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The importance of health co-benefits under different climate policy cooperation frameworks

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Abstract

Reducing greenhouse gas emissions has the ‘co-benefit’ of also reducing air pollution and associated impacts on human health. Here, we incorporate health co-benefits into estimates of the optimal climate policy for three different climate policy regimes. The first fully internalizes the climate externality at the global level via a uniform carbon price (the ‘cooperative equilibrium’), thus minimizing total mitigation costs. The second connects to the concept of ‘common but differentiated responsibilities’ where nations coordinate their actions while accounting for different national capabilities considering socioeconomic conditions. The third assumes nations act only in their own self-interest. We find that air quality co-benefits motivate substantially reduced emissions under all three policy regimes, but that some form of global cooperation is required to prevent runaway temperature rise. However, co-benefits do warrant high levels of mitigation in certain regions even in the self-interested case, suggesting that air quality impacts may expand the range of possible policy outcomes whereby global temperatures do not increase unabated.

1. Introduction

Reducing greenhouse gas (GHG) emissions has the ‘co-benefit’ of also reducing air pollution, which is the leading environmental risk factor for disease globally; exposure to ambient fine particulate matter ($PM_{2.5}$) is alone responsible for an estimated 7.5–10.3 million deaths globally per year [1]. A large number of studies have quantified the air quality-related benefits that would occur given various GHG reduction scenarios, for example the implementation of specific policies or the achievement of specific climate targets [2–5]. These studies generally find that reducing GHG emissions can lead to large benefits for society, both in human health and economic terms, and thus should provide strong additional incentive for climate action.

Existing studies also find, however, that the health co-benefits from improved air quality will be distributed unevenly across space and time [2–5]. Some nations will experience large health co-benefits while others will not, and some will benefit early on while others experience more gradual improvements. These factors may influence how countries account for health co-benefits when designing their climate policies.

In this paper, we use a recently developed cost-benefit model to analyze how health co-benefits influence optimal climate policy design under three different perspectives of international cooperation. The first fully internalizes the climate externality at the global level via a uniform carbon price (the 'cooperative equilibrium'), thus minimizing total mitigation costs. The second connects to the concept of 'common but differentiated responsibilities' where nations coordinate their actions to acknowledge different national capabilities considering socioeconomic conditions and produces welfare optimal outcomes that account for background inequalities [6, 7]. This scenario is particularly salient, given increased attention that justice and equity considerations are currently receiving in the climate policy debate [8–10] and may serve as an alternative anchor for climate negotiations. The third approach assumes that nations act only in their own rational self-interest instead of cooperating, taking the actions of others as given (the 'Nash equilibrium'). Health co-benefits are especially important for an accurate estimate of climate policies that are in a nation's rational self-interest because most health co-benefits accrue locally and in the near-term, in contrast to many of the benefits from CO_2 reductions.

2. Methods

We conducted all modeling using the RICE + AIR cost-benefit integrated assessment model [11]. We describe the core components of the model below, though both RICE [12, 13] and AIR [11] have been described in detail elsewhere. We then explain how we use the model to implement the three policy regimes.

2.1. The RICE model

The Regionalized Integrated Climate Economy (RICE) model is a cost-benefit model widely used by researchers and governments to estimate the social cost of carbon and optimal climate policy [12–14]. Briefly, RICE is a regionalized 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, labor, and total factor productivity, which together produce that region's gross output via a Cobb–Douglas production function. Capital accumulates via a savings rate, which adds investment to the stock of capital in the next time period as a percentage of net output in the current period; at the same time, the stock of capital depreciates at an exogenous rate. Baseline regional carbon emissions are computed as the product of gross output and an exogenously determined, region-specific carbon intensity pathway. These carbon emissions can be reduced (mitigated) at a cost to gross output via emission control policies. Any remaining carbon emissions enter the climate module where they influence global temperature and, ultimately, the economy through climate-related damages, which affect regions differently. The optimal policy maximizes an objective function that balances these various costs and benefits (see below).

We make three changes to the standard version of RICE, which we have described in detail elsewhere [11, 15–17]. First, we update the population projections using data from the UN World Population Prospects. Second, we update the exogenous radiative forcing to values used in RCP6.0, which aligns with the latest versions of DICE (the global counterpart to RICE) [18]. Third, none of our solution concepts involves Negishi weights in the objective function [11, 17].

More specifically, our version of RICE employs a discounted and separable constant elasticity objective function with population weights (equation (1)), where W denotes social welfare, L population, c per capita consumption, ρ the rate of pure time preference and η inequality aversion (diminishing marginal utility). The subscripts i and t are the region and time indices respectively. Unless otherwise noted, we assume the default discounting parameters in RICE of $\rho = 1.5\%$ and $\eta = 1.5$

$$W(c_{it}) = \sum_{it} \frac{L_{it}}{(1+\rho)^t} \frac{c_{it}^{1-\eta}}{1-\eta}. \tag{1}$$

2.2. The AIR module

We recently developed the Aerosol Impacts and Responses (AIR) module to introduce the air quality dimension into RICE [11]. AIR creates a feedback mechanism whereby reducing CO_2 also reduces air pollutant emissions from co-emitting sources, thus capturing two key impacts: (a) the public health benefit from improved air quality, and (b) the climate impacts associated with near-term temperature increases attributable to reductions in air pollutant emissions (several air pollutants are also climate forcers and together produce net warming overall).

