each income group grows at China's GDP per capita growth rate between 2015 and 2019.

For the US we likewise adopt a lognormal assumption for the bottom half of earners based on data from the Current Population Survey in 2019. Here we also exclude the top half of the distribution to better fit the range relevant for poverty estimation. Because the U.S. official poverty line depends on household size, we instead estimate the implied poverty line ($15,310) that generates official poverty rates for 2019 (10.5%).

The resulting projected poverty headcounts for 2030 and 2040 are shown in the tables below. We compute poverty headcounts for two different carbon tax (decarbonization) pathways:

- The 2˚C decarbonization pathway analyzed in Figures 2 and 3 of the main text, referred to below as "2˚C"
- The optimal decarbonization pathway under the assumption of progressive revenue recycling (blue line of main text Figure 5, referred to below as "Optimum")

For each, we compute two different poverty rates; one for Recycling scenario, and one for the No Recycling scenario. As an example, comparing the poverty rates for the scenarios with and without progressive revenue recycling under the Optimum decarbonization pathway for India in 2030, we see

* The poverty line used by the US Census Bureau varies by year and is equivalized by household size and derived from the cost of a minimum food diet multiplied by three to account for other family expenses. We apply the line at our lognormal fit to the income distribution produces the empirical poverty rate for 2019, and hold that line fixed for our poverty rate estimate in 2030 and 2040.

† The reason we use the historical data to project to 2020 is that there is no more recent publicly available data for India. Due to the politicization of the most recent estimation effort, the results of the 2016 wave of the Indian National Sample Survey have not been published.

that progressive revenue recycling reduces poverty in India from 3.2% to 1.3% of the population, or by nearly 30 million people when multiplied by India's projected 2030 population (Supplementary Table 2, second row). Under the 2 ˚C decarbonization pathway, progressive revenue recycling reduces the 2030 poverty rate in India from 3.1% to 1.8% (Supplementary Table 2, first row). In both cases the poverty rate is significantly reduced by redistributing the carbon tax revenues equally per capita to the whole Indian population. Supplementary Tables 3 and 4 report estimates for China and the USA, respectively.

Supplementary Table 2: Poverty rates projected for 2030 and 2040 in India. The poverty line used for India is the World Bank's extreme poverty line of $1.90 per day.

	2030		**2040**	
	No Recycling	**Recycling**	**No Recycling**	**Recycling**
2˚C	3.1%	1.8%	0.6%	0.2%
Optimum	3.2%	1.3%	0.6%	0.2%

Supplementary Table 3: Poverty rates projected for 2030 and 2040 in China. The poverty line used for China is $2.25 a day.

	2030		**2040**	
	No Recycling	**Recycling**	**No Recycling**	**Recycling**
2˚C	1.7%	0.8%	0.9%	0.3%
Optimum	1.8%	0.7%	1.0%	0.3%

Supplementary Table 4: Poverty rates projected for 2030 and 2040 in the United States. The poverty line used for the USA is $15,310 2019 dollars.

	2030		**2040**	
	No Recycling	**Recycling**	**No Recycling**	**Recycling**
2˚C	8.5%	8.0%	7.0%	6.4%
Optimum	8.6%	8.0%	7.1%	6.5%

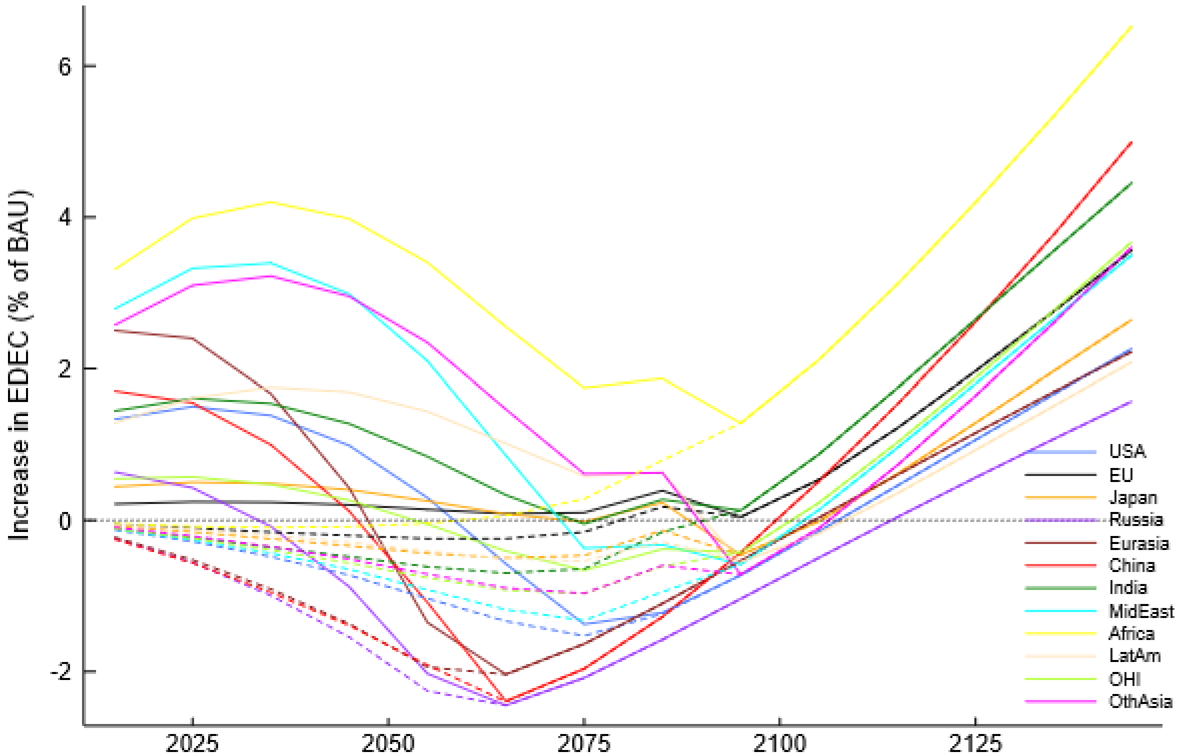
3. Wellbeing in the 2°C scenario

Here we show that the equal per capita recycling increases overall regional wellbeing compared to no recycling (Supplementary Figure 3). Wellbeing is expressed as the change in equally distributed equivalent consumption (EDEC) relative to the business-as-usual scenario.[‡] The percentage change in the figure shows how much more each quintile would have to consume along the business-as-usual pathway to arrive at the same regional wellbeing as in the relevant 2°C scenario, at each point in time.

Dashed lines in Supplementary Figure 3 show that without the equal per capita recycling, all regions are worse off relative to business-as-usual without revenue recycling until after 2100. This wellbeing loss is, for instance, equivalent to a 1.1% consumption loss for everyone in the US in 2070. Lower wellbeing comes from immediate mitigation costs and delayed benefits, with no change in inequality.

The solid lines in Supplementary Figure 3 show that with equal per capita recycling, wellbeing increases in the short-to-medium term because there is less inequality, turning the well-known intertemporal trade-off into a synergy. The difference between the curves with and without recycling in Supplementary Figure 3 measures the positive effect of inequality reduction: in 2040, the increase in welfare from reduced inequality is roughly equivalent to a 1% consumption increase for everyone in India and the US. Overall, the revenues from the carbon tax are large enough to make the reductions in inequality more important for wellbeing than the aggregate loss from mitigation costs along the 2°C pathway.

[‡] The EDEC is the level of consumption (in USD) that if given to the entire population of a region yields the same level of welfare of the region under the actual consumption levels.



Supplementary Figure 3. Change in wellbeing compared to BAU at each point in time and for each region. The 2°C target is implemented. Wellbeing is reported as equally distributed equivalent consumption with a constant elasticity of marginal utility, η=1.5. Solid lines depict the Recycling scenario, dashed lines the No Recycling scenario.

