Contrasting Suitability and Ambition in Regional Carbon Mitigation

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Contrasting Suitability and Ambition in Regional Carbon Mitigation

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Abstract

Substantially enhancing carbon mitigation ambition is a crucial step towards achieving the Paris climate goal. Yet this attempt is hampered by poor knowledge on the net economic effect of mitigation for each emitter, by taking into account potential cost and benefit. Here we use a global economic model with regional and sectoral disaggregation details to assess the mitigation costs for 27 major emitting countries and regions, and further contrast the costs against the potential benefits of mitigation valued as avoided social cost of carbon. We find substantial variabilities across these emitters in both cost and benefit of mitigating each ton of carbon dioxide and, more importantly, a strong negative spatial correlation between cost and benefit. The relative suitability of carbon mitigation, defined as the ratio of normalized benefit to normalized cost, shows great spatial mismatch with the mitigation ambition of emitters indicated in their first intended nationally determined contributions. China is relatively suitable for domestic carbon mitigation and could largely enhance their mitigation ambition. The European Union, which is economically less suitable to reduce domestic emissions, could work with many developing countries which are more suitable but less capable to reduce emissions. Our work provides important information to improve concerted climate action and formulate more efficient mitigation strategy.

Main text

In December 2015, 195 countries approved the Paris Agreement aiming to limit the rise of global mean surface temperature to well below 2°C above the pre-industrial level and to work towards 1.5°C warming [1]. Each party country agrees to submit its intended nationally determined contribution (NDC) every five years to report its emission mitigation ambition and implementation efforts. Whether the Paris climate goal can be achieved depends on the level of each country's climate mitigation ambition, which is in turn affected by that country's vulnerability to climate change, costs and affordability of mitigation, and other socioeconomic and political factors [2]. Current mitigation efforts are not sufficient to keep the temperature rise within 2°C [3-5], and fulfilling the mitigation ambition in all existing NDCs would still mean 3°C warming [5]. Achieving the 2°C or 1.5°C goal would require that party countries triple or quintuple their ambitions [5]. However, a primary barrier for a party country to enhance its mitigation ambition is incomplete and uncertain information on the economic costs and benefits of fulfilling such ambition. This is particularly true for major emitters due to large amounts of potential costs and benefits.

Past studies have estimated the costs of carbon dioxide (CO_2) emission reduction under the Shared Socio-economic Pathways (SSPs) based on integrated assessment models (IAMs) [6], and have used carbon price, gross domestic product (GDP) loss or consumption loss as cost metrics [6-9]. The IAMs include a broad range of models with different settings of economic mechanisms [10] important for assessing the carbon mitigation costs. Several IAMs depict details of energy technology but include a simple economic module, by incorporating a growth function (e.g., in the REMIND model [11] and WITCH [12]) or using GDP as an exogenous input (e.g., in POLES [13]). Other IAMs are built based on computable general equilibrium models (CGEs), including GCAM [14], AIM/CGE [11], and EPPA [15]. These CGE-based models describe more realistic behaviours of economic agents, including producers, consumers, governments and investors, in response to price changes of goods and factors caused by carbon abatement. Although some models assume regions to be economically isolated (e.g., RICE [16]), in reality, one region's carbon reduction cost will be affected by other regions' mitigation actions through changes in international trade and capital flows. Thus many global models have adopted the GTAP database to take into account the role of trade [15, 11], including the GTAP-E CGE model [17].

Knowledge on the potential benefits, in addition to costs, of carbon mitigation is necessary to allow an understanding of the net economic effect. Here, the cost of carbon emission reduction (RCC, US$ per tCO_2) is defined as the potential GDP loss in a given country/region as a result of action to remove one metric tonne of CO_2 emissions. The estimated RCC can be contrasted against the potential benefits of emission reduction, whose economic value is defined here to be equivalent to the social cost of carbon (SCC, US$ per tCO_2) [18-24] for each metric tonne of CO_2 emissions that can be otherwise removed. In particular, the method established by Ricke et al. [25] allows calculation of country-specific SCCs based on climate model projections, empirical climate-driven economic damage estimation and socioeconomic projections. However, the RCC has not been quantitatively compared with the SCC for all individual emitters of the whole world. This results in poor knowledge on the net economic effect (contrasting benefit and cost) of emission mitigation for many emitters, and thus on whether the mitigation ambition of a given emitter, relative to others, is in line with the cross-regional ranking of the net effect for that emitter.

Here we contrast the RCC against the potential benefit, valuated to be equivalent to the SCC, for each of 27 countries or aggregated regions (Figure 1), under 10 mitigation scenarios linked to the SSPs and Representative Concentration Pathways (RCPs). To derive the RCC, emissions are assumed to be cut in 2020, for which year all data are available (Supplementary Figure 1); this time choice is also consistent with the time horizon of SCC used here (2020 onwards). As detailed in Methods, we separate the individual major emitting countries and regions, such as China, the United States, the European Union, Japan, Russia, India, that are the major participants in global climate negotiations. The amount of emissions removed under each scenario are defined as the difference in emissions between each scenario and SSP5-RCP8.5 (aka SSP5-Baseline), which is assumed to represent the highest emissions [26]. Under each scenario, the average of projected emissions from a total of five IAMs (AIM/CGE, GCAM4, REMIND-MAGPIE, IMAGE and WITCH-GLOBIOM) [6] is used as the best estimate, with the range of emissions used as the uncertainty range. The RCC is calculated with GTAP-E [17] by implementing carbon tax to achieve the emission reduction; and the SCC data are taken from Ricke et al. [25]. We then construct the relative suitability for mitigation (RSM) as the ratio of normalized SCC to normalized RCC for each emitter. The normalization, which is based on the min-max method, is conducted to cancel out the effect of systematic errors (for all emitters) in the absolute values of RCC and SCC. We further contrast the each emitter's RSM against its emission mitigation ambition, which is represented as the emitter's NDC-ambition score estimated based on its first released NDC [2,27]. We find a large gap between the RSM and ambition of each emitter, and offers insight to enhance mitigation ambition through improvement of international cooperation with mutual economic benefits.