The approach underlying the AIR module consists of five steps: First, we estimate the baseline (before carbon mitigation) emissions of primary $PM_{2.5}$, nitrogen oxides, sulfur dioxide, organic carbon, and black carbon for all region-time pairs with income-dependent emission intensity projections (emissions per unit GDP) based on the GAINS model [19]. Specifically, we assume air pollutant emissions in the coming decades follow the ECLIPSEV5a baseline scenario, which includes current and planned air quality legislation, but no climate policy. Second, we determine the change in air pollutant emissions that would result from a change in CO_2 emissions using information embedded in the Shared

Socioeconomic Pathway project [20]. Third, we link changes in air pollutant emissions to changes in estimated average human exposure to $PM_{2.5}$ by applying the source receptor matrix from the TM5-FASST model [21]. This enables a calculation of the number of life-years gained from reduced premature mortality [22, 23]. Fourth, we estimate global temperature changes from air pollutant emission co-reductions using coefficients derived from the MAGICC climate model [24]. Finally, we monetize the impacts by multiplying the estimated life-years gained by a value of a life-year, estimated as two years of regional per capita income. Note that the use of regional per capita income does not mean that life-years are worth less in poorer regions, because of the transformation that occurs via the η parameter [11]. After this valuation, aerosol impacts can feed directly into the standard RICE optimization without further modification.

The three fundamental high-level equations are as follows, beginning with equation (2), which estimates the baseline (before CO_2 mitigation) level of emissions, E^0_{itp}:

$$E^0_{itp} = \alpha_{itp}\left(\frac{Y_{it}}{L_{it}}\right) \times Y_{it}. \qquad (2)$$

Baseline emissions for a given pollutant p in each region-time pair (it) is a function of an emissions intensity factor, α_{itp}, and output, Y_{it}. The emission intensity (emissions per unit of output) is region and pollutant specific and depends on the per capita income level of the region, defined above as the output divided by the population, L_{it}. Emissions after a given level of CO_2 mitigation, E_{itp}, are a function of the baseline emissions, E^0_{itp}, the carbon mitigation rate, μ_{it}, and a scale factor, κ, that relates a percentage reduction in CO_2 emissions to a percentage reduction in aerosol emissions (equation (3)) and are specific to each pollutant. We use scale factors from the Shared Socioeconomic Pathways [20]. This change in aerosol emissions from mitigation, ΔE, can be converted to a change in human exposure to air pollution, ΔC_{it}, using a pollutant-specific source-receptor matrix, SR_p, as in equation (4):

$$E_{itp}\left(\mu_{it}\right) = E^0_{itp} \times \left(1 - \kappa_{itp} \times \mu_{it}\right) \qquad (3)$$

$$\Delta C_{it} = \sum SRp \times \Delta E_{itp}. \qquad (4)$$

We assume that changes in exposure from $PM_{2.5}$, NOx and SO_2 are additive (black and organic carbon are used only for climate purposes—see below) and that emission reductions in one region only affect that same region. Attributing a change in exposure into an estimate of years of life lost is straightforward using well-established methods [23, 25] that we do not repeat here, except to note that we assume a log-linear exposure-response function for all-cause mortality, based on a World Health Organization meta-analysis [22]. A single function for all-cause mortality enables the use of internally consistent long-term (2100) projections of population and mortality from the UN. This approach generally produces higher attributable mortality burdens when compared to the cause-specific Integrated Exposure–Response functions, but more comparable burdens to those estimated by the newer Global Exposure Mortality Model [1, 26, 27].

As mentioned above, the AIR module also includes the climate 'co-costs' into the modeling approach. Specifically, equation (3) already estimates the post-mitigation level of emissions for the relevant pollutants. The net global radiative forcing attributable to these pollutants is taken as the sum of the individual contributions. We estimate the individual contributions by multiplying post-mitigation emission levels with a coefficient relating a unit of pollutant to a change in global radiative forcing, which in turn influences global temperature. These relationships were derived through runs of the MAGICC climate model [24], by observing the change in global temperature that results from an emission pulse. The total temperature rise above preindustrial levels for any period then represents the combined temperature effects of air pollutants, CO_2, and other GHG emissions. This temperature change leads to climate damages through the model's internal climate damage function.

After adding these radiative forcing effects, the model accounts for both of the major impacts from reducing air pollutant emissions; the health co-benefits and the climate co-harms.

2.3. Modeling different policy regimes

The modeling capabilities outlined above allow for novel analyses of optimal climate policy given potential synergies and tradeoffs between climate impacts, mitigation costs, air quality factors and socioeconomic inequality. These factors can be explored under a range of policy regimes and under different assumptions about the relative priority society gives to future generations and the poor. Here we model three different policy perspectives about international cooperation:

(a) *Cost minimization (cooperative equilibrium)*: the key assumption here is that the recommended climate policy is implemented in order to maximize (discounted) global wellbeing according to equation (1), subject to the constraint of a uniform global carbon price. Economists often consider a uniform global carbon price to be the gold-standard solution to the climate problem because it minimizes costs for any desired level of global mitigation. An in-depth treatment of how co-benefits influence this solution can be found in Scovronick *et al* [11].

(b) *Regional Equity*: it is possible to remove the above constraint of a globally uniform carbon price and instead allow for differentiated carbon prices for each region, such that all regions' prices together maximize the global utilitarian objective of equation (1) [6, 28]. The immediate implication is that the optimal carbon price paths are different across regions and thus the decarbonization pathways differ from those in the cost minimization (CM) scenario. In this case, richer regions are allowed to contribute more mitigation effort than poorer regions via higher carbon prices, thus enabling poorer regions to continue developing. Arguably, this approach allows the model to calculate optimal distribution given the equity objective represented by equation (1), together with an assumption that future inequality will not be corrected by other means. More generally, removing the uniform price constraint allows better representation of values of justice, and can be viewed as one implementation of the principle of 'common but differentiated responsibilities and respective capabilities' of nations, as articulated in the UNFCCC [28, 29] (note that recent work [9] highlights alternative price differentiation frameworks, such as equalizing relative regional mitigation cost shares, and points to important policy challenges that may arise from tradeoffs between economic efficiency goals and concerns for equity). The regional equity (RE) case can be conceptualized as a second-best policy from an economic efficiency perspective, optimized to a situation in which massive global income inequality is known to loom uncorrected in the background [30].