4. Global redistribution

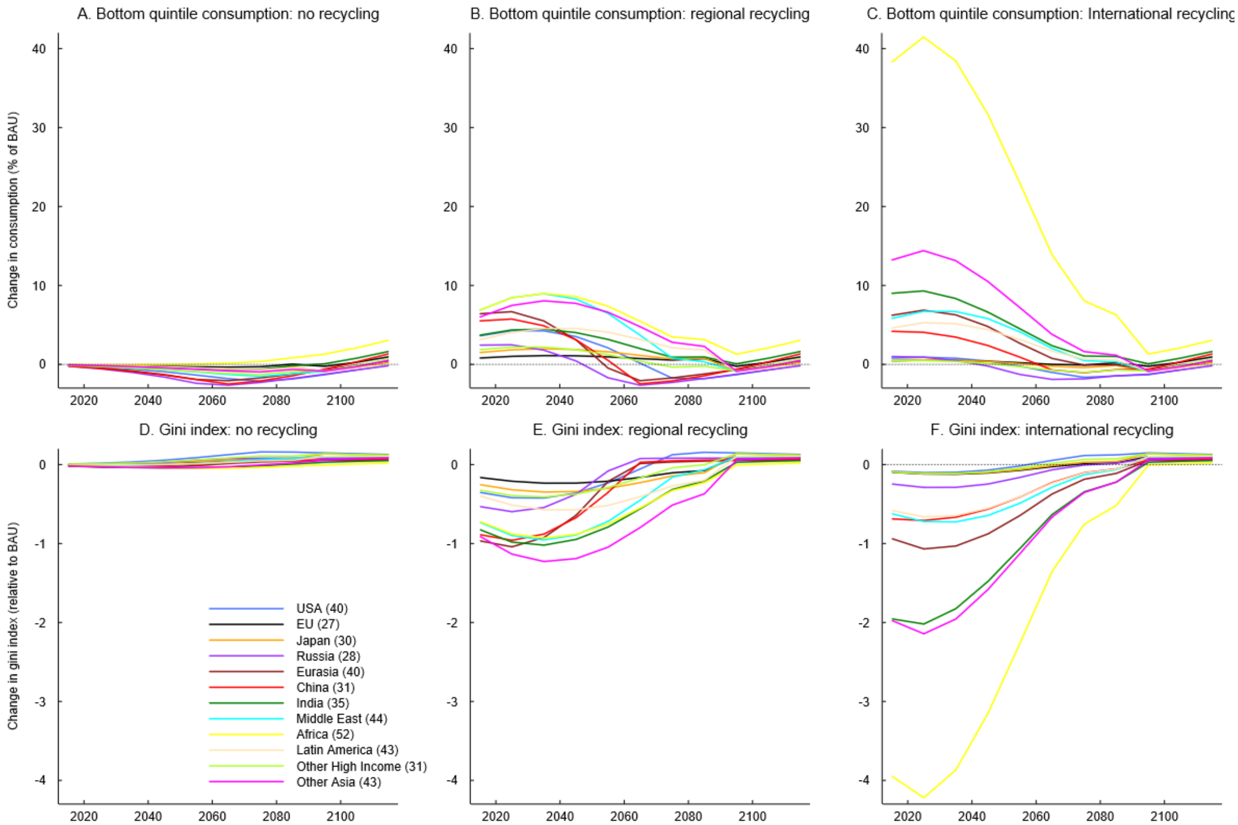
Here we compare our main results (when regional carbon revenues are redistributed within-region equal per capita) to results when global revenues are redistributed equal per capita globally. In Supplementary Figure 4 we present the impacts on bottom-quintile consumption and inequality for the 2 ˚C pathway.

In Supplementary Figure 5 we plot optimal decarbonization and temperature paths for a number of different assumptions about the use of carbon tax revenues. In black we plot the "No Recycling" (dashed) and regional "Recycling" (solid) optima that correspond to our main results reported in Figure 5. In addition, we consider three different ways of transferring the carbon tax revenues internationally:

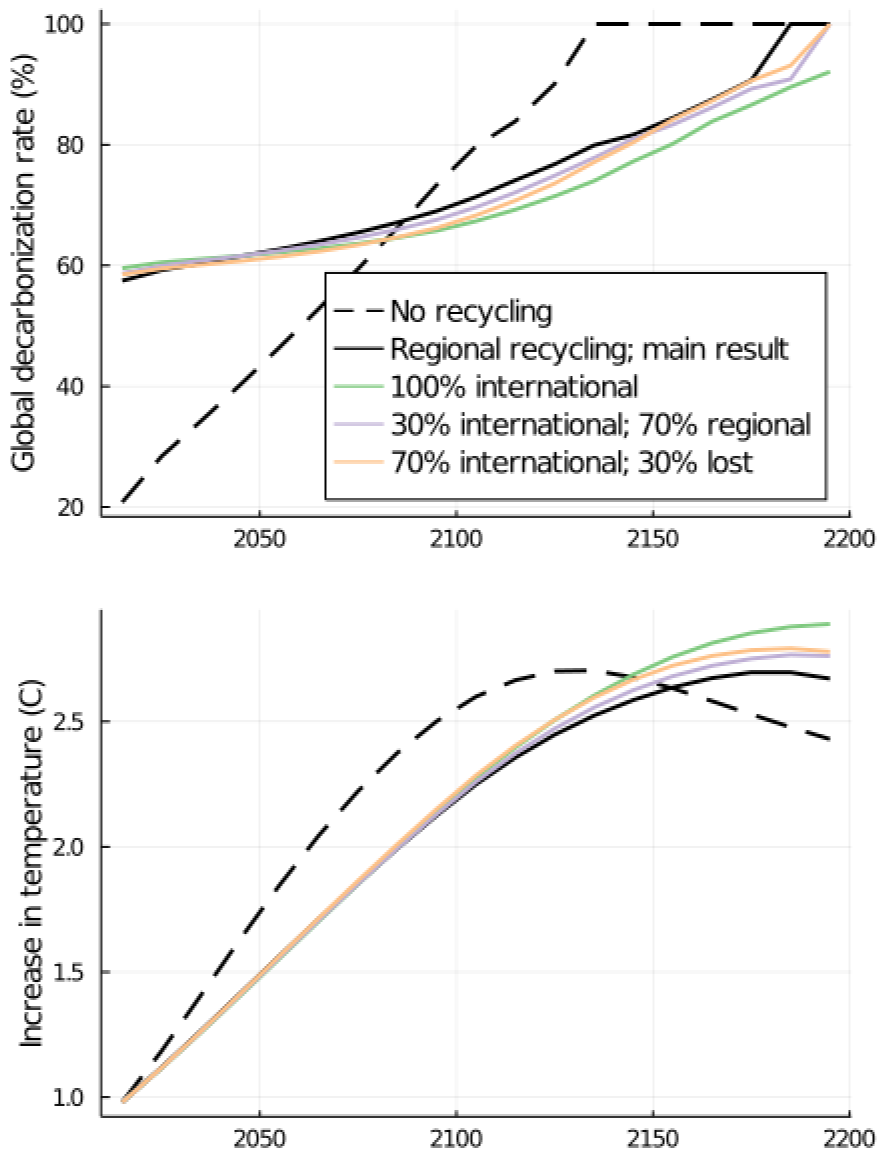
- 100% of global revenues are distributed equal per capita across the globe
- 70% global revenues are distributed equal per capital across the globe, while 30% of revenues are lost (for example, due to administrative costs associated with the disbursement of revenues).
- 30% of each region's revenue is put into a pot that is distributed equal per capita across the globe, while 70% of regional revenues are distributed equal per capita within the region

As the figure shows, the different variants with international recycling have a very similar decarbonization trajectory to the default assumption under which carbon tax revenues are recycled only within regions. The reason is that the incentive to decarbonize is already strong when revenues are only recycled regionally, so that even the benefit of transferring high-income region dividends to the poorest in lower-income countries does not substantially increase the incentive. However, this does not imply that international recycling has no important additional welfare gains. As seen in Supplementary Figure 6, international recycling produces a large welfare benefit to several regions versus the main result in which revenues are only recycled within regions, including Africa (in particular), India, and other parts of (non-China) Asia.

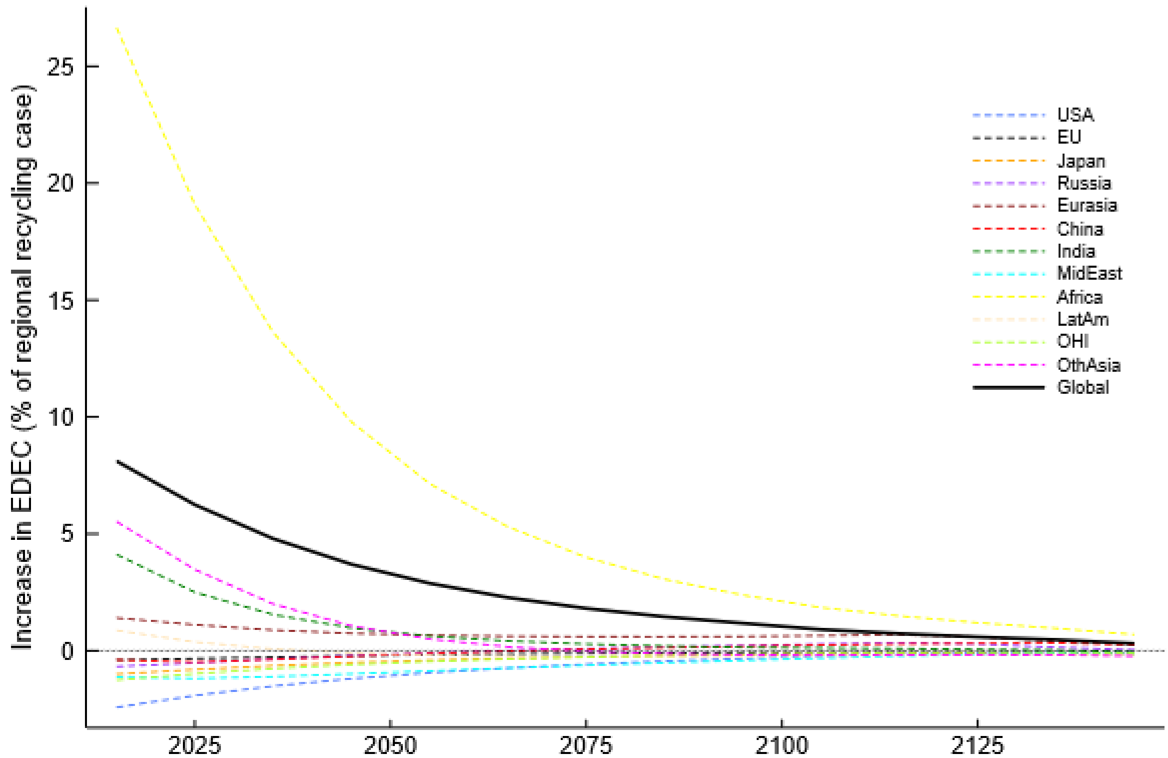
An interesting extension of our work would be to examine different regional carbon prices, allowing very different mitigation effort between regions at different levels of development.[69]