Reduction Cost of Carbon. Figure 2 shows the spatial distribution of RCCs under each mitigation scenario. Results are shown for 23 scenarios, including the 10 scenarios with available SCC results and the other 13 scenarios for completeness. The global average RCC ranges from US\$16.5 per tCO_2 (15.4–17.7) for Scenario SSP3-Baseline to 45.8 per tCO_2 (37.7–62.4) for SSP1-RCP1.9. Scenarios with higher mitigation targets tend to have higher global average RCCs. This is because higher emissions mitigation will lead to a higher marginal mitigation cost [28-30]. In GTAP-E, the emission mitigation through carbon tax raises the cost of fossil fuel use and thus reduces the industrial production and GDP. A larger carbon abatement requires a higher carbon tax and thus a greater reduction in production for cutting one unit of emission.

Figure 2 shows that under almost every scenario, the European Union and Switzerland have the highest values of RCC whereas Thailand and Rest of Western Asia have the lowest RCCs. Taking Scenario SSP2-RCP4.5 (which roughly represents middle of the road) as an example, the RCCs of the European Union and Switzerland are US\$ 97.2 (89.7–114.7) per tCO_2 and US\$ 93.3 per tCO_2 (86.2–111.2), respectively, which are more than five times that of the United

States at US$ 18.4 per tCO_2 (17.1–21.5). Regions such as Thailand (US$ -14.0 per tCO_2 (-19.0 – -10.4)), Rest of Western Asia (US$ -4.5 per tCO_2 (-25.4–3.5)) and China (US$ -0.8 per tCO_2 (-2.6–0.9) would even obtain negative RCC values under SSP2-RCP4.5 — in other words, these regions would obtain an economic gain from emission reduction. This is because when all countries take action to reduce emissions and raise the cost of production worldwide, these countries with relatively low reduction cost would have the relatively smaller decline of capital rent, and attract more capital inflow for investment (Supplementary Figure 2).

The inter-regional difference in RCC is largely determined by the difference in mitigation marginal cost, which is reflected in the carbon tax rate and is highly dependent on energy consumption mix and energy intensity, across the countries/regions. In particular, the countries with higher proportions of fossil fuels in their energy consumption mix require lower carbon tax rates to achieve the same percentage of carbon abatement, because for them fossil fuels can be substituted by non-fossil energy at relatively low costs. Examples of these countries include Malaysia, Thailand, Korea, Rest of Southeast Asia and Mexico, for which more than 80% of energy consumption is supplied by fossil fuels. In addition, the countries with higher energy intensities tend to have lower carbon tax rates, because they can reduce energy intensities at lower costs. As China, India and the United States have higher energy intensities than the European Union and Switzerland, they have much lower mitigation marginal costs than the latter two emitters.

Comparing the regional RCC and SCC further shows that emitters with higher SCCs tend to have lower RCCs for all 10 scenarios with both RCC and SCC results available (Figure 3 and Supplementary Figure 3). This contrast is associated with the geographical (latitudinal) distribution of economies. As explained above, the inter-regional inequality in RCC is mainly due to the differences in energy consumption mix and energy intensity, which leads to the RCC being generally higher in developed than in developing regions. In contrast, the SCC tends to be lower at high latitudes, where developed regions are mainly located, and higher at low latitudes, where many developing regions are located [25,31]. Although all countries would suffer great losses as warming is aggravated in the long term, countries at high latitudes tend to suffer less (and may even gain) from warming in the short run [7,31].

Relative suitability of mitigation. We further evaluate the RSM results to examine which emitters are more suitable to cut emissions based on a cost-benefit analysis. Figure 4 shows that under the 10 mitigation scenarios, Rest of Western Asia (1.5–3.5, depending on the scenario) and India (1.2–4.4) have the highest values of RSM, and the European Union have the lowest (0.01–0.04). The RSM values for China and the United States are much larger than that for the European Union, with values of 0.73, 0.97 and 0.02 in Scenario SSP2-RCP4.5 (Figure 4). For many emitters, the values of RSM do not change significantly across the 10 mitigation scenarios. However, there are occasions when the RSM of an emitter under one scenario substantially deviates from the RSM values under other scenarios, mainly as a result of a small percentage reduction in emissions leading to a small value of RCC. For example, under SSP3-RCP6.0, Brazil only need to cut emissions by 0.6%, as compared to a global average mitigation of 4.3%.

Detailed RSM results for each region under each scenario can be found in Supplementary Table 4.

Contrasting the cross-regional ranking of RCC and RSM is useful, given that mitigation cost is often proposed as a key parameter to guide regional mitigation [32]. We find significant mismatch between the ranking of RSM and RCC under every mitigation scenario (Supplementary Table 4). Under Scenario SSP2-RCP4.5, the RSM of Korea ranks the 16th highest, in contrast to its RCC ranking at the 3th lowest; and the RSM of the United States ranks the 3th highest, in contrast to its RCC ranking at the 16rd lowest (Supplementary Figure 4). The contrast in ranking between RSM and RCC suggests that considering both costs and benefits of emission mitigation of each emitter (relative to other emitters) would provide more complete information for determining regional mitigation ambition to achieve global emission reduction.

RSM and NDC Ambition. Figure 1 contrasts the RSM and NDC-ambition score [2,27] of each emitter under Scenario SSP2-RCP4.5. Results for other mitigation scenarios are similar (Supplementary Table 4). Although China, Rest of Western Asia, Rest of South-East Asia and the United States are relatively suitable mitigation regions with high values of RSM (ranked in top 1/3), their NDCs do not show correspondingly strong mitigation ambition (ranked in bottom 1/3). These emitters could enhance their ambition not only because they are often major emitters but also because they are economically more suitable regions of carbon mitigation (compared to other regions). China's political leadership has announced their intention to become carbon neutral before 2060 [33,34], and it is expected that the country will announce substantially strengthened emission mitigation ambition in its next NDCs, although the details are yet to be released. The United States will very likely re-join the Paris Agreement and might even enhance their ambition under the newly elected political leadership [35]. The enhanced ambition of these top two emitting countries would be very important for boosting global climate action to levels consistent with the Paris goal.

Figure 1 shows that Rest of East Asia and Rest of South America rank medium (middle 1/3) in RSM but low in mitigation ambition (bottom 1/3). These developing countries might need external financial and technical aids through international collaborations to enhance their affordability, capability and thus ambition of carbon mitigation. Figure 1 also shows that the European Union and Switzerland have relatively low values of RSM but are among the most ambitious regions in emission mitigation. These developed countries could consider to help the aforementioned developing regions with higher RSM but lowest ambition to reduce carbon emissions through financial and technical mechanisms. This would boost the world's ambition and action as a whole to mitigate climate change at lower costs than if individual, uncoordinated actions are taken. Several developed countries and states have attempted to link their local carbon markets, aiming to reduce carbon emissions through capital and technology transfer. For example, California and Québec have linked their Emissions Trading Systems in 2014, and the European carbon market keeps expanding [36].