(c) *Self-Interest (non-cooperative equilibrium)*: here, nations act entirely within their own self-interest when weighing the costs of mitigation against the climate and health benefits; their selected climate policy does not consider the wellbeing of citizens of other regions. This can be implemented using an open-loop 'Nash Equilibrium' approach, as in Nordhaus [12]. The Nash Equilibrium satisfies a number of standard assumptions about strategic behavior, namely that nations maximize their own net benefits by taking into account the actions of other nations, there is no cooperation between nations, and in equilibrium no nation would benefit by unilaterally changing its chosen actions. This regime does not produce a globally optimal cooperative outcome—it is optimal only in the sense of being the most favorable outcome for each self-interested region conditional on the same self-interested choices by all other regions. These results are policy relevant, as they aim to quantify the emissions reductions that may be most politically feasible for nations to make. Furthermore, once these levels are quantified, they support a strong argument that any nation making less than these reductions is acting contrary to its own self-interest.

3. Results

Figure 1 reports optimal policy results in terms of cumulative carbon emissions (top panel) and associated temperature increase (bottom panel) given the three policy regimes, both without ('reference case') and with air quality co-benefits. In the reference case of both cooperative scenarios, optimal cumulative emissions are approximately 1250 GtC globally, which limits peak temperature rise to about 3 °C. Despite the relatively similar emissions and temperature profiles at the global level, however, the regions that emit clearly differ. For example, Africa emits much more in the RE case compared to the CM case because the former gives more priority to socioeconomic differences in determining optimal policy. In the self-interest (SI) reference case, where nations do not consider the wellbeing of people in other parts of the world, global emissions end up more than three times higher, leading to runaway temperature rise.

Emissions fall substantially in all three regimes after accounting for air quality co-benefits. In the two cooperative regimes, the added incentive provided by the co-benefits makes it optimal to keep emissions below the 'trillionth tonne' [31]. In contrast, in the SI regime, the added incentive is not sufficient to avoid very high temperatures.

The total global emissions in the SI case, however, mask important outcomes in several key regions (figure 2). In the SI regime, all regions show somewhat increased mitigation in the co-benefits case compared to the corresponding reference case, but the differences are most pronounced in China, Sub-Saharan Africa and in particular, India. Without co-benefits, India pursues modest mitigation throughout this century; with co-benefits it decarbonizes fully by ~2070. The same effect underlies the differences in these regions between the co-benefits and reference cases in the RE regime. On the other hand, in most of the high-emitting regions (e.g. Europe, USA, Japan), health co-benefits provide relatively little additional incentive to mitigate, either because the air is already clean or because carbon emissions and air pollution is less strongly coupled. For these regions, high mitigation levels are only warranted in a cooperative regime, where they mitigate to avoid climate impacts that will primarily harm other regions (see supplementary figure 1 (available online at stacks.iop.org/ERL/16/055027/mmedia) for the carbon price pathways associated with each mitigation trajectory).

The finding that health co-benefits in the SI regime do not motivate global mitigation sufficient