Supplementary Figure 4. Tradeoffs between climate action, poverty alleviation, and inequality turn into synergies with an equal per capita carbon dividend. The left two columns reproduce Figure 2 of the main text where regional carbon dividends are recycled equal per capita within-region. The right column reports the effect when 100% of global revenues are recycled equal per capita globally.



Supplementary Figure 5. Optimal mitigation with and without equal per capita carbon dividend, including international transfers. The black solid line reproduces the main result where regional carbon dividends are recycled equal per capita within-region. The other lines report the effect when a given percentage of global revenues are recycled equal per capita globally.



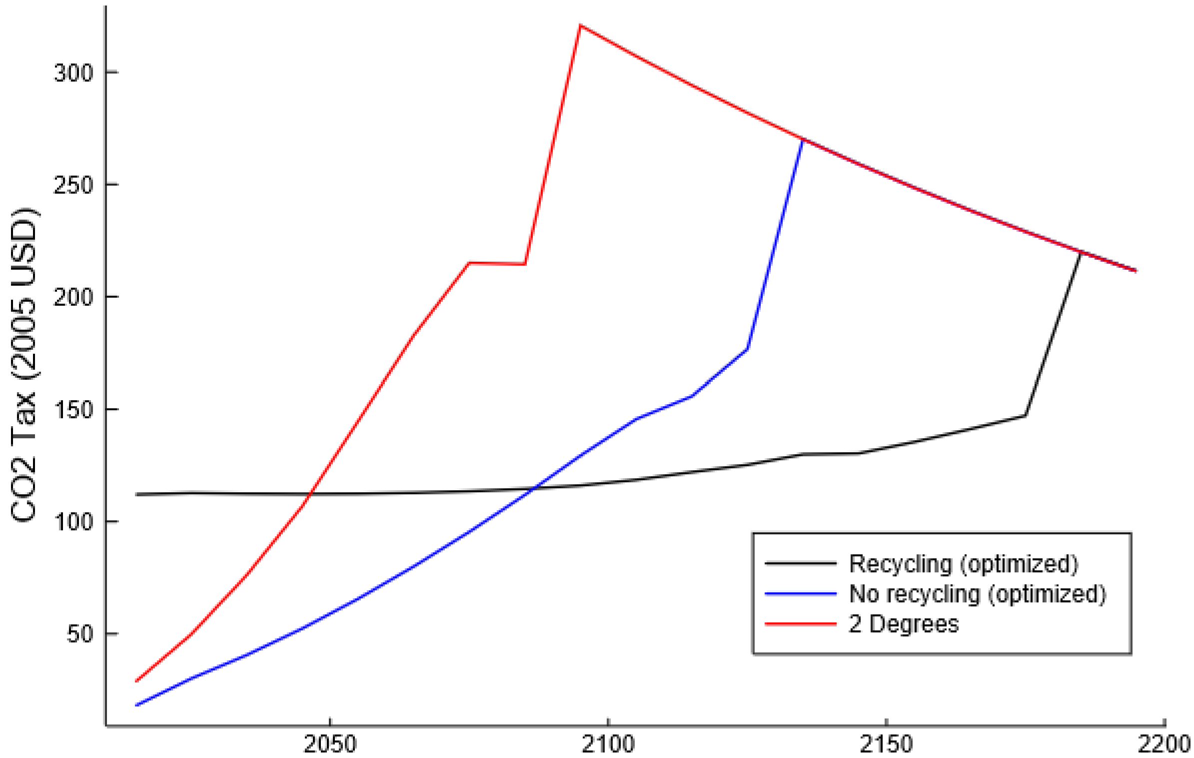
Supplementary Figure 6. Percent change in wellbeing in the optimal policy where 100% of global revenues are recycled equal-per-capita globally compared to the optimal policy with within-region recycling only (solid black versus solid green lines in Supplementary Figure 5). Wellbeing is reported as equally distributed equivalent consumption with a constant elasticity of marginal utility, η=1.5.

5. Carbon tax and dividend trajectories

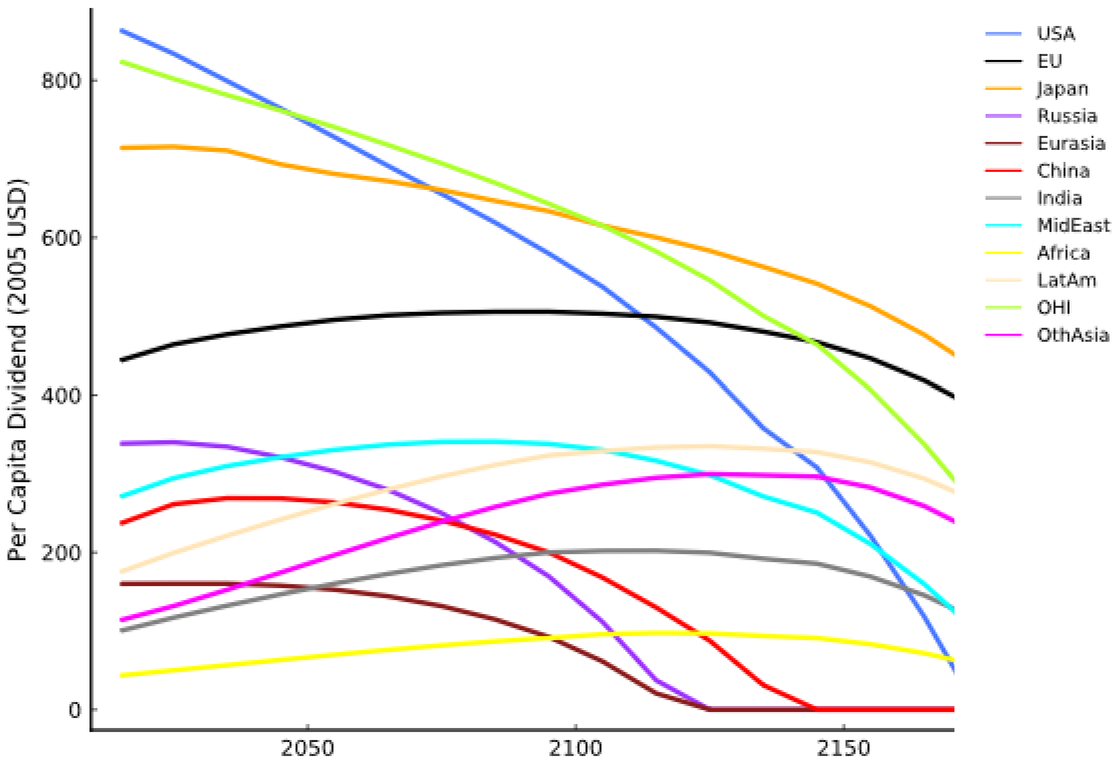
Supplementary Figure 7 reports carbon tax trajectories for the three central scenarios described in the main paper. As a point of comparison, the High-Level Commission on Carbon Pricing (2017)[70] chaired by Nicholas Stern and Joseph Stiglitz concludes that achieving the Paris temperature target requires a global carbon price of at least USD 40–80/tCO_2 in 2020 and USD 50–100/tCO_2 by 2030. The IMF (2019)[71] estimates that a global carbon price of 75 USD/tCO_2 in 2030 is necessary to reach the two-degree warming target, while Dietz and Venmans (2019) report a carbon price target starting at 45 USD/tCO_2 in the initial year and rising to 60 USD/tCO_2 in the 10th year and to 791 USD/tCO_2 in 100 years.[72]

It is more difficult to make comparisons with the optimal carbon price literature than with the 2 ˚C literature. Unlike most models, NICE features endogenous redistribution of revenues and heterogeneous households at the sub-national level. In addition, and perhaps more importantly, optimal prices can be highly sensitive to choices about the rate of time preference and inequality aversion. In one important recent paper, Hansel et al. (2020)[73] make a number of updates to the DICE model that have the net effect of increasing the social cost of carbon, including improving the climate model and allowing for higher temperature-related damages. Under similar discounting settings, our carbon taxes are somewhat lower than theirs, but well within the range of uncertainty they report.