To further demonstrate the economic mutual benefits of cross-regional emission mitigation collaboration, we conduct a hypothetical experiment based on Scenario SSP2-RCP4.5, in which

European Union, a region with low RSM and high ambition, transfers 10% of their mitigation amount (30.4 (28.3–40.6) million tCO_2) to China, a region with high RSM and low ambition (although with a recent ambitious pledge for carbon neutrality [33,34]). We find that the RCC of the European Union would decrease significantly from US$ 97.2 per tCO_2 (89.7–114.7) to US$ 90.1 per tCO_2 (82.5–105.7). For China, its RCC would only increase slightly from US$ -0.8 per tCO_2 (-2.6–0.9) to US$ 0.9 per tCO_2 (-0.7–2.2). Therefore, the double-win situation could be achieved through the Sustainable Development Mechanism [1], with necessary improvements, to support China's carbon mitigation. This Sino-Europe collaboration would also avoid US$ 4.65 (3.55–7.37) billions of GDP loss for the world through trade-associated inter-regional connections. If the transferred portion of emission mitigation increases to 50%, the avoided world GDP loss would increase to US$ 20.2 (15.8 – 31.2) billion; and the RCC would become US$ 5.9 per tCO_2 (4.5–6.9) for China and US$ 52.1 per tCO_2 (42.0–64.3) for the European Union. Country-specific results for GDP changes are shown in Supplementary Table 5.

Discussion. Our study is subject to a few uncertainties and limitations. First, the emissions under each scenario are averaged over simulation results from five IAM models. Although the accuracy of each model is subject to errors in model parameters and assumptions [6], the multi-model averaging reduces the influence of errors in individual models. Second, we use SSP5-RCP8.5 to be the scenario with the highest emissions, relative to which we calculate the emission reductions under other scenarios. Exceptions occur under SSP3-Basline (which is not used in evaluating RSM), under which three emitters have emissions higher than under SSP5-RCP8.5. In this case, we assume there is zero emission mitigation for that emitter. Third, the calculation of SCC follows Ricke et al. [25], and is affected by the statistical method and functional forms used to assess economic damage, although the relative ranking of countries is robust under each scenario [31]. Fourth, the GTAP-E model used to calculate the RCC is a static economic model, which calculate the changes in individual economies from one equilibrium to another without explicitly specifying the path of economic evolution. Fifth, our calculation of RCC is done for 2020, which is consistent with the time horizon of SCC (2020 onwards). Our additional calculation of RCC for 2030 also shows cross-regional ranking similar to that for 2020 (Supplementary Table 4). Finally, although the uncertainties in the absolute values of both RCC and SCC are large for individual emitters, the negative spatial correlation between RCC and SCC is consistent across the mitigation scenarios (Supplementary Figure 3), so is the cross-regional ranking of RSM (Supplementary Table 4).

This study offers a RSM-based framework to help raise regional emission mitigation ambition towards achieving the Paris goal. More affordable and capable emitters with relatively high RSM but low NDC ambition, such as China and Thailand, might consider to substantially raise their mitigation ambition for their own economic and environmental interests. More affordable emitters with low RSM but high ambition, particularly the European Union and Switzerland, and less affordable developing countries with high RSM but low ambition might consider to work collaboratively to reduce emissions and share credit of such action. Such cooperation would be more economically viable for both parties and is supported by the 6th Article of the Paris Agreement [1]. Together, enhancement of domestic and internationally collaborative mitigation action, aided by better knowledge on cost and benefit and thus enhanced ambition, will be crucial for successful climate change mitigation.

Methods

2.1. Region and scenario setting

We separate the world into 27 countries and aggregated regions based on economic volume and geographical location, similar to our previous study [37,38]. These regions are detailed in Supplementary Table 1. We obtain the emission data for different scenarios from the SSP database (https://tntcat.iiasa.ac.at/SspDb/) [6,39-42]. The scenarios with a brief methodology framework are specified in Supplementary Figure 1. The SSP database includes 5 groups: OECD (the OECD 90 countries and the European Union member states and candidates), REF (the reforming economies of Eastern Europe and the Former Soviet Union), ASIA (Asian countries except the Middle East, Japan and the Former Soviet Union states), MAF (the Middle East and Africa), and LAM (Latin America and the Caribbean).

Then, we calculate the mitigation target in the year of 2020 for each group under each scenario as the relative difference in emissions between SSP5-RCP8.5 (which is assumed to represent the highest emissions [26]) and that scenario.

$$M_{s,g} = (E_{s`,g} - E_{s,g}) / E_{s`,g}$$

Here, M and E denote the mitigation target and emission, respectively. The subscript s denotes a scenario, s` denotes the reference scenario SSP5-RCP8.5, and g denotes each of the 5 groups (OECD, REF, ASIA, MAF and LAM). $M_{s,g}$ is set to be zero when $E_{s,g}$ is greater than $E_{s`,g}$, which situation only occurs under SSP3-Baseline for which three emitters (Rest of Europe, Central Asia and Russia Federation) have emissions higher than under SSP5-RCP8.5 by 10%.

Subsequently, the mitigation target of each of the 27 country/region ($M_{s,r}$) is set to be the same as the target of the group ($M_{s,g}$) to which that country/region belongs. Detailed results of the mitigation targets are shown in Supplementary Table 2.

2.2. RCC calculation

We calculate the RCC with the GTAP-E model [43,44]. For each scenario, the economic effect of emission reduction is simulated in GTAP-E by implementing carbon tax at a level consistent with the emission mitigation target in 2020. All RCC values are expressed in 2014 constant price.

The GTAP-E model is a multi-regional, multi-sector economic equilibrium model, developed based on the GTAP model. As a comparative static analysis model, GTAP-E assumes that the returns to scale of production remain unchanged in the completely competitive market; and producers maximize the profits while consumers maximize the utility. The equilibrium of total supply and demand determines the values of endogenous variables, such as commodities prices, wages, capital return, and land rents. All economies (countries and regions) connect with each other through commodity trade.