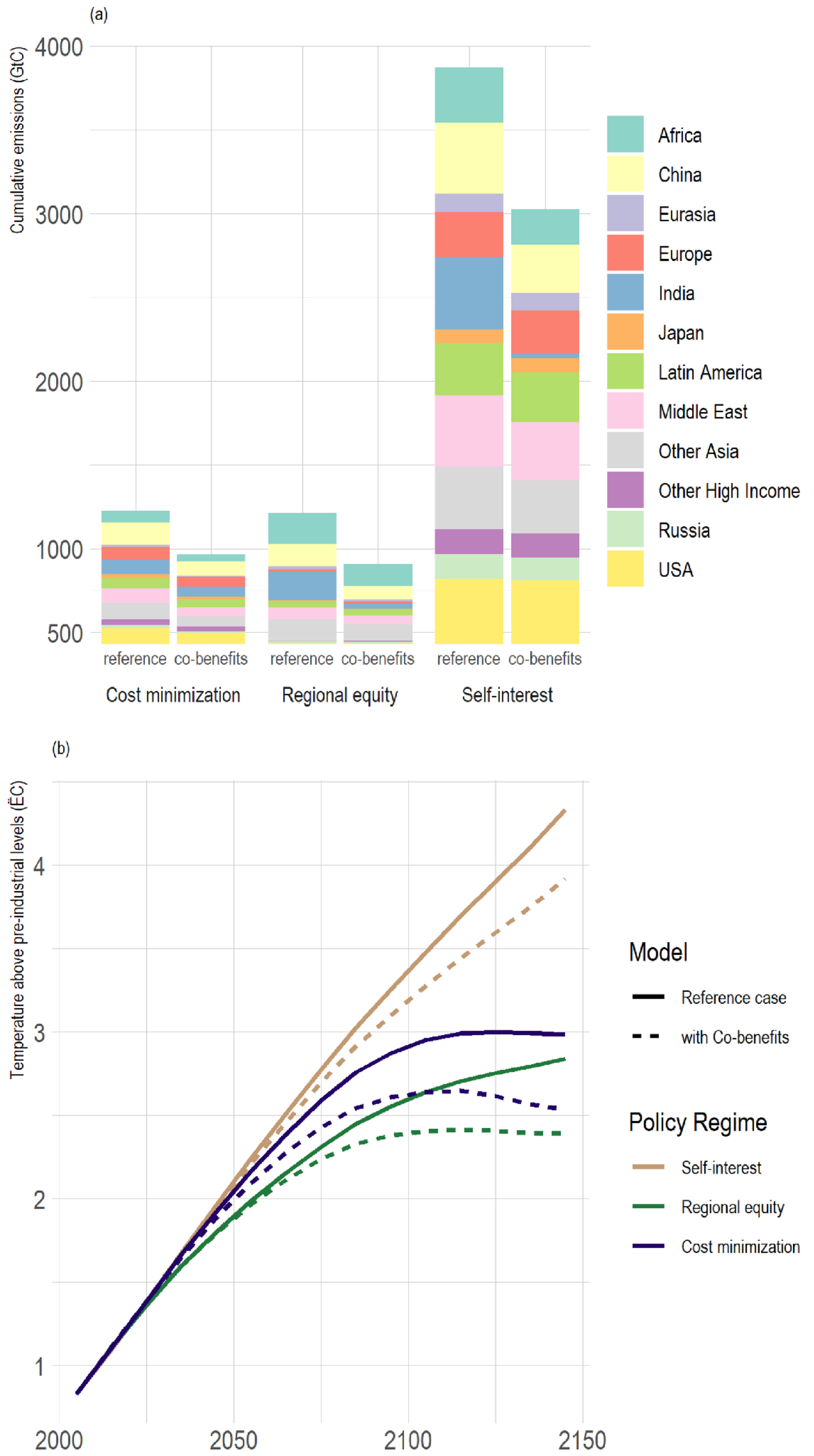

Figure 1. Optimal cumulative emissions by region under each policy regime (panel (a)), and associated temperature trajectories (panel (b)). Cumulative emissions (gigatonnes of carbon, GtC) start at 462 Gt to reflect global historical emissions.

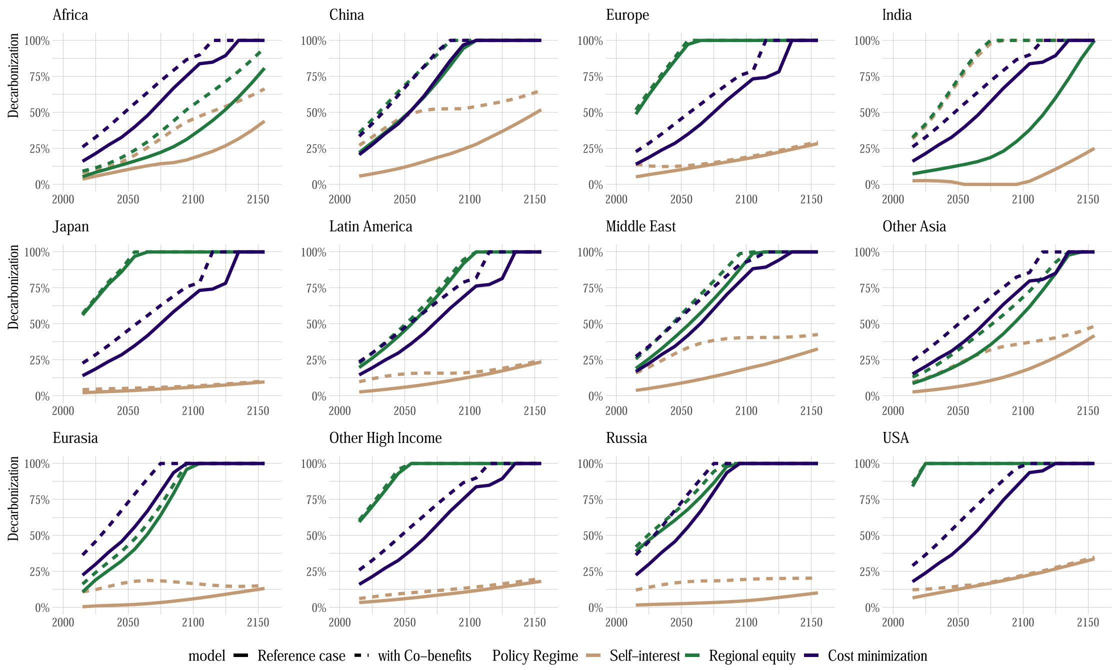

Figure 2. Optimal mitigation in the CM, RE and SI regimes, with and without co-benefits.

to avoid dangerous climate change is robust to a number of sensitivity analyses, including an assumption of much worse climate impacts, or if the avoided deaths are valued according to the value of a statistical life (instead of by life-years) (supplementary figure 2). In fact, keeping temperature increases in the SI regime below 3.5 °C entails either near-zero discounting or much higher levels of health or other co-benefits (or higher valuations) (supplementary figure 2, supplementary table). A combination of factors could also achieve that outcome.

The complexity of climate policy decision-making, and the importance of health co-benefits, is further evident from figure 3, which reports the normalized regional mitigation costs relative to the monetized benefits (both from avoided climate impacts and improved air quality) under all three policy regimes, reported in present value. In all regions, some level of mitigation occurs in the SI case, meaning that business-as-usual without any climate policy is sub-optimal. Which of the three regimes is most preferable, however, varies substantially across regions. At one extreme, are several wealthy regions (e.g. Russia, Japan, USA) where the self-interested perspective is clearly preferable to the alternatives; mitigation costs are relatively low, especially compared to Regional Equity, but total benefits are still substantial because the climate benefits (avoided climate damages) they get come almost exclusively from climate action in other regions. Note though, that expressing these wellbeing impacts in present-day discounted terms masks variation in how costs and benefits evolve over time for the three policy scenarios (supplementary figure 3).

