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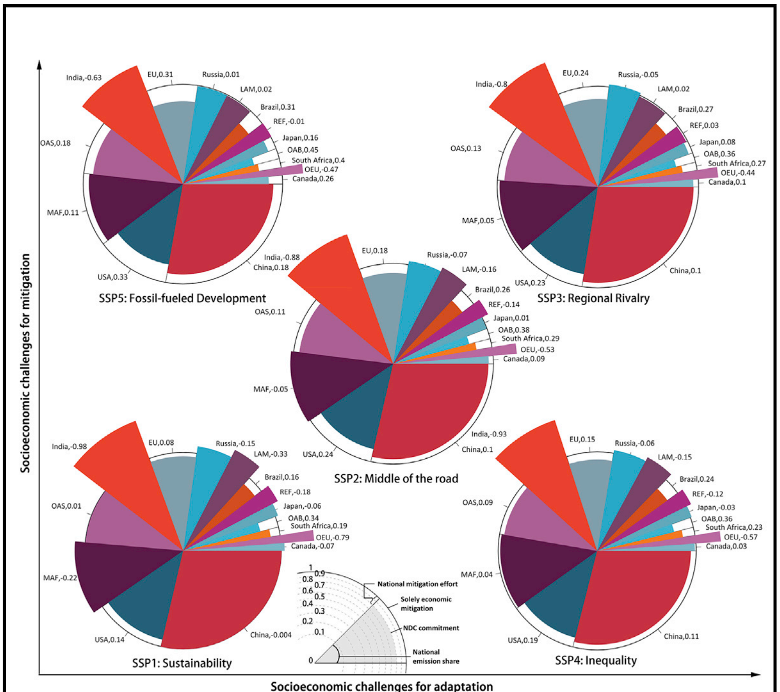
Solely economic mitigation strategy suggests upward revision of nationally determined contributions

Graphical abstract



Reviewing the NDCs under the five socioeconomic development paths. *The pie chart shows the national solely economic emissionshare in 2030, while the wedges show the national NDC commitments in 2030. Smaller wedge shows more ambitious commitment.*

Highlights

- We review the 2030 NDCs from an economic perspective
- We provide a solely economic mitigation pathway up to 2100 for 15 regions
- The NDCs from India and Russia are higher to secure an economically favorable level
- Countries can further reduce emissions to achieve economic efficiency globally

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In brief

Yang et al. provide a solely economic perspective to review and compare the nationally determined contributions (NDCs). Assuming no international cooperation, they treat emission reduction as a purely economic behavior motivated by avoiding future economic damages from climate change. While previous reviews based on equity principles have received little consensus, this economic perspective could add to the discussion to promote further enhancement of national pledges by virtue of national comparisons.

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Article

Solely economic mitigation strategy suggests upward revision of nationally determined contributions

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SCIENCE FOR SOCIETY The Paris Agreement relies on the reviewing process of national climate commitments to produce enhanced national pledges by virtue of national comparisons. At present, most reviews are based on equity principles, which countries have little agreement on. This paper provides an alternative perspective to the current discussion and treats emission reduction as a solely economic behavior motivated by avoiding future economic damages from climate change. Assuming no consensus over equity or international cooperation, we generate a solely economic mitigation pathway up to 2100. At each term, the national climate damage caused by an additional unit of carbon emission is no higher than the additional mitigation cost. This solely economic emission path can be informative for countries to control their national emissions at an economically favorable level while providing an alternative economic perspective for comparing national pledges.

SUMMARY

The use of equity principles to review the nationally determined contributions (NDCs) is critical to facilitating more ambitious climate actions. However, disagreement over the equity principles persists. We instead treat emission reduction as a solely economic behavior motivated by avoiding future economic damage from climate change. Assuming no international cooperation, we provide a solely economic mitigation pathway to review national climate pledges until 2100. Using the value in 2030 to review the NDCs, we find that the NDCs of China, the USA, and the EU are 1.5, 1.4, and 0.9 respective $GtCO_{2eq}$ lower than their solely economic emission levels, whereas India commits 3.8 $GtCO_{2eq}$ more than its solely economic emission level. We also propose an equal-effort cooperation scenario toward 2°C where each country reduces emissions by 28% of their solely economic levels in 2030. Through exploration of the economic trade-offs, our results suggest that more ambitious NDCs are urgently needed.

INTRODUCTION

The international climate regime entered a new stage after the Paris Agreement was adopted in 2015, by which countries set their nationally determined contributions (NDCs, all abbreviations can be found at Table 1) in the context of national priorities. With no legally binding constraints in the near term, the key driver in accomplishing these goals is the "pledge and review" system, in which countries put forward a national commitment and assess their progress periodically.[2] Taking stock of the collective progress is critical to producing enhanced national pledges by virtue of national comparisons.[3,4] However, no consensus has been made on the operationalization of equity following the common but differentiated responsibilities and respective capability (CBDR-RC) principles. Therefore, alternative aspects of conducting the NDC review, which ranks and compares national climate efforts, are needed.

NDC review using equity principles is conducted by allocating 2°C or 1.5°C global emission budgets to countries with the use of equity criteria.[5–7] Ambitious countries are those that commit NDCs below the allocation results. Equity can be quantified into five categories: responsibility,[8] capability,[9] equality,[10] responsibility-capability need,[11] and equal cumulative per capita emissions.[12,13] The allocation of the emission budgets varies significantly when applying different principles, and no approach has been agreed upon by all countries.[14,15] A suite of studies combined effort-sharing principles and proposed a hybrid allocation in which each country adopts the least stringent allocation principle to realize the Paris Agreement goal.[16,17] However, these equity principles do not consider the economic efficiency of mitigation.

Comparatively, the cost-effectiveness approach, which is usually realized via integrated assessment models (IAMs), has been developed.[18–20] It can be calculated by total cost minimization or equalizing the marginal abatement cost among all countries depending on the model structure.[21] Robiou du Pont et al. combined cost-effective global emissions with the equality principles and allocated the global cost-optimal emissions from IAMs under the effort-sharing approach.[7,22] However, the benefits associated with decarbonization (i.e., avoided climate damage) were usually masked[23,24] and thus could reduce the incentive to achieve optimum action toward reducing climate change.[25] A recent paper introduced the mitigation benefits into the reviewing process and proposed a self-preservation strategy.[26] This self-preservation strategy offers a higher cumulative net benefit for all countries within this century than that represented by their current NDC pledges. The strategy is built on an assumption of international cooperation, and all four equity principles are used in the calculation.

To facilitate further discussion of the NDC review, we have extended the self-preservation strategies from a noncooperative perspective. Our review approaches fairness by providing an economic perspective, which balances national mitigation costs and benefits. Countries invest in mitigation to reduce future climate damage. The avoided damage is regarded as the *benefit* of emission reduction, whereas the damage is the monetized aggregation of both market and nonmarket loss related to climate change. Market loss includes the value of physical damage from climate hazards (such as droughts and cyclones), whereas nonmarket losses are those that are hard to reflect in market values, such as climate impact on mortality and crime. We equalize the marginal mitigation cost with marginal climate damage in the long term for each region by using the noncooperative scenario of the Regional Integrated Climate-Economy (RICE) model.[27,28] In this noncooperative scenario, marginal mitigation cost and its demerit of reducing economic output are optimized regarding the related marginal climate damage over time. National emission decisions will jointly affect the global temperature; therefore, we use a Nash equilibrium decision-making theorem to calculate the Pareto optimality, which means that no country could have a welfare gain when changing its emission strategies. The resulting emission trajectory suggests a ceiling emission where the marginal mitigation cost is equalized with marginal mitigation benefits (the damage costs of an additional ton of carbon emission) at each point in time. Exceeding the ceiling emission will lead to more significant marginal damage than marginal abatement costs.

The RICE model has been widely employed to investigate Nash noncooperative equilibria and the social cost of carbon.[29–31] The global version of RICE (i.e., the Dynamic Integrated Climate-Economy [DICE] model) is one of three models that have been used to value the benefits of reducing CO_2 emissions from an array of energy, air pollution, and climate change regulations in the US.[32–35] With a rigorous and transparent modeling framework, we conduct the review from two aspects. "Mitigation" indicates the absolute amount of emission reduction, defined as the gap between the economically optimal emission and the national commitment. "Effort" is defined as the percentage of emission reduction compared with national cost-benefit optimal emission. The effort index standardizes national mitigation and makes the review comparable among countries. The optimal level is reached when the marginal mitigation cost is equal to the marginal climate damage avoided at a national level. Although the national emission reductions under the solely economic scenario are theoretically optimal, they are subject to the assumption of Nash equilibrium without any national cooperation. International cooperation, which allows high-mitigation-cost countries to transfer their mitigation effort, can reduce the general mitigation cost, thus having a Pareto improvement for all. However, the international cooperation equilibrium can be challenged by free-rider intentions, which is to say that countries benefit from the carbon reductions of others without themselves contributing to reduction efforts that would impose costs on their citizens.[36,37]

Because cooperation is hard to achieve, we assume no international cooperation or consensus over equity. The results provide an economically rational mitigation approach, thereby enhancing national climate pledges in light of vulnerability and national risk aversion toward climate change. Our calculation offers a ceiling emission value for countries rather than a 1.5°C or 2°C consistent national emission at the NDC commitment year. If one country's emissions are higher than its ceiling emissions, it is regarded as economically inefficient. The review facilitates further ambitious commitment through an identification process by using both absolute and relative quantities. We compare the NDCs with the economically optimal emission. Mitigation is the absolute amount of emission reduction, and effort is the relative quantities of emission reduction. We also use the National Effort Index (NEI) to denote this percentage change, which is defined as the quantity of emission reduction divided by the noncooperative economic emissions. The index makes the review comparable among countries and helps to recognize the effort made by small emitters. Balancing the national cost and benefit in mitigation without cooperation assumption, this paper reviews the NDCs through their solely economic aspects, which can supplement the current equity principles.