GTAP-E includes three representative agents, that are producers, private households, and governments. The activity of producers is described by a sequence of nested constant elasticity of substitution (CES) functions, which aim to reproduce the substitution possibilities across the full set of inputs. On the top level, the total input is composed of two aggregate composite bundles, i.e., intermediate demand and value added. The second level nest decomposes each of the two aggregate composite bundles into their components, such that one is demand for individual intermediate goods and the other is demand for primary factors. The final nest accepts the Armington assumption to allow an incomplete substitution between domestically produced goods and imported goods.

Built upon GTAP, GTAP-E improves the modelling of energy input structure, carbon dioxide emission, and mitigation policy. (1) A new nesting structure of energy commodities is introduced into the bundle of primary factors. The energy composite is combined with capital to produce an energy-capital composite, which is in turn combined with other primary factors in a value-added-energy (VAE) nest through a CES structure. The energy composite comprises electricity and non-electricity energy. The non-electricity energy is composited by coal and non-coal commodities, with non-coal further composited by gas, oil, and petroleum products. (2) The carbon dioxide emission is also introduced, accounting for the emission from the burning of fossil fuels by production sectors and households. The carbon dioxide emission factors of fossil fuels are derived from Vermeulen (2014) [45]. (3) The regional real carbon tax is developed, defined as the nominal tax rate deflated by the income disposition price index. The carbon tax could be employed to achieve the goal of carbon abatement, by reducing the utilization of fossil fuels in production sectors and households.

The consumption preference of private households are represented by the constant differences of elasticities implicit additive expenditure function by Hanoch (1975)[46]. The Cobb–Douglas function is adopted to represent government consumption. The aggregate volume of investment comes from the identity that the nominal investment equals saving, where saving is the sum of domestic saving and net capital inflows from foreign economies. Investment expenditures on the composite goods are described by a Leontief utility function, and subsequently decomposed into demand for domestic and imported goods.

Within each economy, the GTAP-E model allows capital and labour to move between production sectors, and partially allows land to move between crop producing sectors. The full employment of labour is assumed. The savings of regions are pooled to the global investment, and the latter is allocated to different regions according to their return of capital.

The latest version (v10a) of the GTAP database is utilized, which is constructed from the input–output tables of 141 countries and regions across the world with a base year of 2014 [47]. The

GTAP database contains 65 sectors and 5 primary production factors. For this study, the 141 countries and regions have been aggregated to 27 regions (Supplementary Table 1), which specify major producers, consumers, and importers/exporters. The 65 production sectors are aggregated to a total of 8 sectors (Supplementary Table 1).

2.3. SCC and RSM calculations

The RSM for each scenario and country/region is defined as follows:

$RSM_{s,r} = nSCC_{s,r} / nRCC_{s,r}$

Here, the subscripts s and r denote the scenario and country/region, respectively. For each scenario and region, nSCC and nRCC are the values of respective SCC and RCC normalized with the Min-max method, and thus range between 0 and 1. The RCC is calculated by GTAP-E. The SCC for the 27 regions are mapped from the country-level SCC (cSCC, for 2020 onwards) data from Ricke et al. [25].

As detailed in Ricke et al. [25], the cSCC are calculated in several steps. First, the GDP growth rates are calculated based on the GDP and population assumptions in the SSPs [42]. Second, the magnitude and geographic pattern of temperature change under different RCPs, the carbon cycle and the climate system responses are obtained from climate models [48-51]. Third, damage modules are used to convert country-level temperature and precipitation changes into country-level economic damages [52,53]. Finally, the time series of future damage is converted to the present value of cSCC with a discounting module [54,55]. Following Ricke et al. [25], we adopt the cSCC data computed by the central specification of the Burke–Hsiang–Miguel (BHM) damage function (short run, no income differentiation) and a growth adjusted discount rate ($\rho = 2\%$, $\mu = 1.5$). The values of cSCC are converted to 2014 constant price in this study.

Supplementary Table 4 presents results of SCC, RCC, nSCC, nRCC and RSM for each scenario and country/region.

2.4. NDC ambition score

We use the NDC ambition score of each country from Robiou du Pont and Meinshausen (2018) [27], which was calculated based on the country's first released NDC. Tørstad et al [2] also used this score to discuss regional emission mitigation ambition. The score was determined based on the degree of warming, ranging from 1.2°C (most ambitious) to above 5.1°C (least ambitious), had the NDC of a given country been applied globally.

According to the ambition scores, we classify the regions into three categories: high ambition (top 1/3), medium ambition (middle 1/3), and low ambition (bottom 1/3). For 8 aggregated regions (including Central Asia, Rest of Central America, Rest of Europe, Rest of North Africa, Rest of South America, Rest of Southeast Asia, Rest of Sub-Saharan Africa, and Rest of Western Asia) containing countries with different ambition scores, we take the emission weighted score to represent the ambition of that region. For United Arab Emirates, the score is considered as the same as Rest of Western Asia. Detailed results of ambition scores are shown in Supplementary Table 1.

Data availability

All data used here are cited in the text or provided in the supplementary files. The datasets generated during this study are available from the corresponding authors.

Code availability

All computer codes generated during this study are available from the corresponding authors upon reasonable request.

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Author contributions

Y.L., M.D., and J.L. conceived the research. Y.L., M.D., Q.C. and J.L. designed the research. Q.C., M.D. and Y.L. performed the research with inputs from Yawen.L., Q.L. and D.T.. M.D., Q.C. Y.L. and J.L. analysed the results. M.D., J.L., Q.C. and Y.L. led the writing with inputs from K.H. and K.F. All authors discussed the results and commented on the manuscript.

Competing interests

The authors declare no competing interests.