For a number of other regions, more favorable outcomes occur under one of the cooperative regimes. In Africa for example, large net benefits accrue in all regimes, but particularly with RE where they do not decarbonize rapidly but gain from high levels of mitigation in other, wealthier regions. India, like Africa, strongly benefits under all three regimes, but unlike in Africa, this is contingent in large part on the health co-benefits. China's benefits are split more evenly between climate and health. This regional heterogeneity implies that, in purely cost-benefit terms, regions where a cooperative regime is superior to the SI regime will prefer some sort of negotiated outcome (and vice versa).

4. Discussion

We have evaluated the role of air quality-related health co-benefits on optimal climate policy under three widely discussed policy regimes. In all three, the inclusion of health co-benefits motivates substantial reductions in global emissions. In the globally cooperative CM regime that prioritizes least-cost mitigation via a uniform global carbon price, all countries decarbonize more quickly, driven by the large health co-benefits gained in relatively few, mostly developing, regions (see also Scovronick *et al* [11]). In the other cooperative regime (RE), which is sympathetic to the principle of common-but-differentiated responsibilities, the health co-benefits motivate substantially more mitigation in several lower-income regions that would not have been expected to mitigate much otherwise. In both of these cooperative

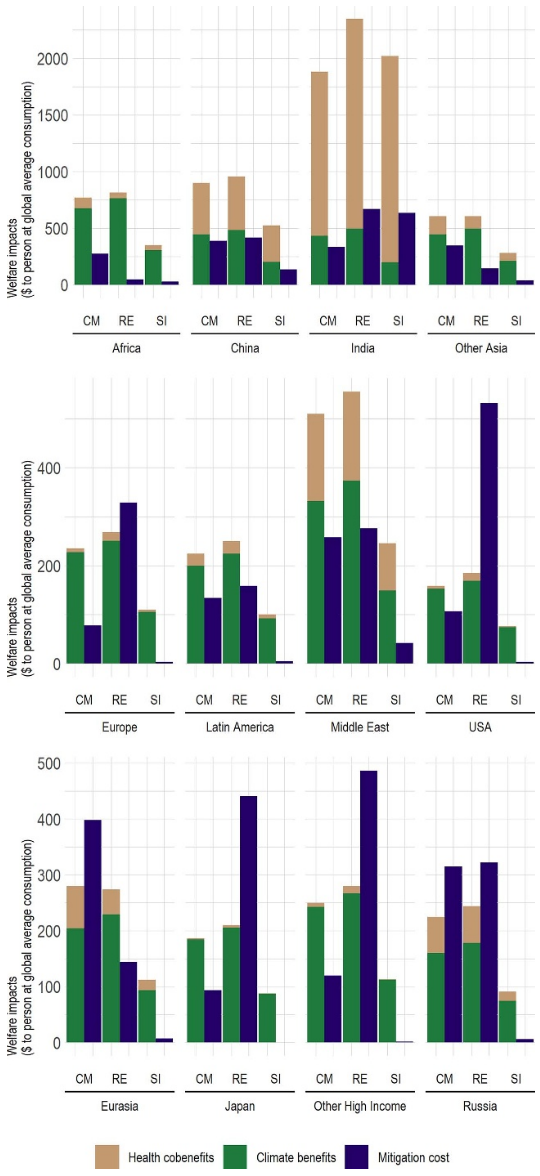

Figure 3. Normalized present value of per capita costs and benefits under all three policy scenarios in the optimum with co-benefits. The bars show the three types of impacts to each region under the CM, RE, and SI scenario. Future impacts are discounted and normalized by the marginal utility of world average consumption in the first period [32]. This normalization allows us to express regional impacts in welfare terms and captures the idea that one dollar of consumption has a larger effect on well-being in low-income regions relative to high-income ones. The units of welfare impacts for any given region can be interpreted as the level of consumption that would cause an equivalent change in well-being for a hypothetical person living at the world average per capita consumption level (∼8305 USD in 2005 PPP). For instance, under the RE policy scenario, the benefits to a person living in India are equivalent to a more than $2000 increase in consumption for a person living at the world average per capita consumption level. The corresponding benefits for the United States are equivalent to a less than $100 consumption increase for this hypothetical person. The normalization, from Fankhauser *et al* [32], is described in more detail in the supplementary information.

regimes, the health co-benefits ensure that the world keeps emissions below the 'trillionth tonne' threshold that would not have been optimal otherwise, and that global temperature rise therefore remains well below 3 °C.

In contrast, the SI regime produces runaway temperature rise regardless of whether health co-benefits are included. This occurs because in several high-emitting regions, the capacity for co-benefits is relatively low and does not outweigh additional mitigation costs. These regions also benefit from climate action elsewhere. If we assume wealthier nations opt for self-interest, our results imply that limiting optimal global temperature rise to anything close to the Paris Agreement targets would require that they: (a) accrue health co-benefits that are much larger (or are valued much more highly) than what we estimate here; (b) gain other types of co-benefits beyond those related to air quality, (c) find a way to dramatically reduce mitigation costs, and/or (d) assume a very low discount rate in present-day decision making.

In reality, however, the world contains a heterogeneous mix of climate policy perspectives, with some more oriented towards self-interest and others more towards cooperation. Different combinations of these perspectives can yield meaningful climate action; for instance, if historically high-emitting regions (e.g. USA, Europe, Japan) act strongly for reasons of global efficiency or justice, while other newly high-emitting regions (India, China) act to gain health co-benefits. In fact, health co-benefits alone provide India a strong incentive to mitigate: in both the RE and SI regimes, including health co-benefits flips their optimal mitigation over this century from very little to 100%. This occurs due to India's high benefit-cost ratio once the health impacts from improved air quality are accounted for, an observation that has been reported elsewhere in analyses of explicit climate targets [2].