RESULTS

We divided the world into 15 regions according to the international climate regime. Countries with formally stated emission-reduction targets under the Kyoto Protocol (also known as the Annex-B countries) were grouped into six. The US, the EU (including the UK), Russia, Canada, and Japan were taken separately, and the rest were taken as other Annex-B countries. Four developing countries taking the lead in climate negotiations (also known as the BASIC group), namely China, India, Brazil, and South Africa, were also analyzed separately. To ease computational difficulties, we divided the rest of the world into five regions according to geographical locations, namely the Middle East and Africa (MAF; with the exception of South Africa), other Asia (OAS; with the exception of the Middle East, China, India, Japan, and former Soviet Union states), Latin America and the Caribbean (LAM; with the exception of Brazil), the reforming economies of

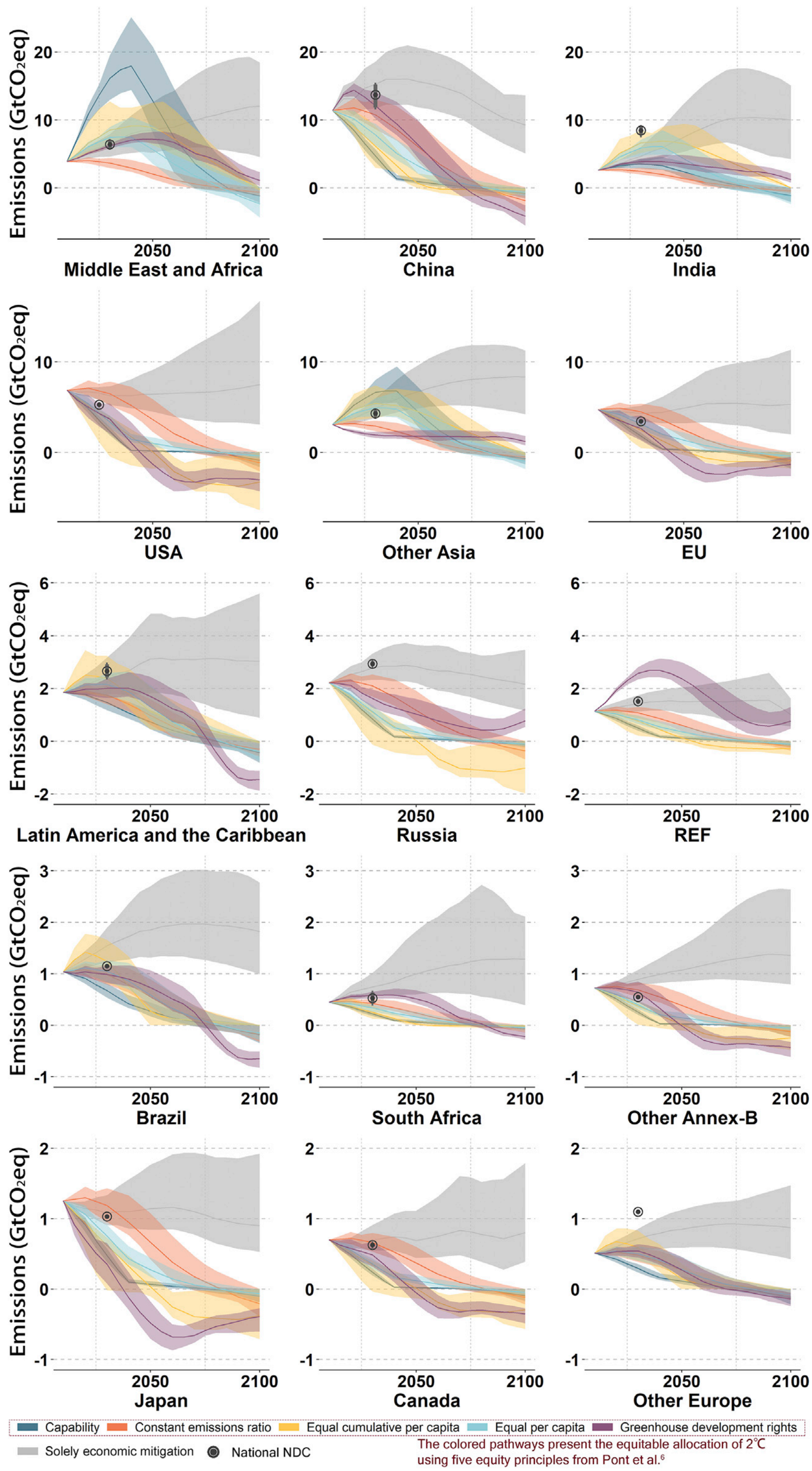

Figure 1. Comparisons of national emission change under different equity criteria and from the economic aspect

The solely economic emission provides a national cost-benefit emission trajectory under the noncooperative Nash equilibrium. The uncertainty comes from the alternative rates of social time preference, generational inequality aversion, and socioeconomic development. The 2°C equity allocation assigns cost-effective global emission using the five equity principles. REF: the reforming economies of Eastern Europe and the former Soviet Union.

Eastern Europe and the former Soviet Union (REF), and other Europe (OEU). The above regional definitions will be used for MAF, OAS, and LAM in the following context. Detailed information is provided in the supplemental experimental procedures.

Solely economic perspective versus equity perspective

We account for the uncertainty regarding socioeconomic development and social preferences to generate the economically optimal emission path for regions (Figure 1, range in gray) and then compare our results with five equitable 2°C allocations (capability, constant emission ratio, equal cumulative per capita, equal per capita, and greenhouse development right) from Robiou du Pont et al.[7] (Figure 1, colored range). Capability emphasizes the availability of resources to mitigate and allocates carbon budgets by per capita gross domestic product (GDP). The constant emission ratio (also known as the "grandfathering law") maintains the base year's national emissions rate. Equal cumulative per capita strengthens historical responsibility and allocates populations with high historical emissions with low-carbon budgets. Equal per capita emphasizes per capita equity and suggests a per capita emission convergence after the convergence period. The greenhouse development right preserves a "right to development" and allocates carbon budgets by weighted capability index and equity index. Further details on competing methodologies for equity allocation can also be found at Paris Equity Check (http://paris-equity-check.org/) and in Table S3.

Under our assumptions, national emission without equality or temperature consideration (Figure 1, gray range) will generally increase at the beginning and slow down as a result of the severe climate damage at the end of this century. Greenhouse gas (GHG) emissions in China, India, and Russia show a declining trend after the peak. However, as a result of conservative estimations of the climate damage and consideration of fossil-fueled development (SSP5), the solely economic emission without cooperation in many regions will increase throughout the period. According to the GDP projections in the shared socioeconomic pathway (SSP) database, MAF and OAS are expected to have a fast economic development throughout the century. Under a noncooperative assumption considering only national mitigation costs and benefits, the solely economic emission path is increasing throughout the time period.

The solely economic mitigation will lead the average surface temperature to 3.5°C–4°C, which is much higher than the 2°C goal suggested; therefore, in most cases, the results are higher than the equitable allocation. The inconsistency between equality allocation can be shown; for example, the constant-emission-ratio principle maintains the ratio of national emissions in the base year. The allocation under this principle will provide more carbon quotas to the developed countries that emit higher today. In contrast, the equal-cumulative-per-capita principle will allocate more emission space for developing countries because they have less historical emission. In some cases, countries can receive emission quotas much higher than their needs. Following the capability allocations, which concern the liability for climate damage with different abilities to pay, MAF and OAS countries will have a high possibility of emitting higher than their needs. Similar results are also applied for greenhouse development rights for the REF when equitable 2°C allocations under these principles are much higher than the solely economic emission. According to their national mitigation cost and estimated climate damage, if the countries emit as the highest 2°C allocations have suggested, the additional climate damage will be much higher than the mitigation cost.

The pioneers and laggards identified by the equitable allocation and noncooperative economic aspects are mostly similar, although there are a few exceptions. The NDCs of India, Latin America, and REF countries satisfied the equity principles but are not economically efficient. India's NDC is lower than the equal cumulative per capita allocation by 0.8 $GtCO_2eq$. However, India's cost-benefit emission suggests committing an additional 3 $GtCO_2eq$ emission reduction than the current NDC. Although the REF commitment conforms to the greenhouse development rights, it is higher than the average level of purely economic emissions, indicating a possibility of facing more significant future damage than the current mitigation cost.

Sensitivity analysis of key parameters

We conducted a range of sensitivity tests, including the socioeconomic uncertainty, the sensitivity test of the social discount rate, the climate impact on productivity, and the equilibrium climate sensitivity (see Tables S1 and S2). The socioeconomic path has the dominant effect on the emission path. The effect of the social discount rate, which represents governments' attitude toward climate change, is also considerable.

Combating climate change is a long-term process involving multiple generations, and the social discount rate presents the generational preference in the decision making. Therefore, valuing the social discount rate is crucial to determining the solely economic emission trajectory given that climate change concerns the decision maker only if they value the future. Within the Ramsey framework, the social discount rate can be estimated by the social time preference (STP) and the elasticity of the marginal utility of consumption (EMUC). The STP describes the consumption preference over time, reflecting the preference to consume earlier or later, which can also be seen as the generational welfare discount rate. The EMUC measures the utility change with consumption regardless of its timing. Following previous discussions and Intergovernmental Panel on Climate Change (IPCC) suggestions, we discuss a range of STP from 0.5% to 2.5% with an EMUC from 0.5 to 2.5.[5,38]

Apart from the two parameters above, we also discuss the uncertainty caused by the alternative path of socioeconomic development, which is reflected by the SSPs with a set of variables. The SSP scenario is driven by a harmonized projection over GDP and population with a descriptive narrative for diverse fields. Because the RICE model is too simplified to reflect the sectoral and policy characteristics, we use the model result from the Global Change Analysis Model (GCAM) and the Integrated Model to Assess the Global Environment (IMAGE) to characterize the SSP in RICE. The purely economic emission with uncertainty is shown in Figure 2.