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Figures

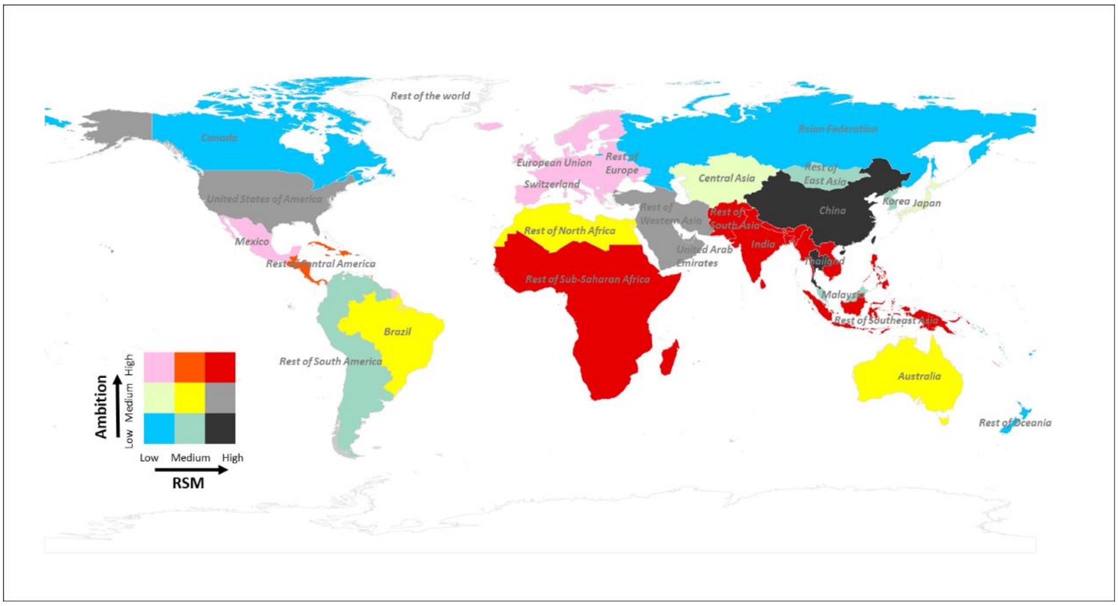


Figure 1: Contrasting suitability and ambition of carbon mitigation among 27 emitting countries and regions. The RSM and NDC ambition for each region under SSP2-RCP4.5. For both RSM and ambition scores, "High" represents the top 1/3 among the 27 regions, "Medium" represents the middle 1/3, and "Low" represents the bottom 1/3.

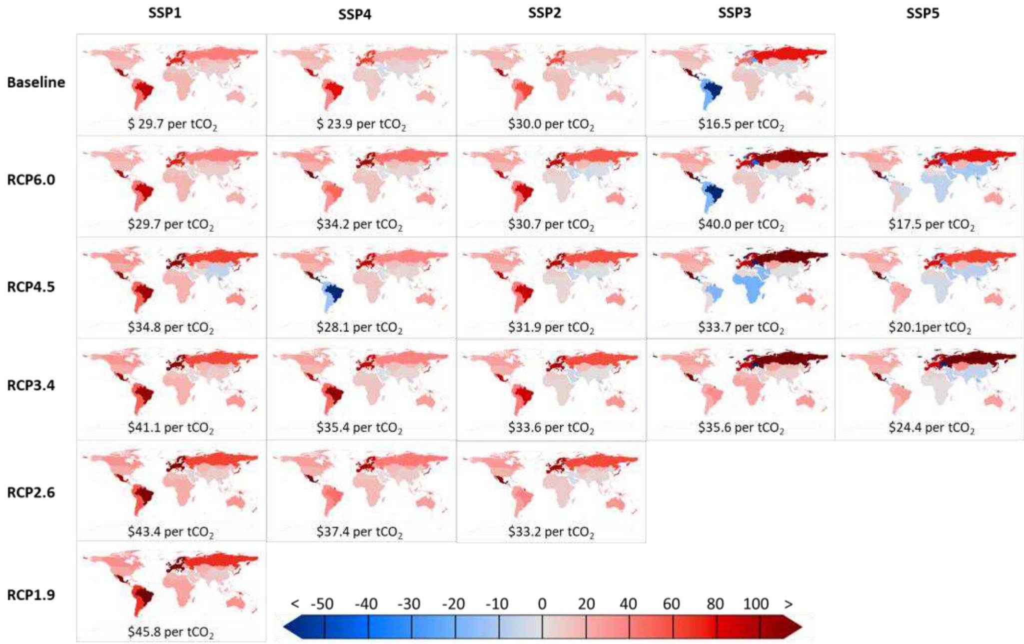


Figure 2: Substantial cross-regional disparity in cost of carbon mitigation. The RCC for each region under each scenario (unit: US$ per tCO_2).

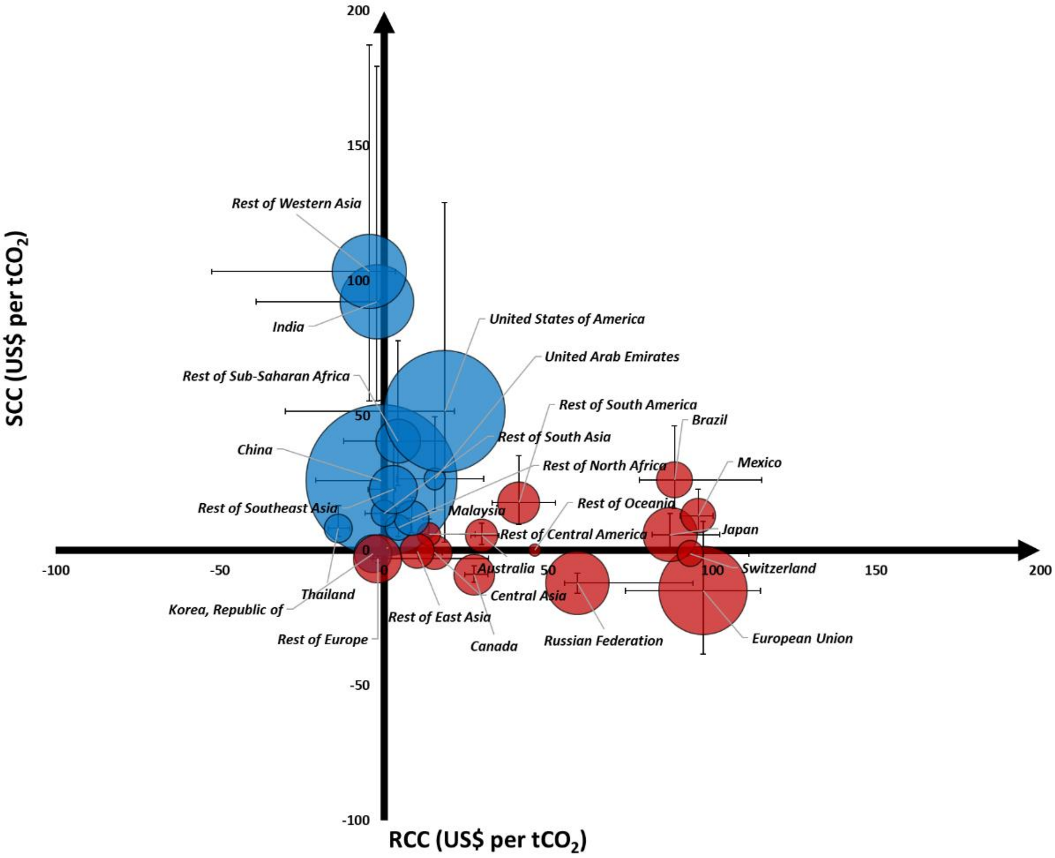


Figure 3 : Contrast between costs and benefits of carbon mitigation for individual emitters. The RCC and SCC for each country/region under SSP2-RCP4.5. The size of the dots denotes the magnitude of regions' CO_2 emissions. Regions with higher SCC than RCC are shown with the blue color, and regions with higher RCC than SCC are shown with red color. The vertical error bar represents the 66% CI of SCC. The horizontal error bar represents the maximum and minimum RCC values based on results from five IAM models.