Our results connect to other important discussions of global climate policy. Our findings build on prior studies that call into question the 'lack of credibility/lack of trust' objection to mitigation voiced by some (generally rich) nations, because India and other key regions clearly have a self-interested reason to act strongly [2]. In addition, the non-cooperative equilibrium estimates the minimally rational climate policy for individual nations, which may be a useful metric for the global stocktake that evaluates the initial round of NDCs in the post-Paris international climate regime [33]. We provide a high-level estimate of that equilibrium for 12 macro-regions; for domestic policy purposes, these estimates should be supplemented with more detailed, region-specific process-based modeling.

This study has several important limitations. First, RICE + AIR is a stylized reduced-form model, which allows for computational efficiency when identifying an optimal policy. We recommend using 'bottom-up' (process-based) integrated assessment models that include explicit technological representation to analyze the details of any specific mitigation scenario [34–37]. Second, we conducted our analysis with a 12-region global model, which assumes each region behaves as a single unit. This is sound for the single country regions (e.g. USA, China, India), but does not account for heterogeneity within the large multi-country regions (e.g. Africa, Latin America). This assumption is likely most problematic for the SI scenario, where individual countries are the ideal unit of analysis. Although no optimizing cost-benefit climate policy model represents anything close to the ∼195 countries in the world, the result of a SI scenario with such a model would likely entail even less mitigation because smaller decision units would be internalizing even less of the climate harms that their emissions cause. Third, our modeling assumes that the health benefits of improved air pollution are fully internalized into decision making. In reality, we know this is not always the case or the air would likely already be cleaner than it is [38].

Finally, our modeling framework contains a number of parametric uncertainties. We test several of these in sensitivity analyses and do not find large changes to our qualitative results. One important uncertainty that we did not consider concerns how much regions would clean up their air independently of climate policy measures, which could be done relatively cheaply in some cases with end-of-pipe technology [11]. Instead, we assumed that this autonomous air pollution policy would unfold according to a current legislation scenario, which may be somewhat conservative; if the air ends up cleaner than expected, it would likely mean fewer co-benefits and thus lower levels of optimal mitigation (also see [11]).

There have been only a small number of other global cost-benefit optimization studies that include health co-benefits [11, 39, 40]. These studies have similarly reported the importance of co-benefits in climate policy decisions, though none has evaluated or compared all three policy regimes analyzed here.

5. Conclusion

We have shown that air quality co-benefits play an important role in motivating climate action. In cooperative policymaking scenarios, the co-benefits help justify levels of mitigation that begin to approach those targeted in the Paris Agreement. In contrast, in a purely self-interested scenario the co-benefits are not nearly sufficient at the global level to meet those targets, but do warrant high levels of mitigation in a few important regions that would otherwise have much less reason to act. In a reality where countries are likely to adopt a patchwork of policy perspectives, health co-benefits expand the possibilities by which the world avoids runaway temperature rise.

Data availability statement

All data that support the findings of this study are included within the article (and any supplementary files). A running version of the RICEAIR model can be found at: https://github.com/Environment-Research/AIR