The socioeconomic development path is the dominant source of uncertainty because it makes the national solely economic emission path remarkably diverse. The range within the SSP trajectory denotes the uncertainty from the STP and EMUC. The nine sets of STP and EMUC are illustrated in Figure 2, which covers a range of STP (0.5%, 1.5%, and 2.5%) and EMUC (0.5, 1.5, and 2.5). With the highest speed of economic development and relatively median decline in carbon intensity, SSP5 has the highest solely economic emission with the widest uncertainty range for most countries. With a greater prospect of economic development, countries have higher mitigation capability while facing a temperature increase. Besides SSP5, the regional rivalry (SSP3) scenario depicts an international fragmentation narrative with a low economic growth and the highest emission intensity at the end of this century. With limited power of global institutions and strong policy orientation toward security, this scenario will lead to a rapidly increasing trend for emission in Latin America, OEU countries, and the REF.

Review the NDCs from a solely economic perspective

On the basis of our analysis of the solely economic emission above, we conduct the national commitment review with regard to the amount of emission reduction and the relative percentage change. We build the NEI to provide an intuitive score of the national climate ambition. The index denotes the percentage of emission reduction reflected by the NDCs compared with the solely economic emission level in the committed year. We define the index as the relative percentage change compared with the cost-benefit emissions (see the experimental procedures). Higher NEI denotes a more ambitious climate pledge accordingly. Following previous calibration,[39] we choose the value of 1.5% social preference with EMUC = 1.5 to conduct the review below because it is most commonly used by government analysis and literature.

The review results could slightly differ under the five SSPs because the cost-benefit emission is sensitive to alternative socioeconomic development paths (Figure 3, pie chart). Socioeconomic factors such as economic growth, population, international relationship, and technological diffusion will lead to different mitigation and adaptation challenges. Therefore, the emission from a solely economic aspect could be different under alternative social development paths. The black ring border denotes a pie chart for global purely economic emissions in 2030 under five SSPs. The global economically optimal emission in 2030 denoted by the pie chart could differ with different socioeconomic assumptions. From SSP1 (sustainable development)

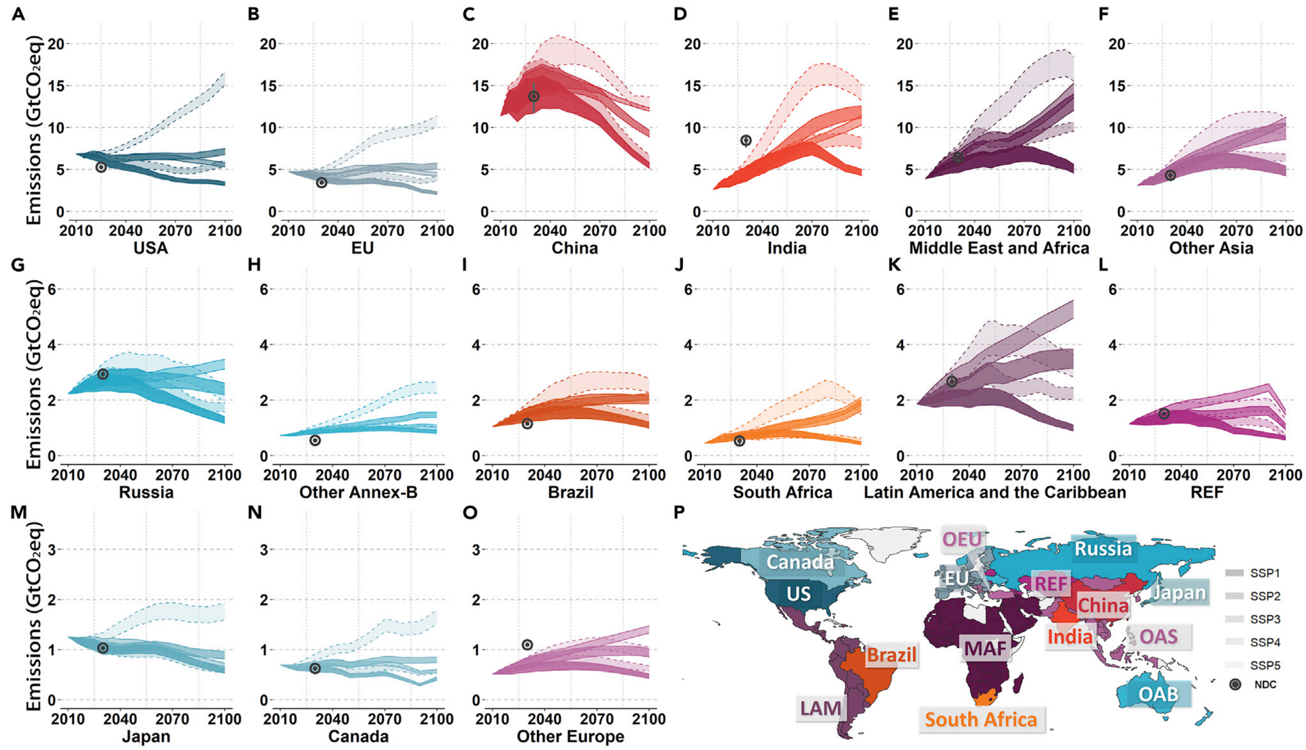

Figure 2. The solely economic national emission trajectory under five SSPs with alternative social time preference and generational inequality aversion rates

(A, B, G, H, M, and N) The Annex-B countries, which have a binding emission target over the Kyoto Protocol.

(C, D, I, and J) The BASIC countries.

(E, F, K, L, and O) The regions grouped by geographical locations.

(P) A map of the fifteen regions.

The range of SSP4 and SSP5 is presented as a dashed line. REF: the reforming economies of Eastern Europe and the former Soviet Union.

to SSP5, the sum of national purely economic emissions is 47.7, 53.1, 55.2, 52.9, and 60 $GtCO_2eq$, respectively. The wedges present the national NDCs in 2030. The gap between the wedge and the ring denotes national mitigation efforts over climate change. The wedges that outranged the ring indicate an insufficient climate commitment. Countries can further reduce their emissions to balance national climate damage in the future with a low cost. Otherwise, the country is making an effort to mitigate. The area between the wedge and the ring is regarded as the amount of emission reduction. Different socioeconomic development paths will alter total GHG emissions as well as the national emission share, therefore slightly changing the results of our evaluation. Evaluation based on SSP1 provides the most stringent results given that the pathway depicts an improving environmental recognition with increasing investment and financial incentives lower the general abatement cost. In contrast, SSP5 presents a fossil-fueled development path, which allows a relatively high emission for countries. This is mostly because of the great economic success projected. In 2100, the GDP under SSP5 is one to two times higher than the moderate projection of SSP2 (middle of the road) and two to eight times higher than the low GDP projection of SSP3. The dominant emitters of GHGs remain the same in all five SSPs. China, the US, and MAF countries are taken as half of the total GHG emissions in 2030, whereas OAS, India, and EU countries make up a quarter of the global emission. Of all regions, India's NDC performs the worst according to the purely economic aspect and outranges the pie for all five socioeconomic paths. The NDC commitment of OEU countries (Turkey, Croatia, etc.) is also insufficient under all the five SSPs. Russia and REF commitments are also risky in the cost-benefit aspect, indicating more serious future climate damage under four SSPs. Taken as around 11% of global emissions in 2030, MAF countries could outride the cost-benefit level if the economy goes through SSP1 or SSP2.

The Paris Agreement can effectively lower the national emissions in 2030 under four socioeconomic development paths. In SSP1, the NDCs have exceeded the solely economic emission level by 4 $GtCO_2eq$. If the world shifts pervasively toward a sustainable path, the current Paris Agreement is not putting sufficient pressure on countries to have ambitious climate pledges. In SSP2 and SSP4, the sum of national commitments is slightly lower than the cost-benefit level under noncooperative assumptions, reducing 1.4 and 1.2 $GtCO_2eq$, respectively. The Paris Agreement is effectively reducing national emission efforts if countries are projected to go on SSP3 or SSP5. Under these two development paths, the NDCs are 3.5 and 8.3 $GtCO_2eq$ lower than the noncooperative economic level.

Sorting the NDCs with regard to the amount of emission reduction and comparing the result with the relative change reflected by effort (Figures 4A and 4B), we recognize the