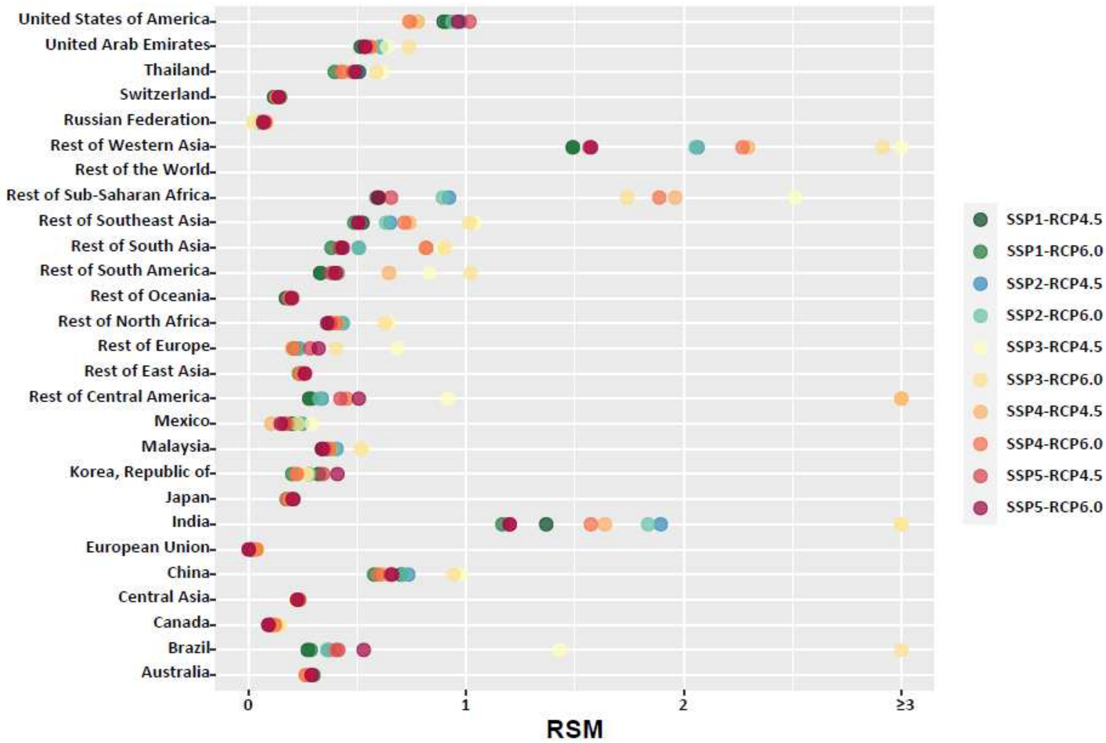
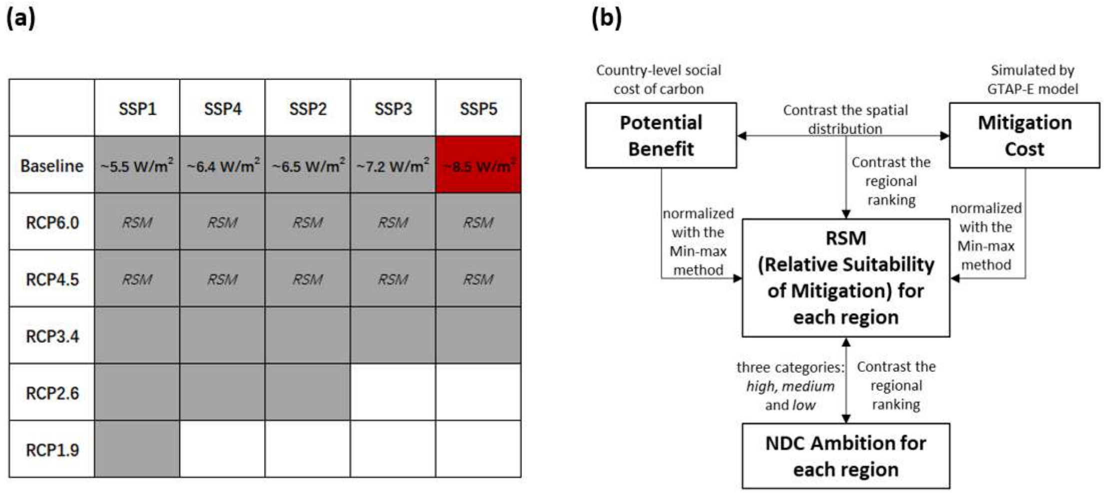
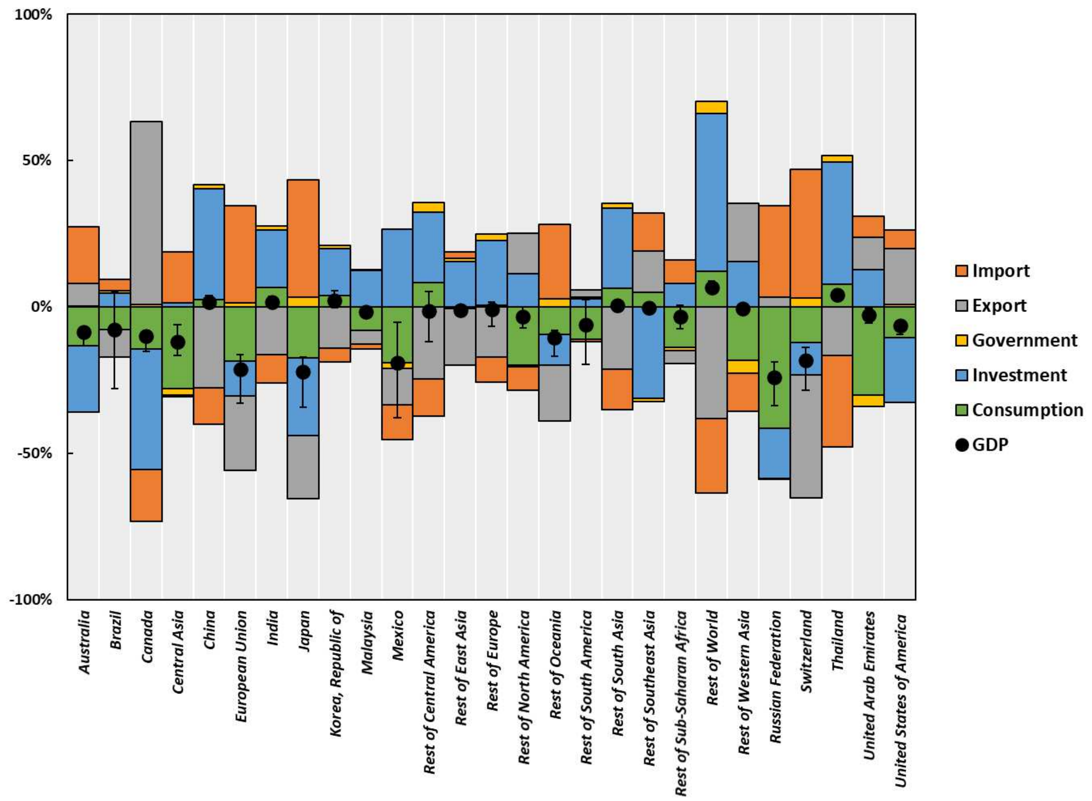