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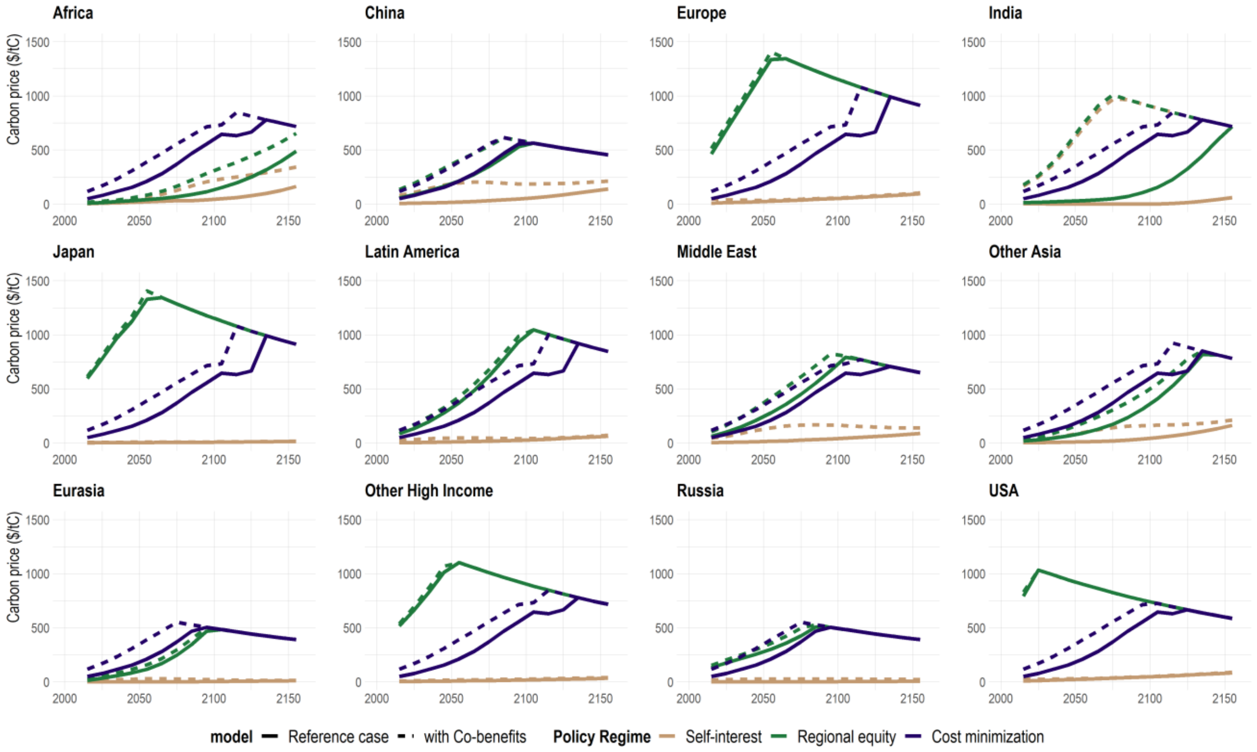
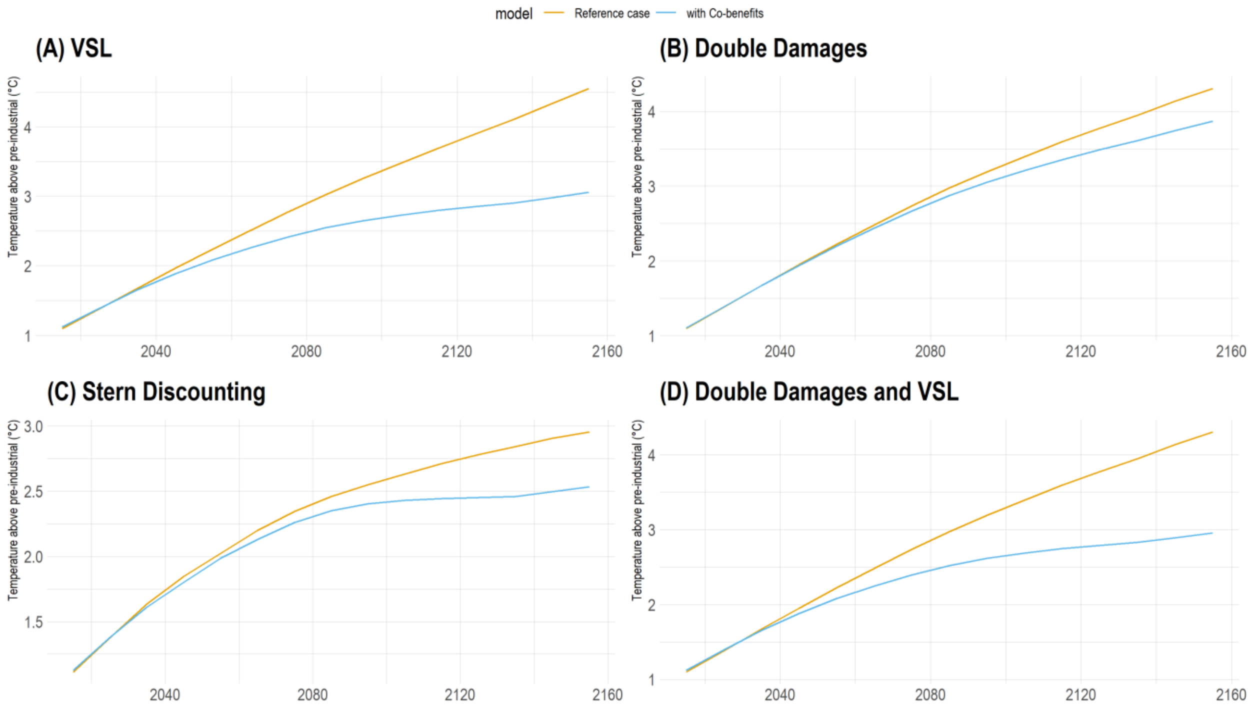
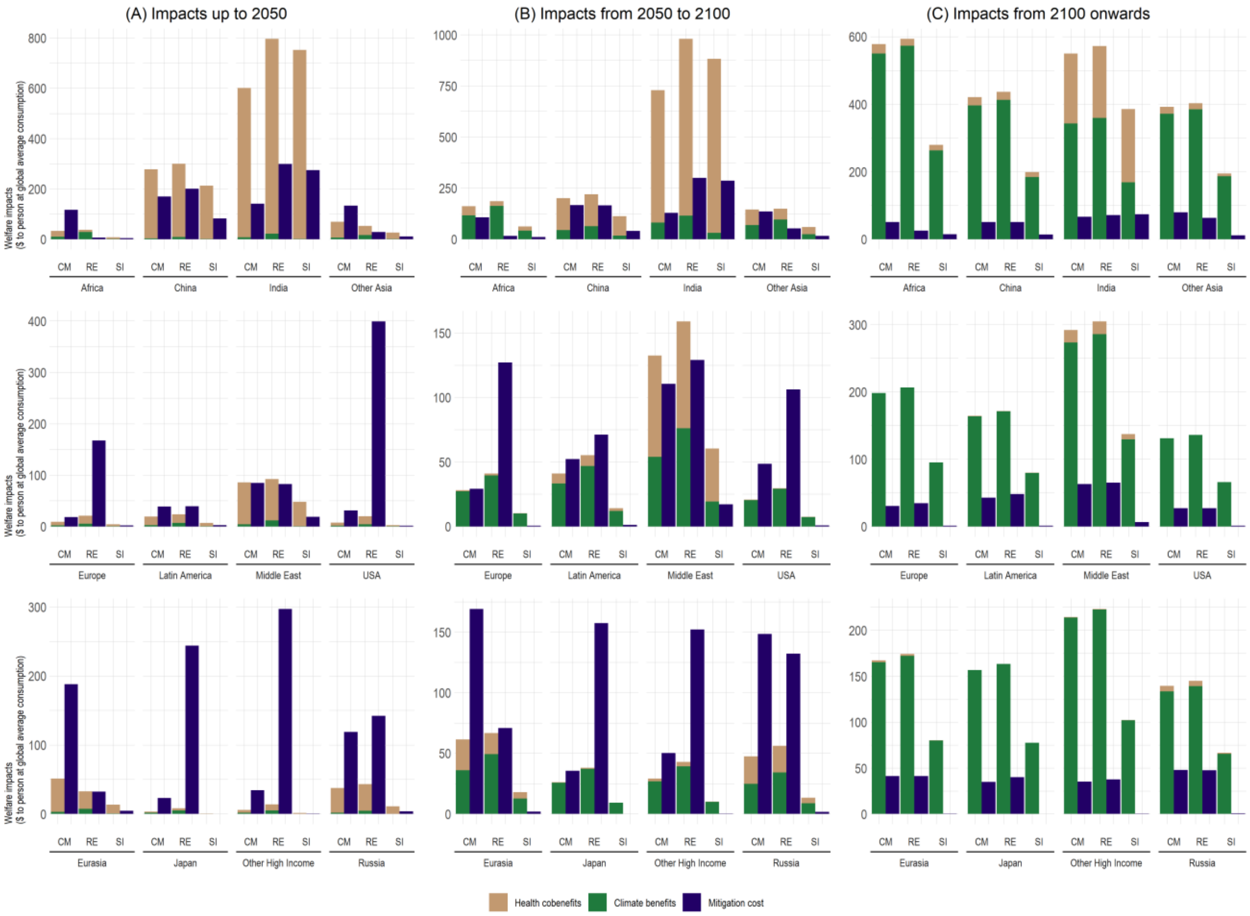
SUPPLEMENTARY INFORMATION