In Supplementary Figure 8 we display the per capita dividends by region in the optimum with the equal per capita recycling. The figures lie within the range of estimates that can be found in the literature. For example, Carattini et al. (2019)[74] report a range of $89 (India) to $838 (Australia) in their simulations for the year 2030 given a carbon price of $40. We obtain regional carbon dividend estimates that range from $50 (Africa) to $834 (USA) in 2030. At the global level, Carattini et al. calculate a per capita dividend range of $189 to $325 for carbon prices between $40 and $80. The global per capita dividend from our calculations would be $230 in 2030 (note that our central scenario distributes carbon tax revenues regionally, not globally), $231 in 2060 and $220 in 2110. Davies et al. (2014)[23] obtain a global per capita dividend that increases from around $560 in 2015 to ca. $1,970 in 2055 and to ca. $3,150 in 2105 (own calculations). These estimates are notably higher compared to our results because Davies et al. have significantly lower decarbonization rates. Marten and van Dender (2019)[75] estimate potential regional revenues with carbon prices of $30 relative to the respective GDP in 2016. We translate these estimates to per capita dividend estimates by using OECD GDP per capita estimates (https://stats.oecd.org/Index.aspx?DataSetCode=PDB_LV). This leads to potential per capita dividends of ca. $570 in the US, ca. $580 in China and ca. $480 in Japan, the same order of magnitude as our estimates.



Supplementary Figure 7: CO_2 tax (in 2005 USD) trajectory for the base case with and without revenue recycling and for the 2 ˚C scenario.



Supplementary Figure 8: Annual carbon tax dividends per capita (in 2005 USD).

6. Assumptions about background inequality

An essential component of the model is the assumed background distribution of consumption q_{ijt}, before damage, mitigation cost, and taxes (see Methods for relevant equations). This distribution (inequality) in the first model period is estimated by aggregating the most recent country-level distributional data from the World Income Inequality Database (WIID)[65] to a regional distribution. The central assumption of the model is that this background distribution remains invariant throughout the modelling horizon, but we conduct sensitivities to different future projections (Supplementary Figure 9), as described in detail below.

The WIID contains distributional information for most countries up to 2018, often from a number of surveys for the same country and year. For each country we took the last year for which data was available and averaged the distribution across all available surveys in that year. Distributions based on consumption surveys were used as provided, while the quintile shares from income and earnings surveys were transformed to correspond more closely to consumption distributions according to the estimated adjustment in Appendix C of Pinkovskiy & Sala-i-Martin (2009).[76] The adjustment is based on matching quintile shares for country-years in which there were both consumption and income surveys, and estimating the relationship between consumption and income shares for the approximately 100 country-years for which both types of data were available. We apply the exact relationship estimated in [[76]].

For single country regions, such as USA, China, India, Russia, and Japan, the resulting country quintile distributions constitute our estimates for q_{ijt} in the current (first) period. For multi-country regions, the country-level distributions are aggregated up to region-level distributions.

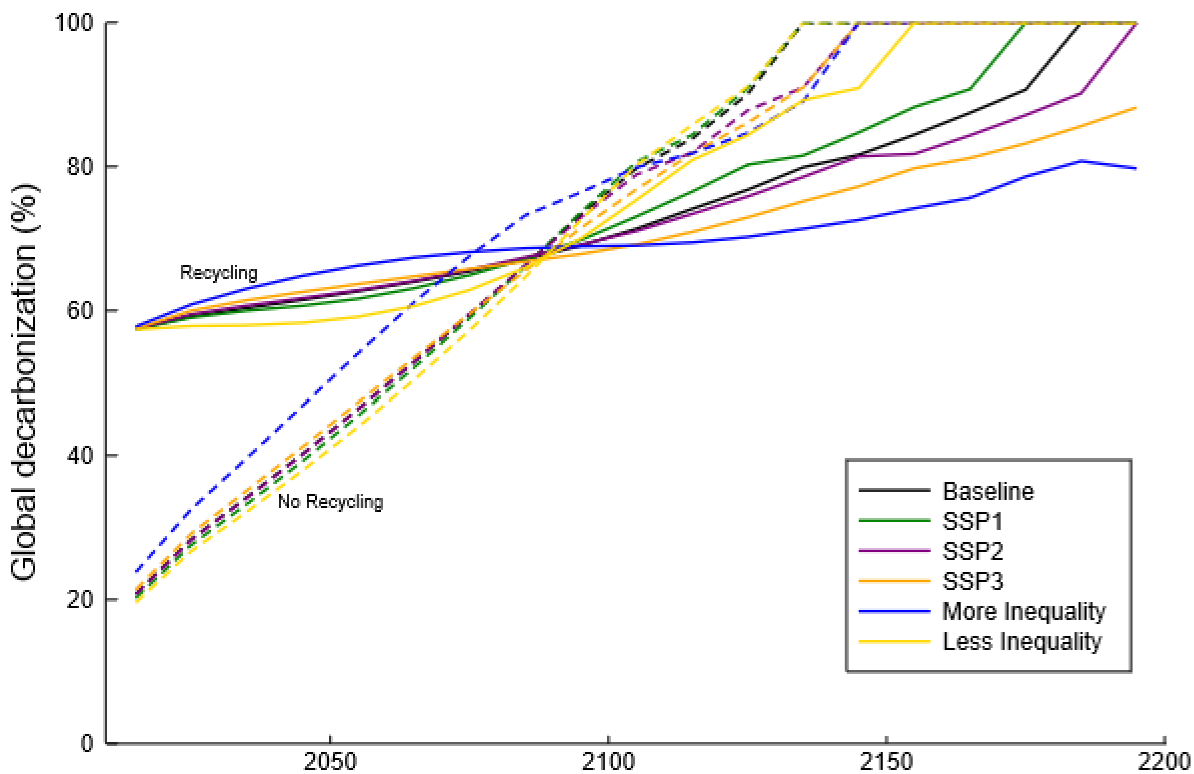
Our central assumption projects these estimates for the current distribution in each region to all future periods, i.e. $q_{ijt} = q_{ij}$. To test the sensitivity of our results to different assumptions about inequality, we consider a number of different projections of the consumption distributions in the twelve model regions through 2100 (under all specifications the distributions remained invariant past 2100). The projection with decreasing inequality is generated as follows: the distribution estimated from the WIID dataset is taken as the initial distribution. For each of the subsequent 10 decades the distribution is transformed by applying a proportional tax with the magnitude $\tau_t = 3\% \times t$ to q_{ijt}, where t is measured as the number of decades since 2015, and the revenue is redistributed equally per capita amongst all the population groups within the region. This has the effect of *decreasing* the Gini coefficient by 3% per decade. So if a region started off with a Gini coefficient of 20%, after 10 decades of this process it has a Gini coefficient of 20%*(1-0.03)^10 = 15%.

The projection with increasing inequality is computed analogously: t decades into the model a lump sum poll tax is levied which funds a $3\% \times t$ proportional subsidy to all quintiles: in each decade, therefore, the Gini coefficient grows by 3%.[§]

In addition to these two “increasing” and “decreasing” inequality assumptions, we test against yet another set of projections of the consumption distribution based on the country-by-country projections of Gini

[§] Since a sufficiently large lump-sum tax can lead to the poorest quintile receiving a negative share, a constraint is added to ensure this does not happen.

coefficients in Rao et al (2019).[77] That article estimates the evolution of the Gini coefficients in each of the five Shared Socioeconomic Pathways (SSPs) by estimating the effect on the Gini of a number of indicators – total factor productivity, education distribution, trade, and redistributive policy – that are projected independently for the SSPs. Here we note that although the SSPs contain projections of these and other variables, our goal here is to isolate the effect of inequality; therefore we make no other changes, since some of these other variables (e.g. population growth) will also affect optimal policy calculations.[78] To produce projections of the regional income distributions consistent with these country-by-country Gini projections we transform the WIID country level distributions by applying a proportional tax that is redistributed equally per capita (just as described in the paragraph above) so that the Gini coefficients transformed distributions have the same rate of change as estimated in Rao et al. These transformed distributions are then aggregated up to regional distributions. From the point of view of inequality, the SSPs are divided into high (SSP3 and 4), low (SSP1 and 5) and middle of the road (SSP2). Because SSP3 and SSP4 as well as SSP1 and SSP5 are so similar, we only plot the results for one of each pair.



Supplementary Figure 9. Optimal climate policy with different assumptions about future background inequality. "Baseline" refers to the case presented in the main text. SSP1 corresponds to the low inequality projection amongst the SSP scenarios and SSP3 corresponds to the high inequality scenario. SSP2 is "middle-of-the-road" and yields similar optimal decarbonization to our baseline scenario. Unlike SSP1, "Less inequality" embodies significant reductions in inequality by the end of the century, so that the "Recycling" optimum decarbonizes significantly earlier than for all the other projections.