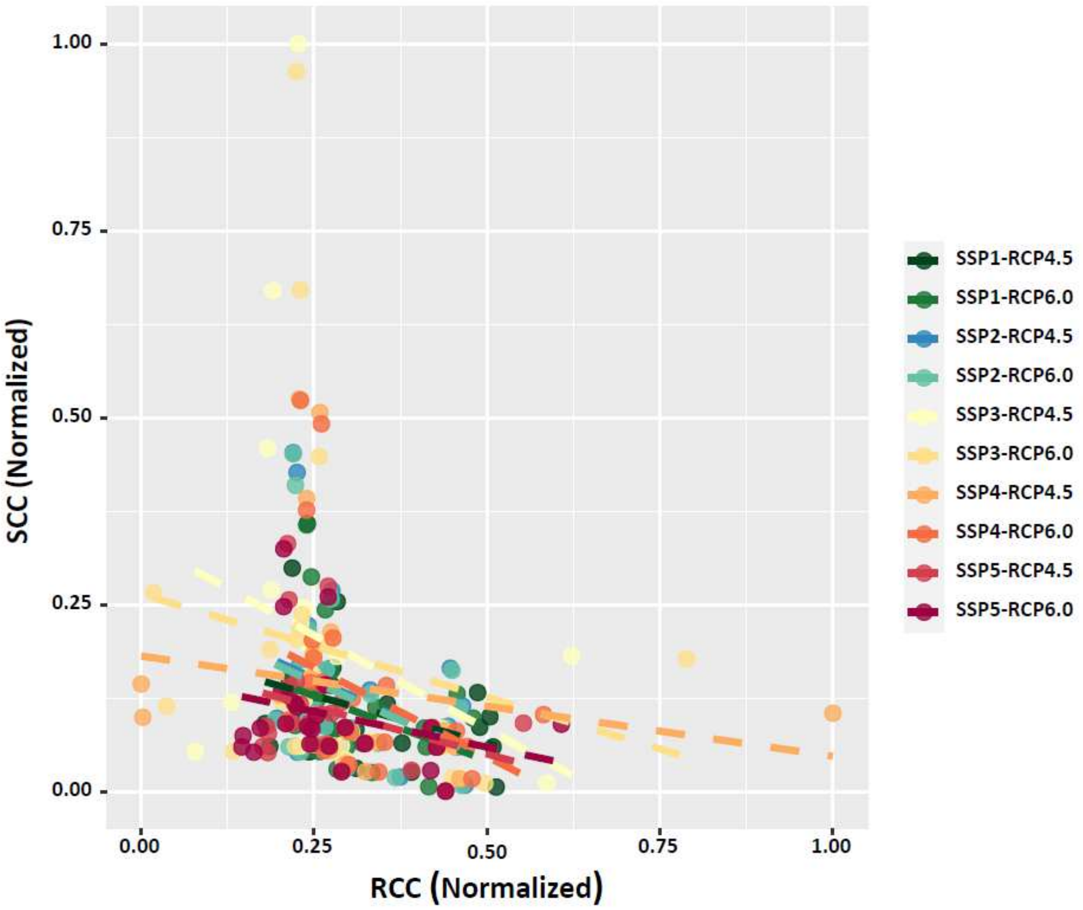
Figure 4： Substantial cross-regional disparity in suitability of carbon mitigation. RSM for each region under each scenario.



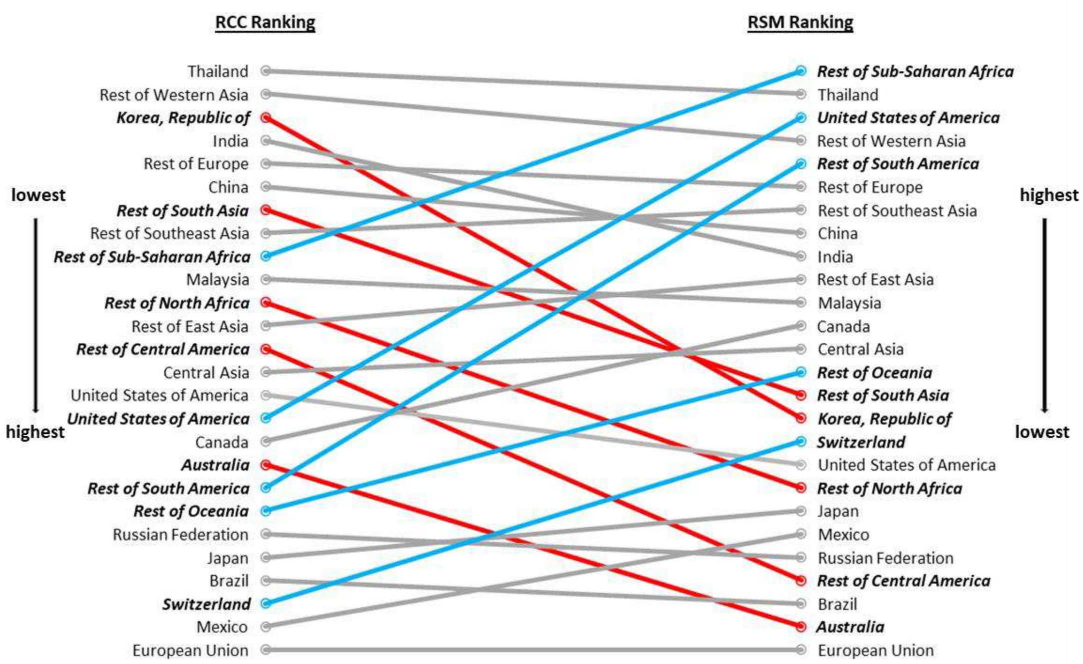
Supplementary Figure 1: Scenarios and framework in this study. (a) A total of 23 scenarios (shown in grey) used to calculate the RCC, relative to the reference scenario SSP5-RCP8.5 (SSP5-Baseline, shown in red). The values in the first row indicate the rough amount of radiative forcing under "Baseline" for each SSP. Ten scenarios indicated with "*RSM*" have both RCC and SCC results available to calculate RSM. (b) Methodological framework of this study.