Supplementary Figure 1. Optimal carbon tax pathways for each policy scenario. Carbon taxes correspond to the decarbonization trajectories reported in Figure 2 of the main text. Note that because the Cost Minimization (CM) scenario is based on a global carbon tax, the tax pathways for this scenario are identical in all regions, but the point at which they reach 100% decarbonization (the so-called “backstop price”) differs; this is why the CM lines stop at different tax levels in different regions. In the other two scenarios (Regional Equity and Self-interest), the tax pathways differ by region.



Supplementary Figure 2. Temperature trajectories under the Self Interest scenario given (A) valuing avoided deaths using the value of a statistical life (VSL), (B) climate damages that are twice what is standard in the RICE model, (C) a much lower discount rate with time preference of 0.1% per year and an elasticity of marginal utility of 1, and (D) the combination of the VSL and doubled climate damages.



Supplementary Figure 3. Monetized present value of per capita costs and benefits relative to BAU in the optima with health co-benefits, aggregated over different time intervals. For each region and policy scenario - Cost Minimization (CM), Regional Equity (RE), and Self-Interest (SI) – the bars show the aggregate of the three types of impact over a different time interval: column A aggregates the impacts from now up to 2050, column B aggregates the impacts from 2050 to 2100, and column C aggregates all the impacts after 2100.

In both Figure 3 of the main text and Supplementary Figure 3 above, future impacts are weighed by the region-specific marginal utility of consumption, and all totals are normalized by the marginal utility of world average consumption in the first period. Take, for example, the (monetary) per capita climate damage in region i and period t to be d_{it}^{CM} in the Cost Minimization scenario and d_{it}^{BAU} under business-as-usual. Then the monetized present value of per capita climate benefits to region i under Cost Minimization as measured in Figure 3 and Supplementary Figure 3 is:

$$\frac{1}{\frac{du(\overline{c}_{2020})}{d\overline{c}_{2020}}} \sum_{t=\underline{t}}^{\overline{t}} \beta^t \frac{du(c_{it})}{dc_{it}} \left(d_{it}^{CM} - d_{it}^{BAU}\right)$$

where β is the pure time discount factor, c_{it} is the consumption in region i during period t, $\overline{c}_{2020}$ is the world average consumption in 2020, and $\underline{t}$ and $\overline{t}$ are the limits of the time period over which we aggregate. In Figure 3, $\underline{t} = 2020$ and $\overline{t}$=2600, while in Supplementary Figure 3, in each of the columns A, B, and C the aggregations are done for 3 different subintervals of time. Analogous expressions hold for the present value of mitigation costs and health co-benefits, and in all three policy scenarios, Cost Minimization, Regional Equity, and Self Interest.

In the expression above, the term $\beta^t \frac{du(c_{it})}{dc_{it}} \left(d_{it}^{CM} - d_{it}^{BAU}\right)$ measures the well-being impact to the average individual in region i at time t of reducing per capita climate damages by the amount $d_{it}^{CM} - d_{it}^{BAU}$. These well-being impacts are then divided by the marginal utility of present average world consumption to measure them in monetary units (rather than units of well-being). This normalization results in every region's per capita impacts being measured as the dollar change in consumption that would have the equivalent welfare impact on someone with the world average consumption level (~ 8,000 $/annum, see Fankhauser et al. 1997[1] for a detailed explanation of the normalization). The impacts are thus comparable across regions in per capita welfare terms, and account for the fact that one dollar change in consumption has a larger effect on well-being on a person in a low-income region than a person in a high-income region.

Supplementary Table. Peak temperature given different life-year values, in years of regional per capita consumption. The default value in the main results assumes two years of regional per capita consumption.

Value of a life year (in years of regional per capita consumption)	**Peak temperature**
2	5.1 ˚C
4	4.9 ˚C
8	4.5 ˚C
16	3.9 ˚C
32	3.5 ˚C
64	3.4 ˚C
128	2.5 ˚C

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