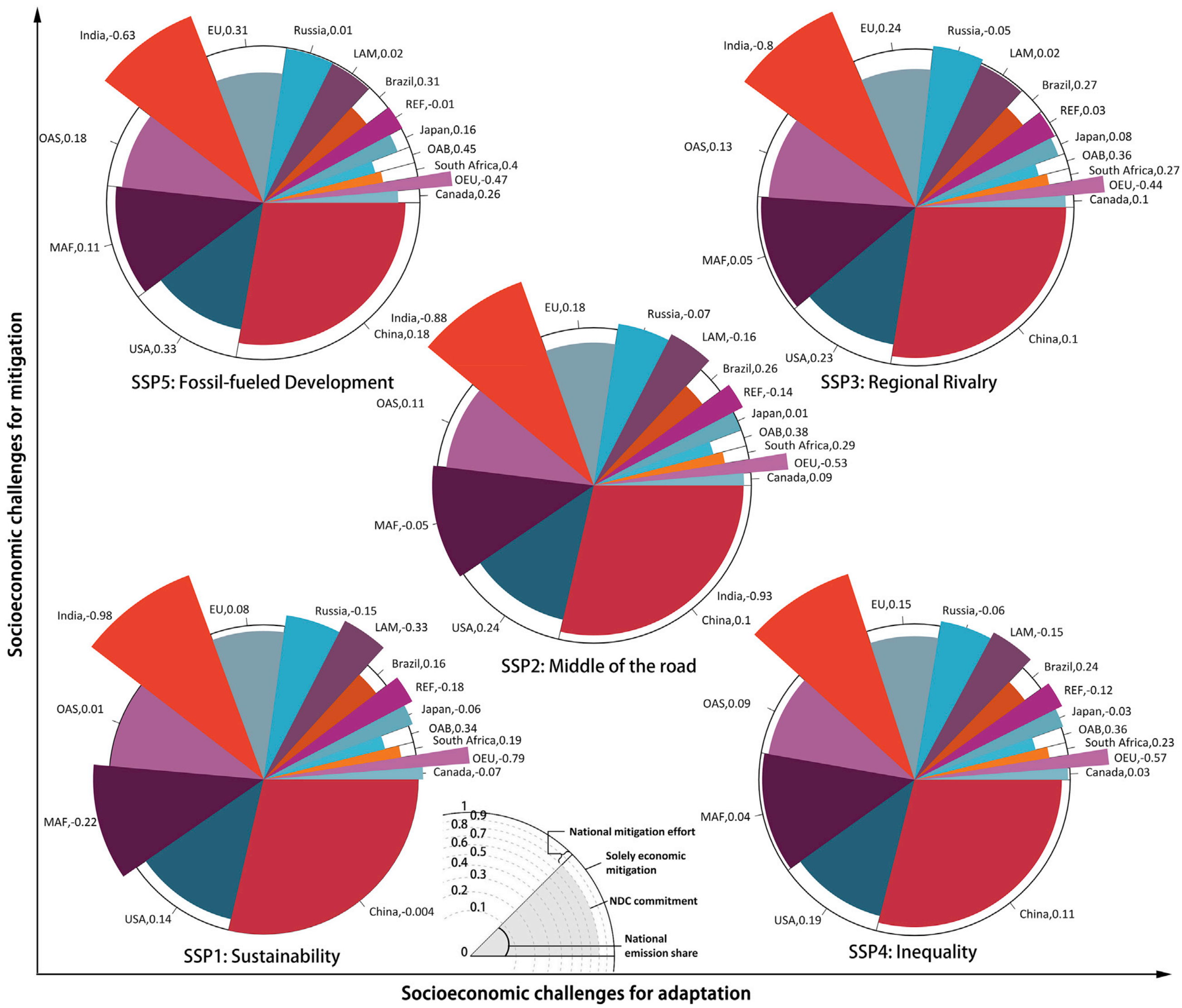

Figure 3. Reviewing the NDCs under the five socioeconomic development paths

The pie charts show the national solely economic emission share in 2030, and the wedges show the national NDC commitments in 2030. The national effort is reflected by the gap between the wedge and the ring, indicating the percentage change of the NDCs compared with the noncooperative emission. The area between the wedge and the ring denotes the amount of emission reduction reflected by NDCs.

contribution from Brazil, South Africa, and other Annex-B countries. These three regions or countries with small emission volumes have committed ambitious NDCs with regard to the solely economic emission level. In contrast, India and OEU countries' inactiveness becomes more obvious given that their NDCs pledge almost double the economically efficient emissions. Given that India is a vulnerable country facing greater climate damage, the economic outcome from its GHG will not make up for the future damage caused by the emission.

Regarding the amount of intended mitigation, China, the US, and the EU are taking the lead, whereas India is hindering progress. The NDC from China committed an average of 1.5 $GtCO_2eq$ emission reduction relative to its solely economic emission in 2030. The US follows with a target of reducing 1.4 $GtCO_2eq$ GHG emissions in 2030. The EU countries also committed a high level of mitigation (reducing 0.9 $GtCO_2eq$ in 2030) comparatively with their purely economic emissions. However, with a high emission volume, India itself can counteract half of the emission reduction for the three countries. By committing to an NDC 3.8 $GtCO_2eq$ higher than its solely economic trajectory, the country is taking a high risk for its future. If other countries follow the noncooperative path and India emits as high as its NDC, the climate damage caused by this additional emission will be much higher than the cost of reducing the emissions.

International cooperation over climate change will significantly reduce the climate damage for all countries (Figures 4C and 4D). We use the RICE model's damage function to calculate cumulative climate damage for a range of 2°C consistent scenarios. The 2°C consistent global mean temperature data are derived from the SR1.5 Scenario Database. If countries do not cooperate and

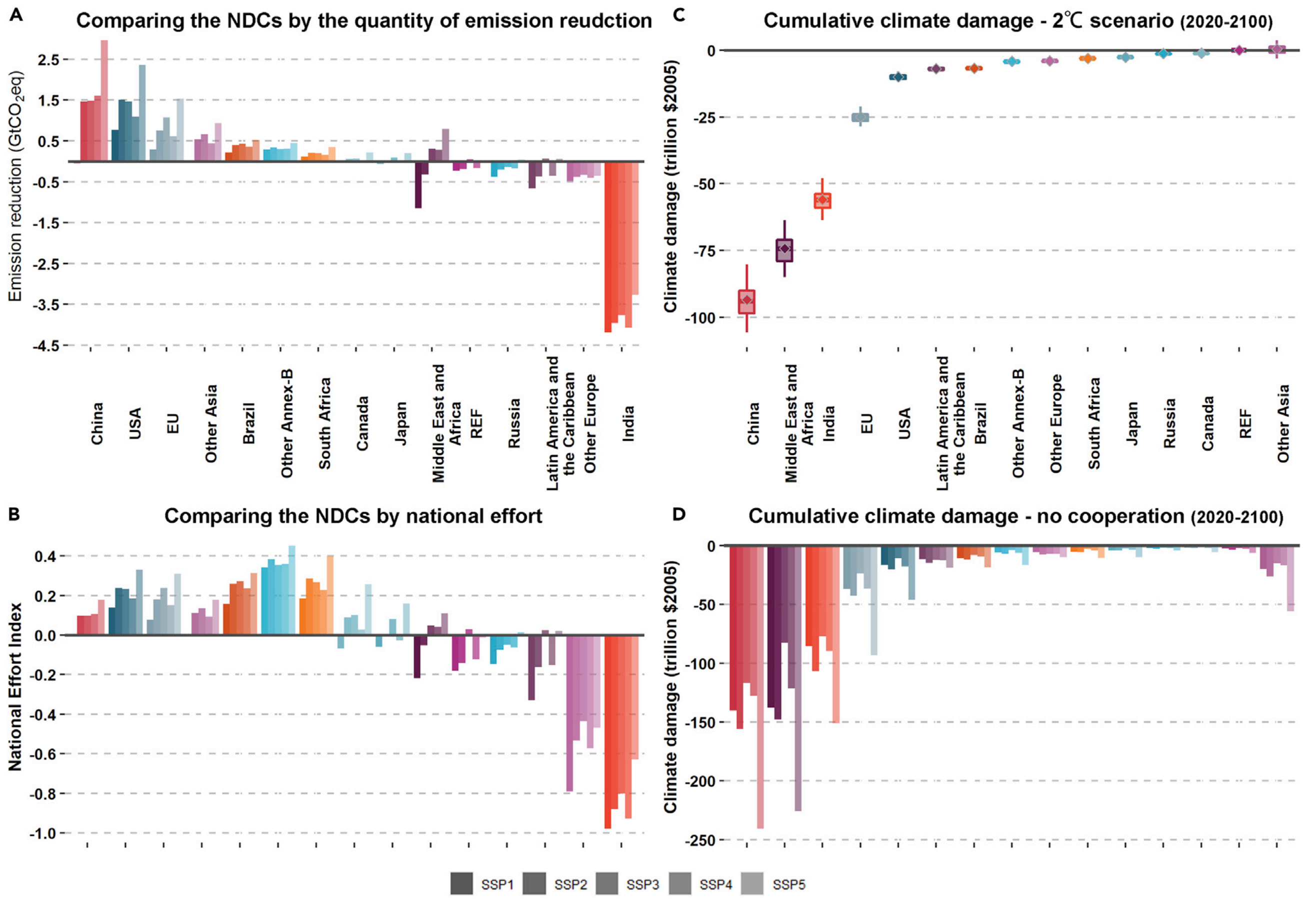

Figure 4. Review of the current national climate pledges with the relative abatement cost and economic damage caused by climate change

(A) The emission gap between current NDCs and the economically optimal emissions.

(B) The relative emission gap of current NDCs presented by the National Effort Index (NEI).

(C) Cumulative climate damage under 2°C consistent scenarios from 2020 to 2100. The lower and upper hinges correspond to the first and third quartiles. The upper and lower whisker extends from the hinge to the largest/smallest value no further than 1.5*inter-quartile range from the hinge.

(D) Cumulative climate damage under solely economic scenario from 2020 to 2100.

look only at the national cost-benefit of climate actions, the cumulative climate damages are estimated to double the 2°C consistent scenarios. With a conservative estimation over climate damage, the estimated climate impact for OAS and the REF are near zero under 2°C consistent paths. However, if the temperature goes beyond 2°C, the climate impact will be significant, especially for OAS. From 2020 to 2100, the cumulative climate impact is estimated to be $27 trillion under the noncooperative scenario, which accounts for 1% of OAS countries' GDP over the period.

China, MAF countries, and South Africa are projected to be the most vulnerable countries in that they could lose an average of 4% of their total economic output within this century (Figure 4D). India, the EU, and the US are projected to lose 1%–2% of GDP under the solely economic mitigation path. However, with a considerable economic volume, the cumulative climate losses are huge. The noncooperative emission path suggests $102 trillion cumulative climate damage for India from 2020 to 2100. The losses could be around $47 trillion for the EU and $22 trillion for the US. Low climate damage in SSP3 does not indicate sustainability given that the low economic output also affects the cumulative loss. The sustainable development path has the lowest ratio of climate impacts to GDP. In contrast, the ratio is 1% higher for most countries if society develops toward SSP5.

Equal-effort cooperation path toward the 2°C goal

To lower the risk of irreversible climate damage, the Paris Agreement has set the goal of limiting global warming well below 2°C within this century. Countries cannot achieve 2°C if they consider only national mitigation costs and benefits. Therefore, we further consider the possibility of cooperation and propose an equal-effort 2°C scenario. Reducing global emissions from a solely economic level to a 2°C consistent level, the equal-effort 2°C scenario suggests that countries reduce the same percentage of purely economic emissions each year.