7. Social welfare assessment and discounting

The objective being maximized by the NICE model is the following standard discounted utilitarian social welfare function:

$$\sum_t e^{-\rho t} \sum_i \frac{P_{it}}{5} \sum_j \frac{c_{ijt}^{1-\eta}}{1-\eta}$$

where c_{ijt} is the average per capita consumption in quintile *j* of region *i* in period t, and P_{it} is the population size of region *i* in period t. Function $u(c) = c^{1-\eta}/(1-\eta)$ is the utility function. The formula has the following interpretation: in each period, in each region the social welfare is equal to the sum of the utility of per capita consumption across quintiles, multiplied by regional population size. The sum of the social welfare in the different regions at a given period gives the total global welfare in that period. The intertemporal social welfare is just the discounted sum of per period global welfare.

There are two important parameters in the social welfare formula. First, parameter ρ is the rate of pure time preference: it is used to weigh the value of future social welfare. Second, parameter η is the consumption elasticity of marginal utility: it is used to evaluate the gain in welfare from an incremental increase in consumption. When $\eta>0$, it is more valuable to social welfare to increase the consumption of a poor person than that of a rich person by the same amount. Hence η also governs how valuable redistribution is.

Parameters ρ and η play a key role in the so-called "Ramsey equation" that provides the value of the social discount rate. The social discount rate is the rate at which future costs and benefits of a policy are discounted: it thus plays a key role in intertemporal economic analysis. According to the Ramsey equation, the social discount rate is equal to $\rho + \eta g$, where *g* is the consumption growth rate. The value of the social discount rate plays a key role in shaping the optimal climate policy (Stern (2006)[79]; Nordhaus (2007)[80]).

The rate of pure time preferences ρ, has been widely debated in the literature (see Stern (2006)[79]; Nordhaus (2007)[80]; and Fleurbaey et al., (2019)[81], for a discussion). There are basically two approaches. The prescriptive approach considers that intergenerational equity requires the rate of pure time preferences to be close to 0%, to treat all generations in the same way. On the other hand, a so-called "descriptive" approach endorsed by Nordhaus requires that the social discount rate should reflect the preferences of a representative consumer. Using values of interest rates, Nordhaus thus proposed to use ρ=1.5%. The latest IPCC report asserts that a "relative consensus emerges in favour of ρ=0".[82] But in an expert survey Drupp et al. (2018)[83] found a mean of *pure time preference of* 1.1%, thus not far from the 1.5% of Nordhaus.

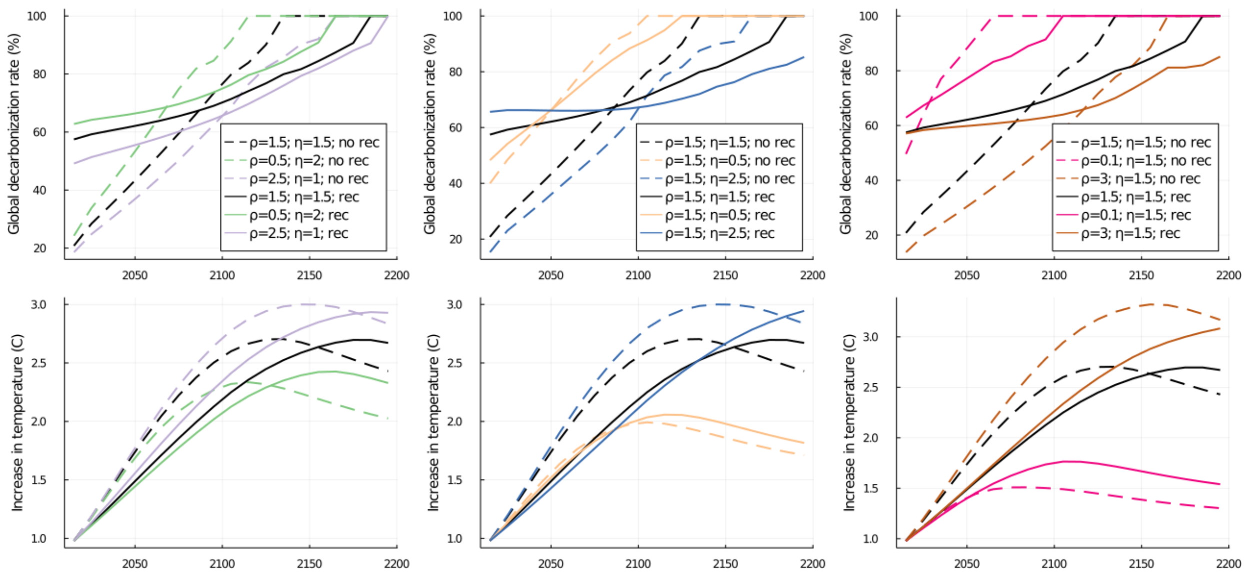
The parameter η serves multiple purposes and has received several interpretations in the literature. As explained above, under one interpretation the parameter quantifies the aversion to inequality (or the preference for redistribution). Thus, in our setting it governs both inequality aversion within a country (or regions), inequality aversion between countries and inequality aversion between generations. Anthoff and Emmerling (2019)[84] proposed an alternative definition of social welfare that disentangles withingeneration and between-generation inequality aversion. Adler et al. (2017) have proposed prioritarian social welfare measures that disentangle risk aversion and inequality aversion. Other formulations are possible.[81] Despite the variety of interpretations, the IPCC report again asserts that a "relative consensus emerges in favor of (…) η between 1 and 3".[82] Focusing on the intergenerational equity interpretation (using the Ramsey discounting formula), Drupp et al. (2018)[83] find an average value of elasticity of marginal utility of 1.35 in their survey of experts on discounting, again not far from our baseline assumption. Possible values are quite dispersed, although mostly concentrated in the range 0.5-3. Studies on between-regions inequality aversion typically find lower values: for instance, Tol (2010)[85] estimated the value of the elasticity of marginal utility to be around 0.7.

Our objective here is not to contribute to the literature about the right formulation of social welfare, but rather to assess the sensitivity of our results to the choice of ρ and η using values in the range usually considered in the literature.

In the leftmost panel of Supplementary Figure 10 we vary both ρ and η in such a way that the social discount rate is held approximately constant by the Ramsey equation at current growth rates. This is in the spirit of the descriptive approach to discounting espoused by Nordhaus (2007)[80], Weitzman (2007)[86], and Dasgupta (2007)[87]. Increasing η while lowering ρ in such a way keeps the current consumption discount rate unchanged, but reduces future discount rates as the growth rates g fall. This results in greater optimal decarbonization rates in the future across all optima. The optima with recycling also decarbonize more initially, since greater values for η increase the value of the carbon tax revenues that are distributed. That effect, combined with the increased future incentive to decarbonize from the decreasing discount rate the optima with recycling have higher decarbonization across the board with larger values for η. The qualitative difference between the "Recycling" and "No Recycling" optimum – whereby the former decarbonizes more initially, and then delays full decarbonization for longer – is independent of the Ramsey consistent specification.

In the middle panels we only vary η (holding ρ fixed at the default value of 1.5%). The optimum under the "No Recycling" policy decarbonizes more and more quickly when η is *lower.* This is due to the fact that η governs intergenerational inequality aversion. Reducing η, while holding ρ fixed, increases the overall benefit from mitigation by weighing the future benefits in avoided climate damages – that accrue to richer people on average – by less. The (initial) effect on the optimum under the "Recycling" policy is inverted: greater η results in greater initial decarbonization. This is because of the same effect that raises the "Recycling" decarbonization rate at higher values of η in the leftmost panels: the value of the reduction in inequality from the progressive use of revenues make a stronger policy optimal. Furthermore, if η is sufficiently low, the difference in optimal decarbonization profile between the "Recycling" and "No Recycling" policies shrinks. At η =0.5 the difference still exhibits the crossing pattern we observe under our default assumptions, but it is already quite small. At η =0 the difference would disappear entirely.