In 2030, the global emission in accord with 2°C is 28% lower than the solely economic emission (Figure 5). The outer circle denotes the average of purely economic emissions under five SSPs (53.8 $GtCO_2eq$ in 2030). Emissions are cost-benefit efficient within the country but lead to a higher global temperature than the Paris Agreement goal suggests. Countries can further reduce their emissions to lower their climate damage and reach global

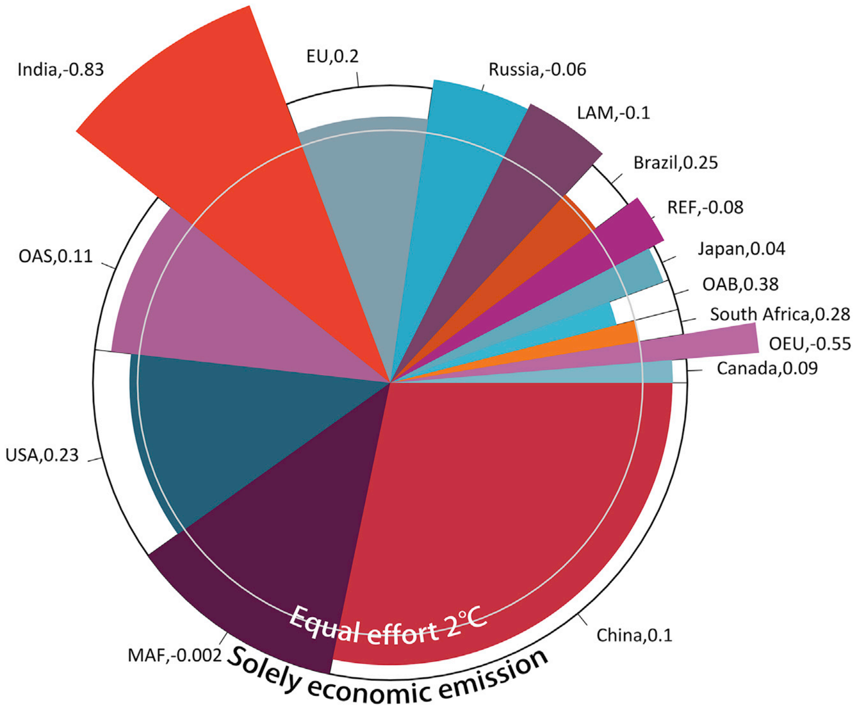

Figure 5. Equal effort 2°C in 2030

The pie chart shows the national solely economic emission share (the outer circle) and equal-effort 2°C emission share (the inner circle) in 2030, and the wedges are the committed NDCs. The national effort is reflected by the gap between the outer circle and wedges, indicating the percentage change of NDCs compared with the economically optimal emission level. The area of gaps denotes the amount of emission reduction.

cost-benefit efficiency by maintaining the global temperature increase at <2°C within this century. The 2°C scenario from the IPCC SR1.5 Scenario Database suggests an average of 38.8 $GtCO_2eq$ GHG emissions in 2030, which is 28% lower than the noncooperative cost-benefit level. In the equal-effort scenario, we suggest that every region take the same percentage of emission reduction, that is, lower their emissions by 28% of the cost-benefit economic level in 2030 (shown in the inner circle).

For countries with an NEI lower than 0.28, although their NDC commitments are cost-benefit efficient under the noncooperative assumption, further emission reduction toward the 2°C goal requires them to reduce their emission to achieve economic efficiency globally with lower climate damage. South Africa committed the same emission reduction in accord with equal-effort 2°C with an NDC 28% lower than the solely economic emission. China, the US, and the EU are suggested to further mitigate 18%, 5%, and 8%, respectively, compared with the solely economic emissions. Given the NDCs they have committed, the three countries are suggested to lower 20%, 6%, and 10% of their NDC commitments.

DISCUSSION

The equity principles used for reviewing the NDCs pledge have been going through a long debate with hardly foreseen consistency among countries. Our study informs the effort-sharing scheme and reviews the NDCs in their solely economic aspects. Mitigation is an investment in the future that brings the benefits of reducing projected climate damage. Even without the temperature goal or the equity-principle debate, in a solely economic aspect, it is economically favorable for countries to control their national emission at a reasonable level to avoid future climate damage. This is crucial for NDC re-evaluation given that six countries have still failed to ratify their intended NDCs (INDCs) officially, and only 90 parties have communicated 2020 NDCs through June 2021.[40] Thus, our results can be informative for countries to control their national emissions at an economically favorable level.

Given many criticisms of the Paris Agreement for allowing countries to do what they will, we compared the total emission reduction from five socioeconomic pathways. The Paris Agreement is considered effective under four SSP paths, reducing 1.4 $GtCO_2eq$ GHG in 2030 on the basis of historical socioeconomic projection (SSP2). This supposes that the world is developing toward SSP1 with a rapid decline in abatement cost. In that case, the cost-benefit results suggest that countries should further reduce emissions of 4 $GtCO_2eq$ compared with the current NDCs.

The average surface temperature will rise to 2.8°C–3.6°C at the end of this century if countries emit in a national cost-benefit manner. The path is not in accord with the Paris Agreement goal and will double the cumulative climate damage for most countries. It would be economically favorable for countries to cooperatively act toward the 2°C goal.[36] Reviewing the NDCs on the basis of cost-benefit analysis provides an alternative perspective for countries to view the emission reduction in an economic aspect. Besides the equal-effort 2°C scenario, further research can explore other possibilities for combining the national cost-benefit review with equity and 1.5°C.

Any IAM-based review method is subject to parameter choice and projection uncertainty. The limitation exists in multiple aspects. Firstly, the damage function is highly restricted to the current estimation with a non-linear assumption over the economic and damage relations. However, an alternative form of damage estimations (e.g., from Burke et al.[41] and Dell et al.[42]) will make the 2°C Paris Agreement economically favorable in the cost-benefit context.[38] The regional specific climate risk-aversion parameters can also be included to alter the national noncooperative level.[43] Secondly, the co-benefits of carbon mitigation, such as local air-quality improvement, are not included. The benefit from mitigation cost is expected to increase when the health co-benefits are accounted for.[44] If the benefit increases, the noncooperative emission will be lower, whereas more ambitious actions would be motivated subsequently. Thirdly, the Nash equilibrium is not necessarily Pareto

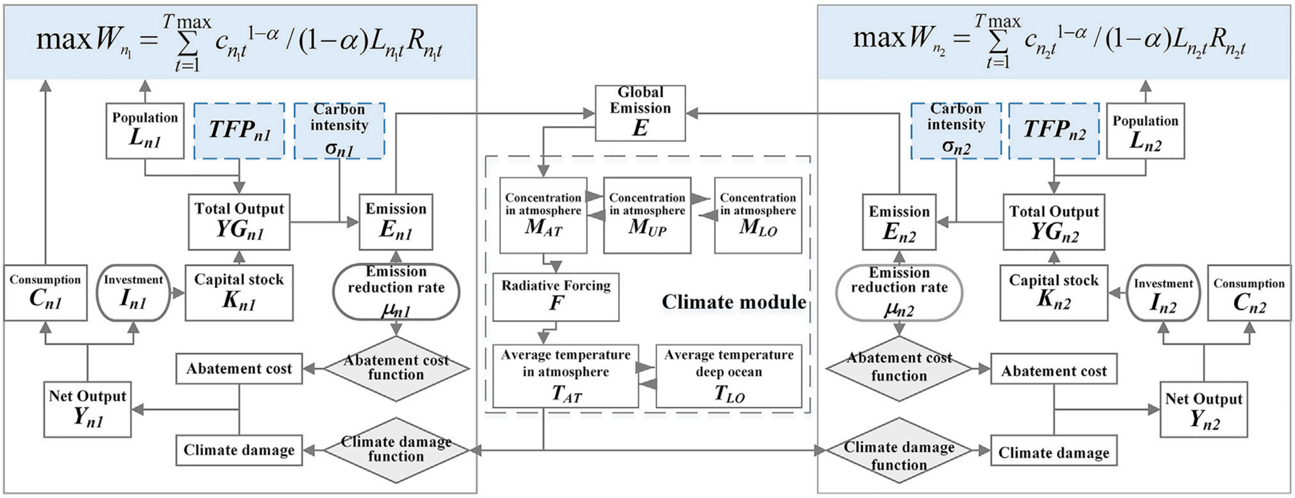

Figure 6. Key variables in the noncooperative RICE model

optimal, and multiple cooperative mechanisms could increase the national payoff.[29,31]

EXPERIMENTAL PROCEDURES

Resource availability

Lead contact

Further information and requests for resources and reagents should be directed to and will be fulfilled by the lead contact, Zhifu Mi (z.mi@ucl.ac.uk).

Materials availability

This study did not generate new unique materials.

Data and code availability

All input data used for this study are openly available: the capital stock is adopted from the International Monetary Fund;[1] the GDP, population, land-use emission, and baseline carbon intensity are publicly available at the SSP database (Database: https://tntcat.iiasa.ac.at/SspDb); the national equitable 2°C allocation is available online at Paris Equity Check (Database: http://paris-equity-check.org/); the NDC data are available at Database: https://www.climatecollege.unimelb.edu.au/ndc-indc-factsheets; and the 2°C consistent temperature data were downloaded from the IPCC SR1.5 Scenario Database (Database: https://data.ene.iiasa.ac.at/iamc-1.5c-explorer/). The data and code generated during this study and the regional definition are available at Figshare (Model Code: https://doi.org/10.6084/m9.figshare.13250138.v2).