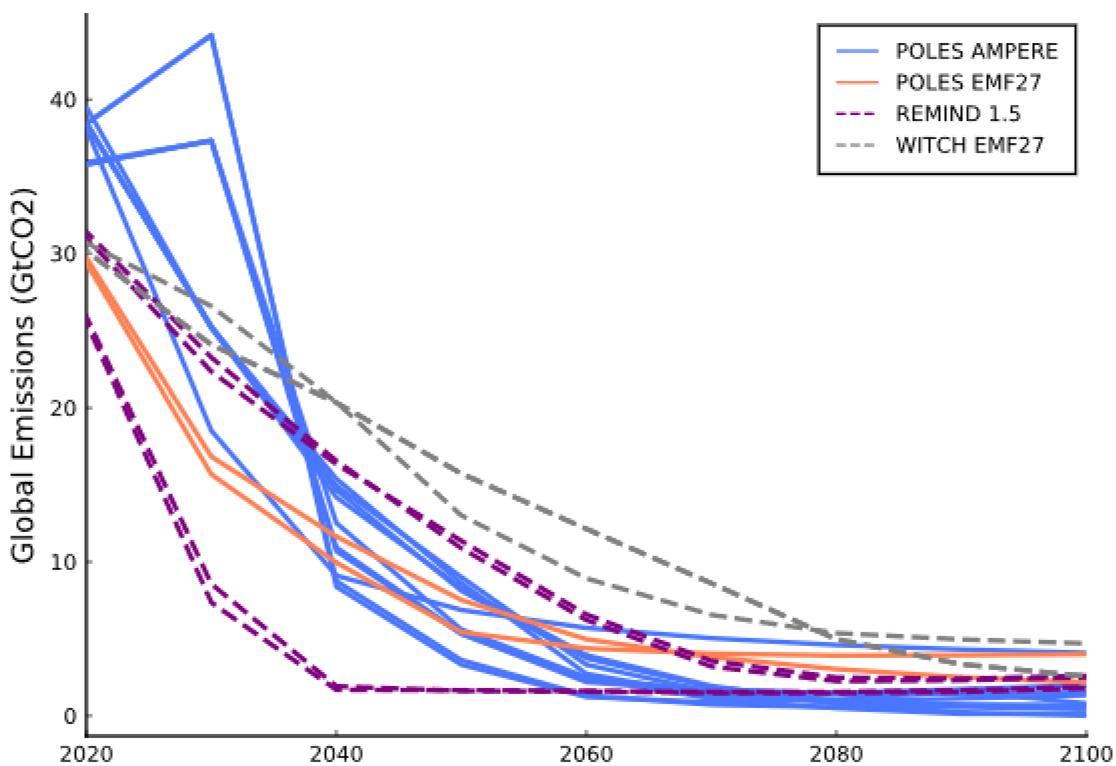
In the rightmost panels we vary ρ (holding η fixed at the default value 1.5). This is the most straightforward effect. The greater pure time preference reduces the value of future avoided climate damages, thus reducing the optimal decarbonization rates. The crossing behavior of the "Recycling" and "No Recycling" optima holds throughout, though in strongly attenuated form for very low discounting, as optimal decarbonization rates are already high initially even for the "No Recycling" policy.



Supplementary Figure 10: Optimal decarbonization rate and temperature paths for different discounting assumptions. The leftmost panels vary the pure rate of time preference, ρ, and the elasticity of marginal utility, η, so that by the Ramsey equation the same consumption discount rate holds at an assumed consumption growth rate of 2%. The middle panels vary only η, and the rightmost panels vary only ρ. The paths for default assumption in the paper, ρ=1.5% and $\eta = 1.5$, are plotted in black in all three columns as a reference point.

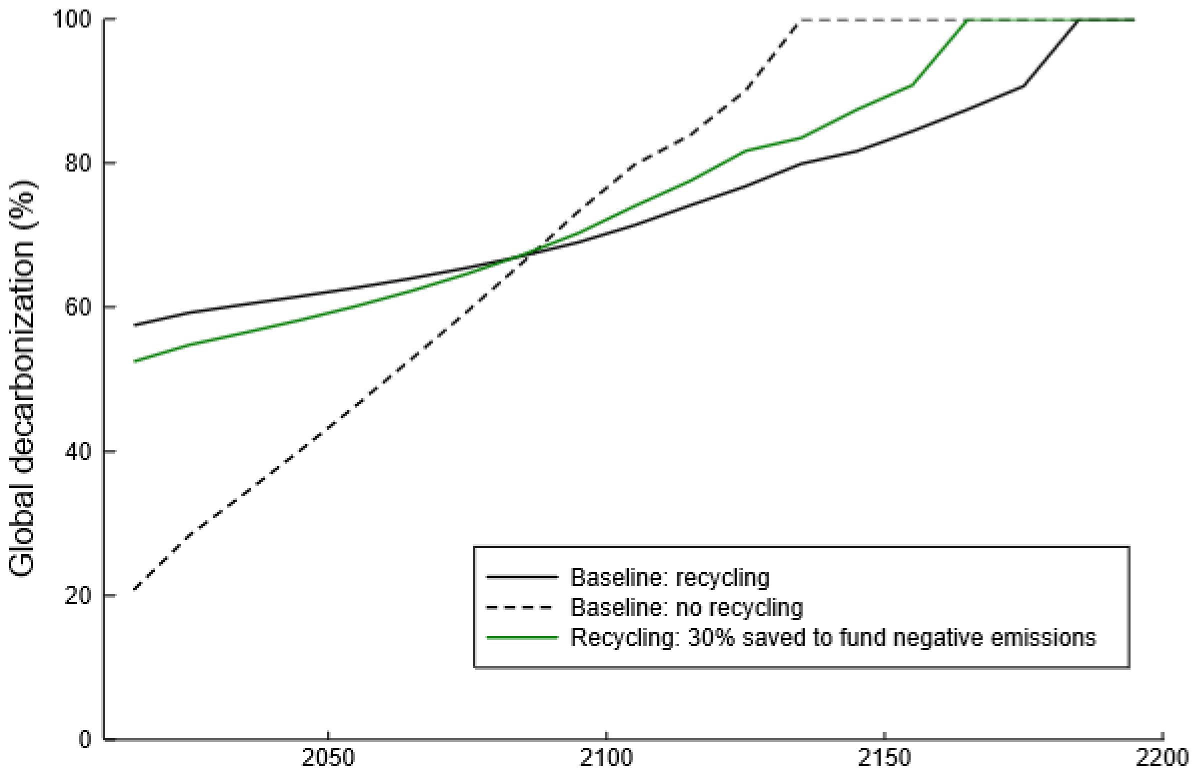
8. On negative emissions

Like many other papers using cost-benefit integrated assessment models, we do not assume net negative emissions at any point over the time horizon considered. This may raise a question about the feasibility of limiting temperature increase to 2°C above pre-industrial levels (the scenario analyzed in Figures 2 and 3 of the main text) without allowing for net negative emissions. Although it is true that ambitious climate targets (2°C, 1.5°C) are often associated with net negative emissions after 2050, there are a number of model runs showing that it may be possible to reach the 2°C target without them. For example, we found 19 such runs in the IPCC AR5 scenario database, from 3 leading process-based integrated assessment models (Supplementary Figure 11 below).



Supplementary Figure 11. Emissions over time (GtCO2) for 450 ppm scenarios (i.e., scenarios compatible with 2°C stabilization) from various model inter-comparison exercises as gathered in the AR5 scenario database (https://tntcat.iiasa.ac.at/AR5DB/). Each color corresponds to a particular model and model version, while the different lines correspond to various scenario assumptions (e.g., in terms of technology availability or near term emission pathway).

Nevertheless, due to the important questions about negative emission technologies – and how to fund them – it is important to connect our work to these discussions. Specifically, it is reasonable to assume that funding future negative emissions would require significant intergenerational streams for such a scheme to work. Therefore, we ran an experiment whereby only a proportion (70%) of carbon tax revenues are redistributed to illustrate the case where those revenues are saved for later to fund negative emissions. The loss of the revenue pushes the optimal mitigation trajectories modestly towards the No Recycling case. Larger fractions saved would make this effect more pronounced and vice-versa.



Supplementary Figure 12. Mitigation trajectories with 30% of revenues saved (not recycled).

9. Relation of this study to optimal taxation literature

A. The redistributional double dividend

The equal per capita recycling we implement in NICE quantifies the possibility of what some authors have termed the "double dividend of redistribution".[88] Such a double dividend can occur if redistribution through the income tax system is insufficient and the total effect of the carbon tax and the recycling is redistributive. An equal-per-capita redistribution renders the environmental tax reform progressive (see Figure 2 of the main text). Even though the initial burden is regressive in some regions without the equal per capita recycling of revenues (Figure 1), uniform lump sum transfers offset these effects. Jacobs and de Mooij (2015)[89] and Klenert et al (2018)[88] show that with a carbon tax and equal per capita redistribution, the optimal tax level differs from the first-best and may be above or below the Pigouvian level, i.e. the level of the tax that takes account only of the inefficiency generated by climate change externalities.

The possibility of a double dividend in general has been much debated in the literature, in particular in relation to the recycling of the carbon tax through a reduction in distortionary taxes such as the income tax. A literature relying on representative-agent models (see, for example, Bovenberg and de Mooij (1994)[90] and Goulder (2013)[91]) has shown that lowering the income tax with the carbon tax revenue only replaces some disincentives with others and cannot generate a double dividend in terms of efficiency gains. Moreover, it has identified a specific deadweight loss due to a "tax interaction effect," when the carbon tax reinforces the disincentives on earnings already present under the income tax.