The RICE model

The RICE model is one of the cost-benefit IAMs (CB-IAMs) with a relatively simple and transparent structure. The CB-IAM, which equalizes the marginal avoided climate damage with marginal emission reduction cost in the long term, is widely used to analyze optimal mitigation policies.[45] The RICE model is widely recognized as the ancestor of the regional CB-IAM, which delivers a national cost-benefit strategy under Nash equilibrium.[27] With a relatively simple model structure and assumption, the RICE model provides policymakers with a transparent and understandable tool in comparison with other CB-IAMs (Figure 6). Two features characterize the model: first, as an economic optimization model, RICE allocates the available income to consumption, investment, and emission reduction in each term to maximize long-term welfare; second, the model captures regional strategic interaction and free-ride behaviors over climate change in its noncooperative scenario.

For the noncooperative scenario, countries only optimize their national mitigation cost to reduce national climate damage. Nash equilibrium is achieved when countries maximize their national welfare, and no countries benefit from changing their mitigation strategies. Although countries can further improve their welfare by undertaking more mitigation efforts[46] or through climate clubbing,[29] we did not include them in our study because they could increase the complexity of the review.

Recalibrating RICE 2010

We follow the RICE 2010 model[28] with the updated climate module documented in DICE 2016[39,47] and extend the model to 15 regions by the international climate regime (supplemental information). The Annex-B countries that have binding emission targets in the Kyoto Protocol are divided into six regions: the EU, the US, Russia, Japan, Canada, and other Annex-B countries. Whereas the US, the EU (28 countries including UK), Russia, and Japan are four highly developed countries with very large economic volumes, Canada is separated because of its withdrawal from the Kyoto Protocol in 2011. Other countries participating in the Kyoto Protocol, except for Ukraine, are grouped into other Annex-B countries. Although Ukraine has been listed in the signatory nations to the Kyoto Protocol, it is the only Annex-B country that did not retire enough assigned amount units during the first commitment period,[48] and the countries have been grouped into the REF according to the SSP 32 region definition. The emerging powers during climate negotiations (i.e., China, India, Brazil, and South Africa, known as the BASIC group) are also considered independently. Other countries are grouped into five regions according to geographical locations, namely the MAF, OAS, LAM, OEU, and REF.

Noncooperative scenario and social preferences

For the noncooperative scenario, we solve the Nash equilibrium by maximizing national welfare until no countries have a welfare gain when they change their emissions. The solely economic emission trajectory is generated as the outcome. National welfare, W_n, is defined as

$$W_n = \sum_{t=1}^{Tmax} \left\{ L_{n,t}(1+\rho)^{-t} \left(\frac{c_{n,t}^{1-\alpha} - 1}{1-\alpha} - 1 \right) \right\}, \qquad \text{(Equation 1)}$$

where $c_n(t)$ represents the consumption per capita of country n in term t, $L_n(t)$ represents the national population of country n, ρ represents the social welfare discount factor (STP), and α represents the EMUC. The values of STP and EMUC have been widely debated. We account for the value range from 0.5 to 2.5 for both factors according to IPCC-AR5 and previous work.

Characterizing SSPs in RICE

We address the certainty by using the SSP framework. The SSP framework includes five consistent narratives of future developments that are quantified for diverse fields, such as demography, economic growth and convergence, energy, land use, air pollution, policies, and trading.[49,50] The qualitative narratives that provide the basis for five development paths are thoroughly described by O'Neill et al.[49] The five SSPs are characterized as sustainability (SSP1),[51]

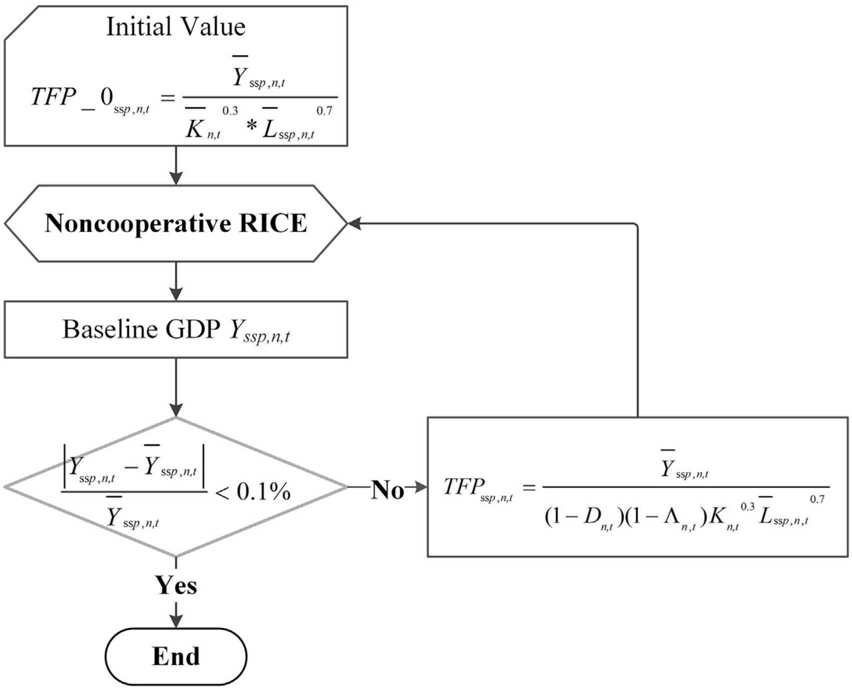

Figure 7. Calibration of the total factor productivity under SSPs

middle of the road (SSP2),[52] regional rivalry (SSP3),[53] inequality (SSP4),[54] and fossil-fueled development (SSP5).[55]

In RICE, the SSP is reflected in the population, total factor productivity (TFP), uncontrolled intensity change, land-use emission, and abatement cost. The net GDP in RICE is presented as

$$Y_{n,t} = \mathrm{TFP}_{n,t}K_{n,t}^{0.3}L_{n,t}^{0.7}(1-D_{n,t})(1-\Lambda_{n,t}), \quad \text{(Equation 2)}$$

where $Y_{n,t}$ represents the net output of climate damage and mitigation costs and $\mathrm{TFP}_{n,t}$ measures the economic efficiency and other factors not explained by labor or capital. $K_{n,t}$ represents the national capital stock, and $L_{n,t}$ represents the population. Using the GDP and population data from the SSP database, we follow Yang et al.[35] and calibrate the $\mathrm{TFP}_{n,t}$ to reflect the economic growth difference of five SSPs (Figure 7).

Society reduces consumption today to invest in capital goods, thereby increasing consumption in the future and maximize long-term social welfare:

$$C_{n,t} = Y_{n,t} - I_{n,t}, \quad \text{(Equation 3)}$$

where C_t represents total consumption and I_t represents a total investment. Capital formation is expressed as follows:

$$K_{n,t} = (1-\delta_K)K_{n,t-1} + I_{n,t}, \quad \text{(Equation 4)}$$

where K_t represents the capital stock in term t and δ_K represents the depreciation rate of the capital stock.

Economic development is accompanied by GHG emissions, and emissions constitute both industrial emissions and land-use emissions. In the original version of RICE, the industrial CO_2 emissions are endogenously optimized, whereas land-use CO_2 emissions and other GHG emissions are treated as exogenous. This paper assumes that GHG emissions are highly related to the industrial process and replaces industrial CO_2 emissions with industrial GHG emissions. We use the SSP baseline results from GCAM to calibrate the uncontrolled intensity decline in GHG emissions. The total GHG emissions are denoted by $E_{n,t}$:

$$E_{n,t} = \sigma_{n,t}(1-\mu_{n,t})TFP_{n,t}K_{n,t}^{0.3}L_{n,t}^{0.7} + LU_{n,t}, \quad \text{(Equation 5)}$$

where $\sigma_{n,t}$ represents the change in carbon intensity without policy. Here, we use the GHG emission data generated from IMAGE and GCAM under SSP baseline assumptions, divided by the baseline GDP, to generate the carbon-intensity parameter $\sigma_{n,t}$. We use the results from the two models because of the model differences in regional definition. $\mu_{n,t}$ represents the emission reduction rate, which is endogenous by optimization. $LU_{n,t}$ represents the emissions induced by land use and land-use change, and we use the SSP baseline land-use emission from GCAM to characterize the land-use change under five socioeconomic pathways.

We use the abatement costs and carbon price from GCAM to recalibrate the abatement cost function under five SSPs in RICE.[35,56] The abatement cost is modeled as a fraction of GDP, and the marginal abatement cost denotes the technology cost of unit emission reduction. The technology cost is naturally different among countries because of the national energy structure and can be further deviated by socioeconomic factors. Developed countries, such as France, might already implement many low-carbon technologies, and it can be costly for them to reduce emissions further. In contrast, countries such as India can still reduce emissions by implementing low-cost technology, such as solar photovoltaics. The marginal abatement cost can also be affected by socioeconomic factors. For example, under SSP3, which is characterized by regional rivalry, implementing low-carbon technology will be costly. Although low-carbon technology is available for some developed countries, the slow technological diffusion speed will also make the mitigation expensive for developing countries. Following the previous work, we choose the abatement cost and carbon price in GCAM to measure the changes in emission-reduction costs. The form of the abatement cost function is defined as

$$\Lambda_{n,t} = a_n\mu_{n,t}^{b_n}\sigma_{n,t}Y_{n,t}. \quad \text{(Equation 6)}$$

The mitigation cost $\Lambda_{n,t}$ is determined by the emission reduction rate $\mu_{n,t}$ and the baseline emission without policies. a_n and b_n are parameters that characterize the difference of mitigation cost change under five SSPs.