Jacobs and de Mooij (2015) highlight the limitations of such representative agent models. In these models, the presence of a carbon tax increases the cost of the income tax, and therefore the cost of public funds, while the income tax provides no distributional benefits. In the presence of heterogeneous agents, in contrast, the income tax serves a distributional purpose. At the optimal income tax, the marginal cost of public funds is one and there is no interaction between the carbon and the income tax through this channel. Still, lowering the income tax with carbon tax revenue would move the tax system away from the optimum and hence a double dividend in efficiency terms would not occur. And the carbon tax cannot improve the distribution either, so that it can be set according to the first-best Pigouvian tax rule (under some preference separability conditions).

A double dividend through redistribution is possible when the income tax is suboptimal and further redistribution with the carbon tax does not interfere too much with the disincentives generated by the income tax. Our simulations with NICE do rely on the assumption that the income tax is suboptimal and therefore that redistribution can be enhanced, but do incorporate some disincentive effects through the mitigation costs which reduce the economic output. Additionally, variant (B) introduced below tests the possibility of larger disincentive effects, in addition to the administrative inefficiency that is invoked in the description of that variant.

Indeed, raising the carbon tax and recycling the revenue may entail other additional costs. We thus explore three generic sensitivity scenarios, which are detailed under (B), (C) and (D) below. Also, additional costs from raising the carbon tax would arise if a production sector would be modelled explicitly through changes in the relative prices of production inputs.[88,92,93] The consequences of including these effects are discussed in (E).

B. Introducing a cost of redistribution

While the optimal tax literature has initially focused on the distortive effects of taxes on resource allocation, several authors have insisted on the cost of implementing a tax system due to the coercive nature of collecting taxes.[94,95] There are several aspects to these costs. First there are administrative costs associated with the mere activity of collecting taxes and managing public spending or transfers. Second there are issues of tax avoidance and tax evasion that reduce the amount of the tax actually collected compared to the presupposed tax basis (see Slemrod and Yitzhaki (2002)[96] for a review of these effects).

Administrative costs vary depending on the type of tax and country. Mitchell (1998)[97] reports a wide range of administrative costs for public social security systems from 3.12% in OECD countries to 27.78% in Latin American countries (with a maximum of 89.49% in some countries). Mayshar (1991)[95] reports administrative costs ranging from less than 1% for taxes on income in the US in the 20th century to 33% for taxes on wages in the UK in the 1920s.

Tax avoidance and tax evasion give rise to a "tax gap," measuring (as a percentage of the tax liability) how much tax should be paid, but is not. In 2001, the Internal Revenue Service in the US reported an overall gross tax gap of 16.3% (18% for the individual income tax, see Slemrod 2007[98]). The Swedish Tax Agency estimated the overall gross tax gap to be 8% in 2000.[98] In the UK, HM Revenue and Customs agency estimate the tax gap on an annual basis: in the most recent numbers (for 2018) the overall gross tax gap is 5.6% (ranging from 3.9% for the income tax to 9.1% for VAT).

Adding administrative costs and the tax gap produce a large range of estimates depending on the country (with very few estimates for developing countries) and the type of tax. A minimum seems to be in the order of magnitude of 10%; a maximum could be up to 50%. Even though carbon taxation entails different administrative and fiscal challenges than other forms of taxation, we opt to implement a more conservative estimate as a sensitivity analysis. One way to model this is to use the same case as in Supplementary Figure 12 (green line) where 30% of the revenue is assumed to be lost and so only 70% is recycled; this conservative 30% level was selected for illustrative purposes and not an estimate of the true level, which may be lower.

C. The poorest quintile receives nothing

Our central case assumes an equal per capita redistribution of revenues raised by the carbon tax. However, such a set-up may not be feasible in practice. To check the robustness of our results, we consider a scenario in which the poorest quintile in every region receives none of the tax revenue (Supplementary Figure 13, green line). Such a situation may come about if governments fail to reach the poorest segments of their population. This may be the case if the national social security system fails to cover all citizens and cash transfers cannot be operated, in economies where a large informal sector – in low and high income countries alike[99] – makes it impossible to implement transfers through tax returns, or in the case of bad policy design, for instance if revenues are used to reduce energy expenses not incurred by the poor, or if revenues are used to reduce the overall budget deficit.

D. The two poorest quintiles receive everything

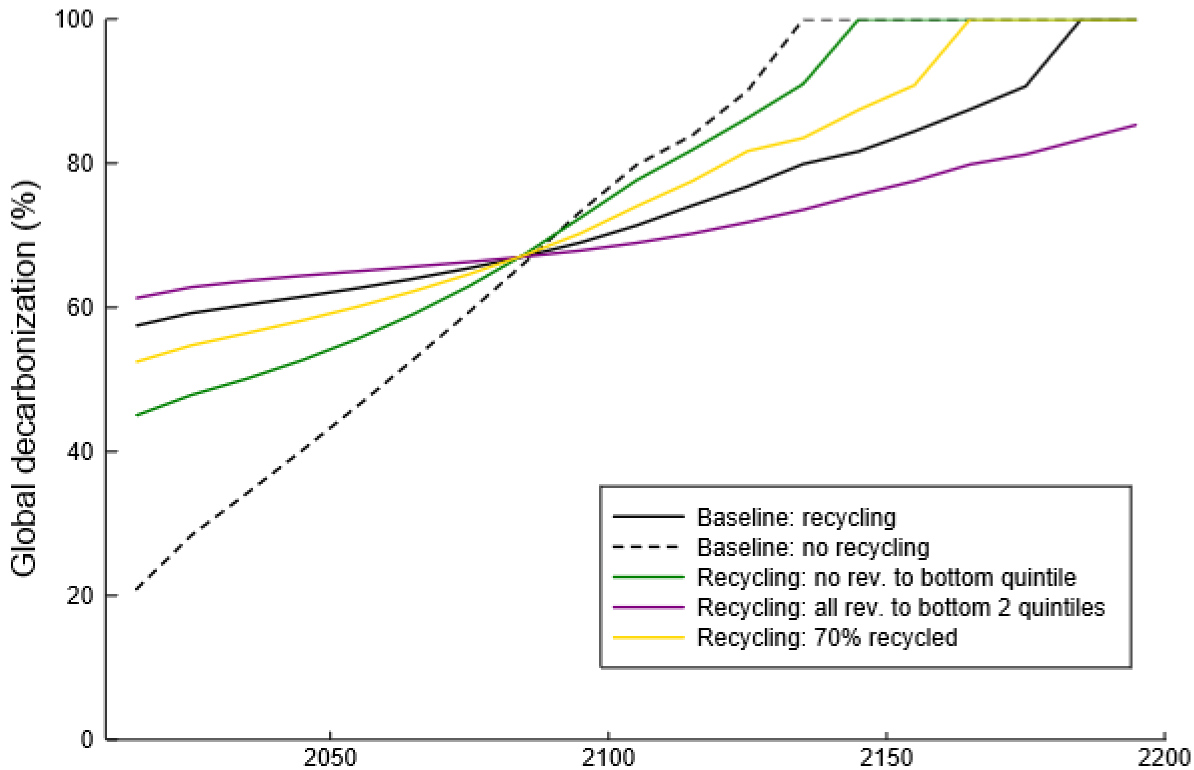
The equal-per-capita redistribution scheme is designed to alleviate inequality. However, depending on national social contexts, an equal per capita redistribution of revenues could be politically unpalatable on the grounds that it is insufficiently progressive towards the poorest households. In such contexts, an alternative would assume a disproportionate use of revenues to the benefit of the poorest households. To check the robustness of our results to this case, we use the generic scenario in which the two poorest quintiles receive, on an equal-per-capita basis, the total revenue raised in their region while the other three quintiles receive nothing (Supplementary Figure 13, purple line). In high-income countries this scenario is motivated by the tax incidence being regressive (see Figure 1). In low-income countries, it is motivated by the fact that revenues may be better used to alleviate poverty.

E. Production side effects

The production of goods is not explicitly modelled in the NICE framework, hence general-equilibrium distributional impacts of carbon taxes are ignored. When a production side is modeled explicitly, as for example in Fullerton and Heutel (2007)[92] and Dissou and Siddiqui (2014)[100], additional distributional effects appear, as raising the price on pollution changes relative factor prices. These changes impact the distribution of income, since high-income households tend to receive a higher share of income from capital than low- and medium-income households.[101-103]

Dissou und Siddiqui (2014)[100] demonstrate that while the distributional effects of the carbon tax are always regressive on the household side (i.e., through the price increase of different commodities), on the production side they are progressive (i.e., changes in relative factor prices disproportionately favor lower-income quintiles). The resulting aggregate effect is U-shaped, with the progressive effects outweighing the regressive effects for low tax rates, while at higher tax rates, the regressive effects of commodity price changes dominate.

Due to a lack of data on factor price incomes by income quintiles for most world regions, it is not feasible to propose a meaningful calibration of the NICE model. Nonetheless we can draw some implications for NICE model outcomes. First, we argue that the results on the distributional effects of uniform lump-sum recycling based on the NICE model would not change qualitatively when including production-side effects, as they tend to be progressive. Second, this progressive effect might be delayed, since household-side effects of carbon prices are immediate, while changes in relative factor prices are general-equilibrium effects that come about in the medium to long term. As a consequence, results from the NICE model provide good short- to medium-term estimations of the distributional effects of uniform lump-sum recycling which still might be roughly correct in the long term.

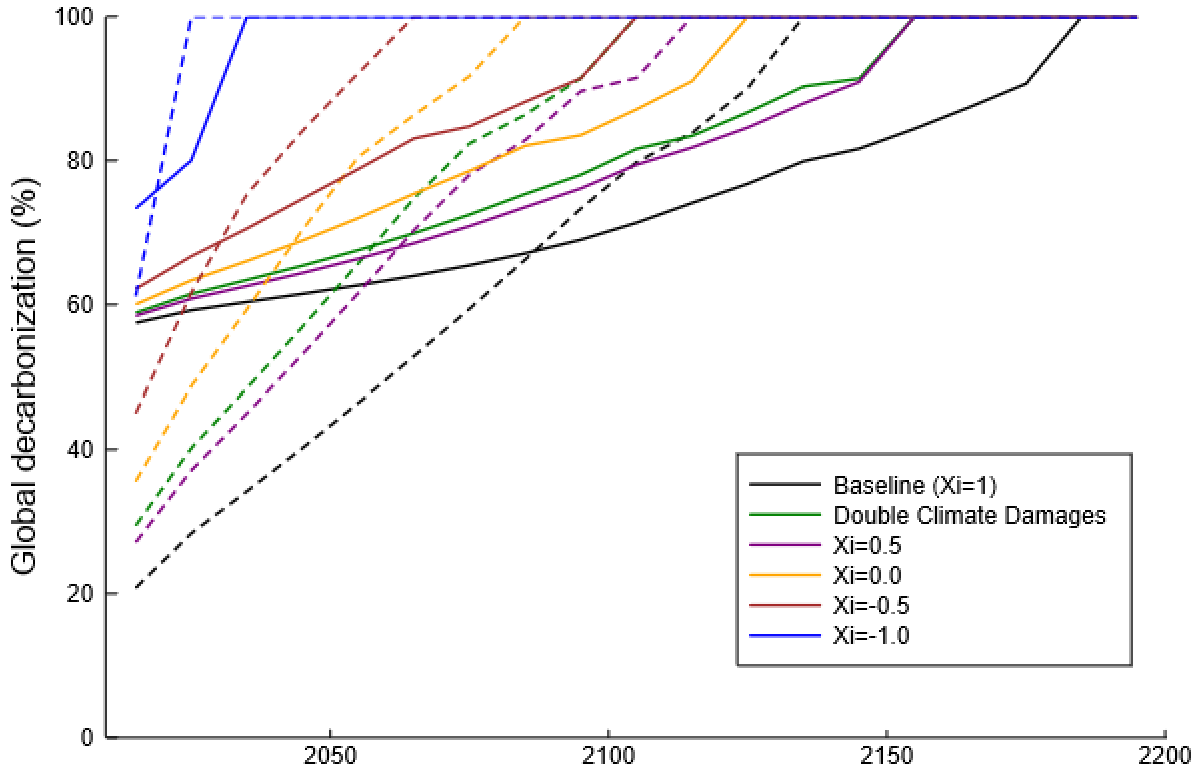


Supplementary Figure 13: Optimal climate policy with different assumptions about redistribution. "Baseline" refers to the case presented in the main text. Yellow line: 30% of revenue is lost, meaning only 70% of the total tax revenue is redistributed. Green line: the poorest quintile in every region receives none of the tax revenue. Purple line: the two poorest quintiles receive, on an equal-per-capita basis, the total revenue raised in their region while the other three quintiles receive nothing.

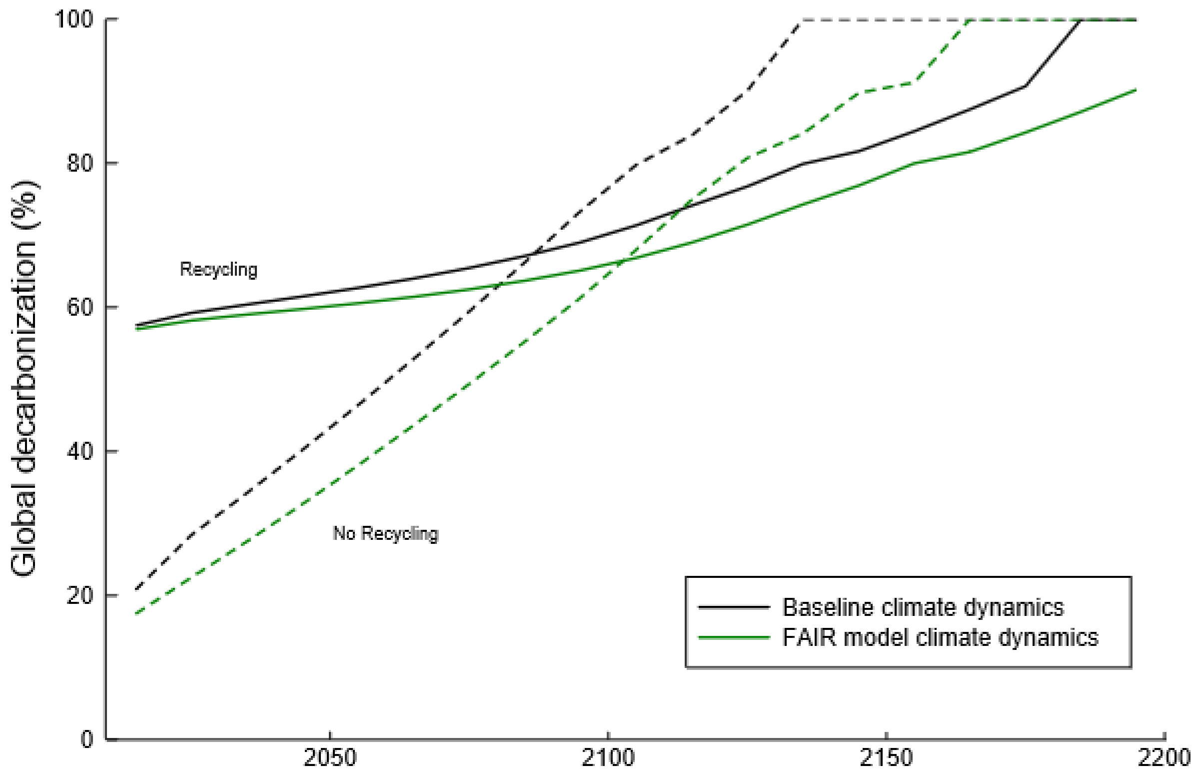
10. Modifications to the climate dynamics and damage assumptions of the NICE model

A recent report from the National Academies of Sciences, Engineering, and Medicine[104] outlined important ways to improve future integrated assessment modeling of climate policy. One concern was that the climate damage functions of existing models are outdated, and likely underestimate the scope of impacts. Therefore, in Supplementary Figure 14 we test different damage specifications, including a case where damages are double the default in NICE, as well as cases where damages are more or less concentrated on the poor. Specifically, our central results assume an elasticity of 1, implying that total damages are distributed across quintiles in proportion to their consumption. This assumption makes the welfare impact of damages essentially equivalent to what they would be in more aggregate cost-benefit models such as DICE, RICE, PAGE, and FUND. In Supplementary Figure 14 we test damage elasticities across a range of values from 1 to -1 (-1 corresponds to damages being distributed inversely proportional to consumption).

A second concern outlined in the report was that the climate module of the DICE/RICE suite of models (which the NICE model inherits) no longer reflects the latest understanding of climate dynamics, and proposed the FAIR model[105] as a more accurate and workable alternative. To test the importance of climate dynamics to the qualitative pattern between the Recycling and No Recycling we replace the default NICE climate module (based on RICE) with the FAIR v1.3 model[105]; as shown in Supplementary Figure 15, results do not differ qualitatively from our main results.



Supplementary Figure 14. Modifications to the damage function in NICE and its effect on optimal mitigation. Dotted lines indicate no recycling and solid lines indicate the equal per capita recycling. The black "baseline" case refers to the case presented in the main text that uses the default NICE damage function, in which aggregate damages are as in the RICE model and are distributed to quintiles in proportion to their consumption. The purple, yellow, brown, and blue cases present results where the distribution of damages is increasingly regressive, with the blue case (xi= -1) corresponding to damages being distributed inversely proportional to consumption (also see Dennig et al. 2015[106]). In contrast, the green case retains the assumption that damages are distributed proportional to consumption as in the main case, but doubles the aggregate regional damage at each temperature compared to the main case. Changing damages in these ways increases the urgency of mitigation, but does not qualitatively change the differences between recycling and non-recycling cases highlighted in the main text.



Supplementary Figure 15. Results of coupling the FAIR climate module to the NICE model. The "Baseline" (black) case replicates the results from Figure 5 in the main text. The "FAIR" (green) case represents the same optimizations, but with a model in which the native NICE climate dynamics have been replaced with an implementation of the FAIR model.

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