NEI

Comparing national efforts among countries is important to motivate further actions.[57] Thus, the NEI is built to convert the absolute emission reduction amount to a relative quantity, indicating the effort contributed by nations in comparison with the national cost-benefit emission under the noncooperative scenario:

$$\mathrm{NEI}_n = -\frac{EC_{n,t} - EN_{n,t}}{EN_{n,t}}. \quad \text{(Equation 7)}$$

The national emission, $EN_{n,t}$, under the noncooperative scenario is taken as the evaluation standard, and $EC_{n,t}$ represents the NDCs that this paper evaluates. The term t is set as the commitment year, and for the Paris Agreement, the national commitment year is 2030. The value demonstrates the effort contributed by nations in comparison with their national cost-benefit emissions. A positive NEI indicates a national mitigation effort toward climate change, and a high NEI value indicates ambitious efforts expressed as a national commitment. A high NEI increases the possibility of achieving a 2°C goal and pursuing further efforts to reach the 1.5°C goal. In contrast, a negative NEI indicates that the national emission commitment level is too high, whereas the marginal mitigation cost is lower than the marginal climate damage. Nations are economically efficient if they achieve further mitigation; otherwise, every nation suffers welfare loss.

Table 1. Abbreviations

Abbreviation	Full name
BASIC group	Brazil, South Africa, India, and China
CBDR-RC	common but differentiated responsibilities and respective capabilities
CB-IAM	cost-benefit integrated assessment model
DICE model	Dynamic Integrated Climate-Economy model
EMUC	elasticity of marginal utility of consumption
GCAM	Global Change Analysis Model
IAM	integrated assessment model
IMAGE	Integrated Model to Assess the Global Environment
NEI	National Effort Index
NDC	national determined contribution
RICE model	Regional Integrated Climate-Economy model
SSP	shared socioeconomic pathway
STP	social time preference

The range of NDCs

To make the NDCs comparable among countries, we adopt the national NDC Factsheet, which provides a comprehensive overview of all submitted NDCs and INDCs with quantification where possible.[58] On the basis of the SSP database, we further adjust the NDCs for the US, China, and India.

The factsheet provides US NDCs in 2030, whereas the original NDC submitted by the US government is for 2025. We calculate the US NDCs on the basis of the US's commitment to "reducing its greenhouse gas emissions by 26%–28% below its 2005 level in 2025, and to make best efforts to reduce its emissions by 28%." The US NDC in 2025 is in the range of 5.21–5.35 $GtCO_2$ according to its 2005 emission. We also use the estimated 2030 US NDC from the NDC Factsheet,[58] which is in the range of 4.76–4.86 $GtCO_2$, to make the NDC comparable with other countries' commitments.

China and India submitted their NDCs by intensity reduction. We calculate the range of their NDCs on the basis of the GDP estimation from five SSPs. The NDC ranges for China and India are larger than estimated by Meinshausen and Alexander.[58] On average, China's commitment in 2030 is 13.72 $GtCO_2$ (11.82–15.24 $GtCO_2$), and India's commitment is 8.46 $GtCO_2$ (7.73–9 $GtCO_2$). For the 15 regions considered in our review, the NDC ranges are shown in Table 2.

Table 2. NDC range for 2030 ($GtCO_2$)

Region	NDC average	Range	
US	4.81	4.76	4.86
EU	3.43	3.43	3.43
Russia	2.93	2.85	3.02
Japan	1.03	1.03	1.03
Other Annex-B	0.55	0.54	0.56
Canada	0.63	0.61	0.65
China	13.71	11.82	15.24
India	8.46	7.73	9.00
Brazil	1.15	1.15	1.15
South Africa	0.53	0.42	0.64
Middle East and Africa	6.40	5.88	6.91
Other Asia	4.30	3.93	4.66
Latin America and the Caribbean	2.67	2.41	2.92
Other Europe	1.10	1.09	1.10
Reforming economies of Eastern Europe and the former Soviet Union	1.51	1.48	1.55

SUPPLEMENTAL INFORMATION

Supplemental information can be found online at https://doi.org/10.1016/j.oneear.2021.07.005.

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AUTHOR CONTRIBUTIONS

Conceptualization, P.Y., Z.M., and Y.Y.; methodology, P.Y. and Z.M.; investigation, P.Y., Z.M., and Y.Y; writing – original draft, P.Y. and Z.M.; writing – review & editing, P.Y., Z.M., and D.C.; funding acquisition, Z.M., L.L., and Y.C.; supervision, Z.M., D.C., and L.L.

DECLARATION OF INTERESTS

The authors declare no competing interests.

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REFERENCES

1. International Monetary Fund (2017). Investment and Capital Stock Dataset. https://data.imf.org/?sk=1CE8A55F-CFA7-4BC0-BCE2-256EE65AC0E4.
2. Jacquet, J., and Jamieson, D. (2016). Soft but significant power in the Paris Agreement. Nat. Clim. Chang. *6*, 643–646. https://doi.org/10.1038/nclimate3006.
3. UNFCCC ((2015). Adoption of the Paris Agreement. Report no. FCCC/CP/2015/L.9/Rev.1. http://unfccc.int/resource/docs/2015/cop21/eng/l09r01.pdf.
4. Rogelj, J., Den Elzen, M., Höhne, N., Fransen, T., Fekete, H., Winkler, H., Schaeffer, R., Sha, F., Riahi, K., and Meinshausen, M. (2016). Paris Agreement climate proposals need a boost to keep warming well below 2°C. Nature *534*, 631–639. https://doi.org/10.1038/nature18307.
5. Intergovernmental Panel on Climate Change (2015). Climate Change 2014: Mitigation of Climate Change (Cambridge University Press).
6. Höhne, N., Den Elzen, M., and Escalante, D. (2014). Regional GHG reduction targets based on effort sharing: a comparison of studies. Clim. Policy *14*, 122–147. https://doi.org/10.1080/14693062.2014.849452.
7. Robiou du Pont, Y., Jeffery, M.L., Gütschow, J., Rogelj, J., Christoff, P., and Meinshausen, M. (2017). Equitable mitigation to achieve the Paris Agreement goals. Nat. Clim. Chang. *7*, 38–43. https://doi.org/10.1038/nclimate3186.
8. Wei, Y.M., Wang, L., Liao, H., Wang, K., Murty, T., and Yan, J. (2014). Responsibility accounting in carbon allocation: a global perspective. Appl. Energ. *130*, 122–133. https://doi.org/10.1016/j.apenergy.2014.05.025.
9. Den Elzen, M., and Höhne, N. (2010). Sharing the reduction effort to limit global warming to 2°C. Clim. Policy *10*, 247–260. https://doi.org/10.3763/cpol.2009.0678A.

10. Chakravarty, S., Chikkatur, A., De Coninck, H., Pacala, S., Socolow, R., and Tavoni, M. (2009). Sharing global CO_2 emission reductions among one billion high emitters. Proc. Natl. Acad. Sci. USA *106*, 11884–11888. https://doi.org/10.1073/pnas.0905232106.

11. Baer, P., Fieldman, G., Athanasiou, T., and Kartha, S. (2008). Greenhouse development rights: towards an equitable framework for global climate policy. Camb. Rev. Int. Aff. *21*, 649–669. https://doi.org/10.1080/09557570802453050.

12. Raupach, M.R., Raupach, M.R., Davis, S.J., Peters, G.P., Andrew, R.M., Canadell, J.G., Ciais, P., Friedlingstein, P., Jotzo, F., Van Vuuren, D.P., et al. (2014). Sharing a quota on cumulative carbon emissions. Nat. Clim. Chang. *4*, 873–879. https://doi.org/10.1038/nclimate2384.

13. Pan, X., Teng, F., Ha, Y., and Wang, G. (2014). Equitable access to sustainable development: based on the comparative study of carbon emission rights allocation schemes. Appl. Energ. *130*, 632–640. https://doi.org/10.1016/j.apenergy.2014.03.072.

14. Schroeder, H., Boykoff, M.T., and Spiers, L. (2012). Equity and state representations in climate negotiations. Nat. Clim. Chang. *2*, 834–836. https://doi.org/10.1038/nclimate1742.

15. Keohane, R.O., and Victor, D.G. (2016). Cooperation and discord in global climate policy. Nat. Clim. Chang. *6*, 570–575. https://doi.org/10.1038/nclimate2937.

16. Meinshausen, M., Jeffery, L., Guetschow, J., Du Pont, Y.R., Rogelj, J., Schaeffer, M., Höhne, N., Den Elzen, M., Oberthür, S., and Meinshausen, N. (2015). National post-2020 greenhouse gas targets and diversity-aware leadership. Nat. Clim. Chang. *5*, 1098–1106. https://doi.org/10.1038/nclimate2826.

17. Robiou du Pont, Y., and Meinshausen, M. (2018). Warming assessment of the bottom-up Paris Agreement emissions pledges. Nat. Commun. *9*, 4810. https://doi.org/10.1038/s41467-018-07223-9.

18. Aldy, J., Pizer, W., Tavoni, M., Reis, L.A., Akimoto, K., Blanford, G., Carraro, C., Clarke, L.E., Edmonds, J., Iyer, G.C., et al. (2016). Economic tools to promote transparency and comparability in the Paris Agreement. Nat. Clim. Chang. *6*, 1000–1004. https://doi.org/10.1038/nclimate3106.

19. Tavoni, M., Kriegler, E., Aboumahboub, T., Calvin, K., de Maere, G., Wise, M., Klein, D., Jewell, J., Kober, T., Lucas, P., et al. (2013). The distribution of the major economies' effort in the Durban Platform scenarios. Clim. Change Econ. *4*, 1340009. https://doi.org/10.1142/S2010007813400095.

20. Wei, Y.M., Han, R., Liang, Q.M., Yu, B.Y., Yao, Y.F., Xue, M.M., Zhang, K., Liu, L.J., Peng, J., Yang, P., et al. (2018). An integrated assessment of INDCs under Shared Socioeconomic Pathways: an implementation of C^3IAM. Nat. Hazards *92*, 585–618. https://doi.org/10.1007/s11069-018-3297-9.

21. Mi, Z., Liao, H., Coffman, D.M., and Wei, Y.M. (2019). Assessment of equity principles for international climate policy based on an integrated assessment model. Nat. Hazards *95*, 309–323. https://doi.org/10.1007/s11069-018-3408-7.

22. Robiou du Pont, Y., Jeffery, M.L., Gütschow, J., Christoff, P., and Meinshausen, M. (2016). National contributions for decarbonizing the world economy in line with the G7 Agreement. Environ. Res. Lett. *11*, 054005.

23. Ringius, L., Torvanger, A., and Underdal, A. (2002). Burden sharing and fairness principles in international climate policy. Int. Environ. Agreem-P. *2*, 1–22. https://doi.org/10.1023/A:1015041613785.

24. Zenghelis, D. (2017). Equity and national mitigation. Nat. Clim. Chang. *7*, 9–10. https://doi.org/10.1038/nclimate3192.

25. Iyer, G., Calvin, K., Clarke, L., Edmonds, J., Hultman, N., Hartin, C., McJeon, H., Aldy, J., and Pizer, W. (2018). Implications of sustainable development considerations for comparability across nationally determined contributions. Nat. Clim. Chang. *8*, 124–129. https://doi.org/10.1038/s41558-017-0039-z.

26. Wei, Y.M., Han, R., Wang, C., Yu, B., Liang, Q.M., Yuan, X.C., Chang, J., Zhao, Q., Liao, H., Tang, B., et al. (2020). Self-preservation strategy for approaching global warming targets in the post-Paris Agreement era. Nat. Commun. *11*, 1624. https://doi.org/10.1038/s41467-020-15453-z.

27. Nordhaus, W.D., and Yang, Z. (1996). A regional dynamic general-equilibrium model of alternative climate-change strategies. Am. Econ. Rev. *86*, 741–765. http://www.jstor.org/stable/2118303.

28. Nordhaus, W.D. (2010). Economic aspects of global warming in a post-Copenhagen environment. Proc. Natl. Acad. Sci. USA *107*, 11721–11726. https://doi.org/10.1073/pnas.1005985107.

29. Nordhaus, W. (2015). Climate clubs: overcoming free-riding in international climate policy. Am. Econ. Rev. *105*, 1339–1370. https://doi.org/10.1257/aer.15000001.

30. Kotchen, M.J. (2018). Which social cost of carbon? A theoretical perspective. J. Assoc. Environ. Resour. Econ. *5*, 673–694. https://doi.org/10.1086/697241.

31. Chen, C., and Zeckhauser, R. (2018). Collective action in an asymmetric world. J. Public Econ. *158*, 103–112. https://doi.org/10.1016/j.jpubeco.2017.12.009.

32. California Assembly Bill 197 (AB-197) (2016).

33. Schlatter, L. (2016). Findings of Fact, Conclusions, and Recommendations: Carbon Dioxide Values State of Minnesota (Office of Administrative Hearings).

34. Larson, A. (2016). Subsidies proposed for New York's upstate power plants. https://www.powermag.com/subsidies-proposed-for-new-yorks-upstate-nuclear-power-plants/.

35. Yang, P., Yao, Y.F., Mi, Z., Cao, Y.F., Liao, H., Yu, B.Y., Liang, Q.M., Coffman, D.M., and Wei, Y.,M. (2018). Social cost of carbon under shared socioeconomic pathways. Glob. Environ. Chang. *53*, 225–232. https://doi.org/10.1016/j.gloenvcha.2018.10.001.

36. Lattanzio, R.K. (2014). International Climate Change Financing: The Green Climate Fund (GCF) (Congressional Research Service). https://www.everycrsreport.com/files/20140505_R41889_9d0d7f034c21dca729f78a95d52371abed94f678.pdf.

37. Green Climate Fund. (2015). Annex IV: Status of pledges and contributions made to the Green Climate Fund. In Seventh Report of the Green Climate Fund to the Conference of the Parties to the United Nations Framework Convention on Climate Change, pp. 80–83.

38. Glanemann, N., Willner, S.N., and Levermann, A. (2020). Paris Climate Agreement passes the cost-benefit test. Nat. Commun. *11*, 110. https://doi.org/10.1038/s41467-019-13961-1.

39. Nordhaus, W.D. (2017). Revisiting the social cost of carbon. Proc. Natl. Acad. Sci. USA *114*, 1518–1523. https://doi.org/10.1073/pnas.1609244114.

40. Yang, P., Cui, C., Li, L., Chen, W., Shi, Y., Mi, Z., and Guan, D. (2020). Carbon emissions in countries that failed to ratify the intended nationally determined contributions: a case study of Kyrgyzstan. J. Environ. Manage. *255*, 109892. https://doi.org/10.1016/j.jenvman.2019.109892.

41. Burke, M., Hsiang, S.M., and Miguel, E. (2015). Global non-linear effect of temperature on economic production. Nature *527*, 235–239. https://doi.org/10.1038/nature15725.

42. Dell, M., Jones, B.F., and Olken, B.A. (2012). Temperature shocks and economic growth: evidence from the last half century. Am. Econ. J. Macroecon. *4*, 66–95. https://doi.org/10.1257/mac.4.3.66.

43. Yang, P., Mi, Z., Coffman, D.M., Cao, Y.F., Yao, Y.F., and Li, J. (2021). The impact of climate risk valuation on the regional mitigation strategies. J. Clean. Prod. 127786. https://doi.org/10.1016/j.jclepro.2021.127786.

44. Markandya, A., Sampedro, J., Smith, S.J., Van Dingenen, R., Pizarro-Irizar, C., Arto, I., and González-Eguino, M. (2018). Health co-benefits from air pollution and mitigation costs of the Paris Agreement: a modelling study. Lancet Planet. Health *2*, e126–e133. https://doi.org/10.1016/S2542-5196(18)30029-9.

45. Weyant, J. (2017). Some contributions of integrated assessment models of global climate change. Rev. Env. Econ. Pol. *11*, 115–137. https://doi.org/10.1093/reep/rew018.

46. Yang, Z. (2008). Strategic Bargaining and Cooperation in Greenhouse Gas Mitigations—An Integrated Assessment Modeling Approach (The MIT Press).

47. Nordhaus, W.D. (2016). Projections and uncertainties about climate change in an era of minimal climate policies. Am. Econ. J. Econ. Pol. *10*, 333–360. https://doi.org/10.1257/pol.20170046.

48. Shishlov, I., Morel, R., and Bellassen, V. (2016). Compliance of the parties to the Kyoto Protocol in the first commitment period. Clim. Policy *16*, 768–782. https://doi.org/10.1080/14693062.2016.1164658.

49. O'Neill, B.C., Kriegler, E., Ebi, K.L., Kemp-Benedict, E., Riahi, K., Rothman, D.S., van Ruijven, B.J., van Vuuren, D.P., Birkmann, J., Kok, K., et al. (2017). The roads ahead: narratives for shared socioeconomic pathways describing world futures in the 21st century. Glob. Environ. Chang. *42*, 169–180. https://doi.org/10.1016/j.gloenvcha.2015.01.004.

50. Riahi, K., Van Vuuren, D.P., Kriegler, E., Edmonds, J., O'neill, B.C., Fujimori, S., Bauer, N., Calvin, K., Dellink, R., Fricko, O., et al. (2017). The shared socioeconomic pathways and their energy, land use, and greenhouse gas emissions implications: an overview. Glob. Environ. Chang. *42*, 153–168. https://doi.org/10.1016/j.gloenvcha.2016.05.009.

51. van Vuuren, D.P., Stehfest, E., Gernaat, D.E., Doelman, J.C., Van den Berg, M., Harmsen, M., de Boer, H.S., Bouwman, L.F., Daioglou, V., Edelenbosch, O.Y., et al. (2017). Energy, land-use and greenhouse gas emissions trajectories under a green growth paradigm. Glob. Environ. Chang. *42*, 237–250. https://doi.org/10.1016/j.gloenvcha.2016.05.008.

52. Fricko, O., Havlik, P., Rogelj, J., Klimont, Z., Gusti, M., Johnson, N., Kolp, P., Strubegger, M., Valin, H., Amann, M., et al. (2017). The marker quantification of the Shared Socioeconomic Pathway 2: a middle-of-the-road scenario for the 21st century. Glob. Environ. Chang. *42*, 251–267. https://doi.org/10.1016/j.gloenvcha.2016.06.004.

53. Fujimori, S., Hasegawa, T., Masui, T., Takahashi, K., Herran, D.S., Dai, H., Hijioka, Y., and Kainuma, M. (2017). SSP3: AIM implementation of shared socioeconomic pathways. Glob. Environ. Chang. *42*, 268–283. https://doi.org/10.1016/j.gloenvcha.2016.06.009.

54. Calvin, K., Bond-Lamberty, B., Clarke, L., Edmonds, J., Eom, J., Hartin, C., Kim, S., Kyle, P., Link, R., Moss, R., et al. (2017). The SSP4: a world of deepening inequality. Glob. Environ. Chang. *42*, 284–296. https://doi.org/10.1016/j.gloenvcha.2016.06.010.

55. Kriegler, E., Bauer, N., Popp, A., Humpenöder, F., Leimbach, M., Strefler, J., Baumstark, L., Bodirsky, B.L., Hilaire, J., Klein, D., et al. (2017). Fossil-fueled development (SSP5): an energy and resource intensive scenario for the 21st century. Glob. Environ. Chang. *42*, 297–315. https://doi.org/10.1016/j.gloenvcha.2016.05.015.

56. van Vuuren, D.P., van der Wijst, K.I., Marsman, S., van den Berg, M., Hof, A.F., and Jones, C.D. (2020). The costs of achieving climate targets and the sources of uncertainty. Nat. Clim. Chang. *10*, 329–334. https://doi.org/10.1038/s41558-020-0732-1.

57. van Renssen, S. (2015). Getting a fair deal. Nat. Clim. Chang. *5*, 513–514. https://doi.org/10.1038/nclimate2661.

58. Meinshausen, M., and Alexander, R. (2017). Climate College—NDC factsheets. http://climatecollege.unimelb.edu.au/indc-factsheets/.