Supplementary Figure 2. Decomposition of GDP change for each region on the expenditure side under SSP2-RCP 4.5. The error bar represents the maximum and minimum GDP change based on results from five IAM models.



Supplementary Figure 3: Contrasting regional RCC and SCC under each mitigation scenario. Results are averaged over five IAMs. The dashed lines indicate linear fitting.



Supplementary Figure 4: Contrasting the regional ranking of RCC and RSM under SSP2-RCP4.5. Regions with gray lines have small differences (within 5) in ranking between RCC and RSM. Regions with blue or red line denote larger differences in ranking between RCC and RSM.

Figures

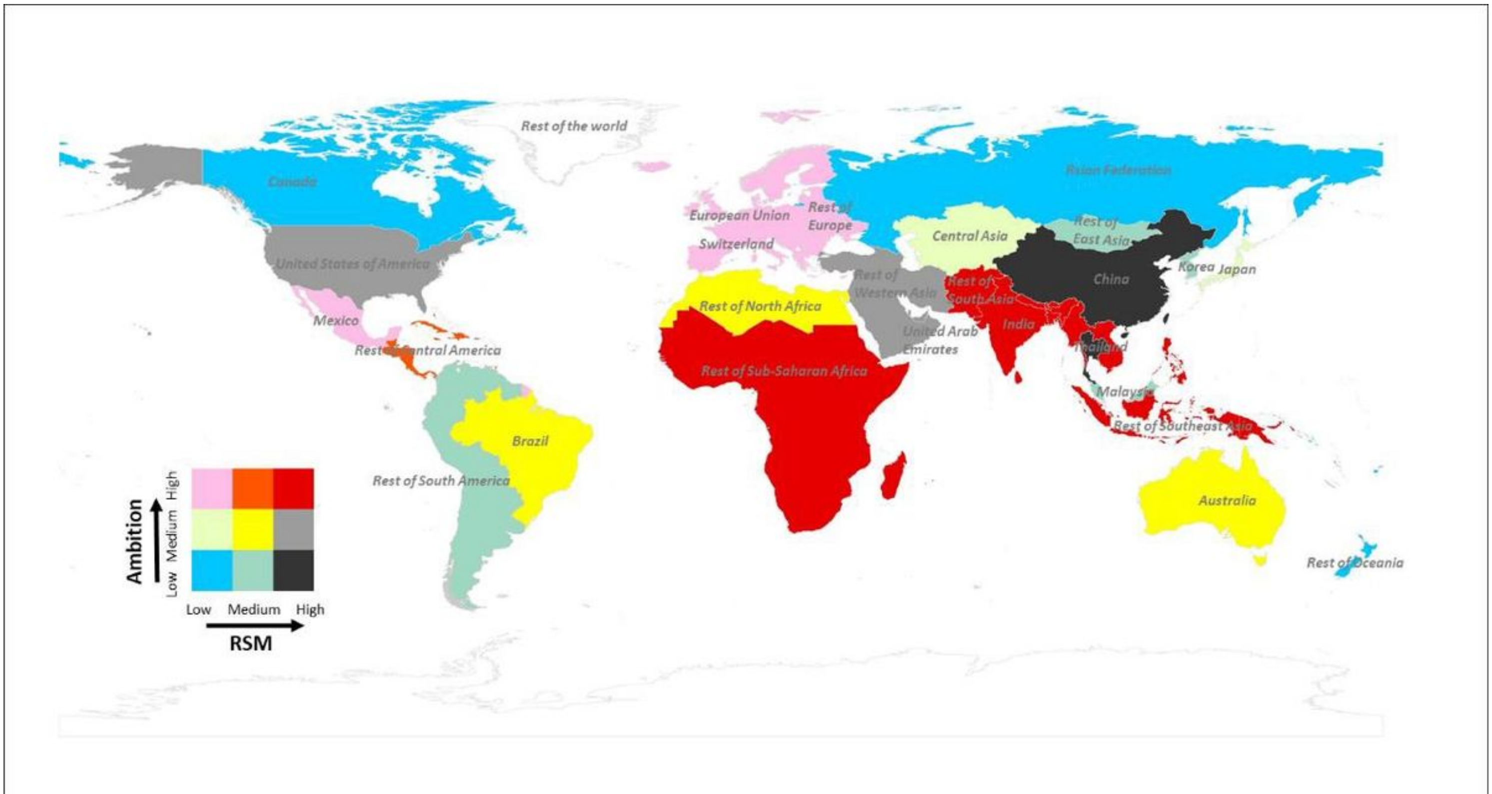


Figure 1

Contrasting suitability and ambition of carbon mitigation among 27 emitting countries and regions. The RSM and NDC ambition for each region under SSP2-RCP4.5. For both RSM and ambition scores, “High” represents the top 1/3 among the 27 regions, “Medium” represents the middle 1/3, and “Low” represents the bottom 1/3. Note: The designations employed and the presentation of the material on this map do not imply the expression of any opinion whatsoever on the part of Research Square concerning the legal status of any country, territory, city or area or of its authorities, or concerning the delimitation of its frontiers or boundaries. This map has been provided by the authors.

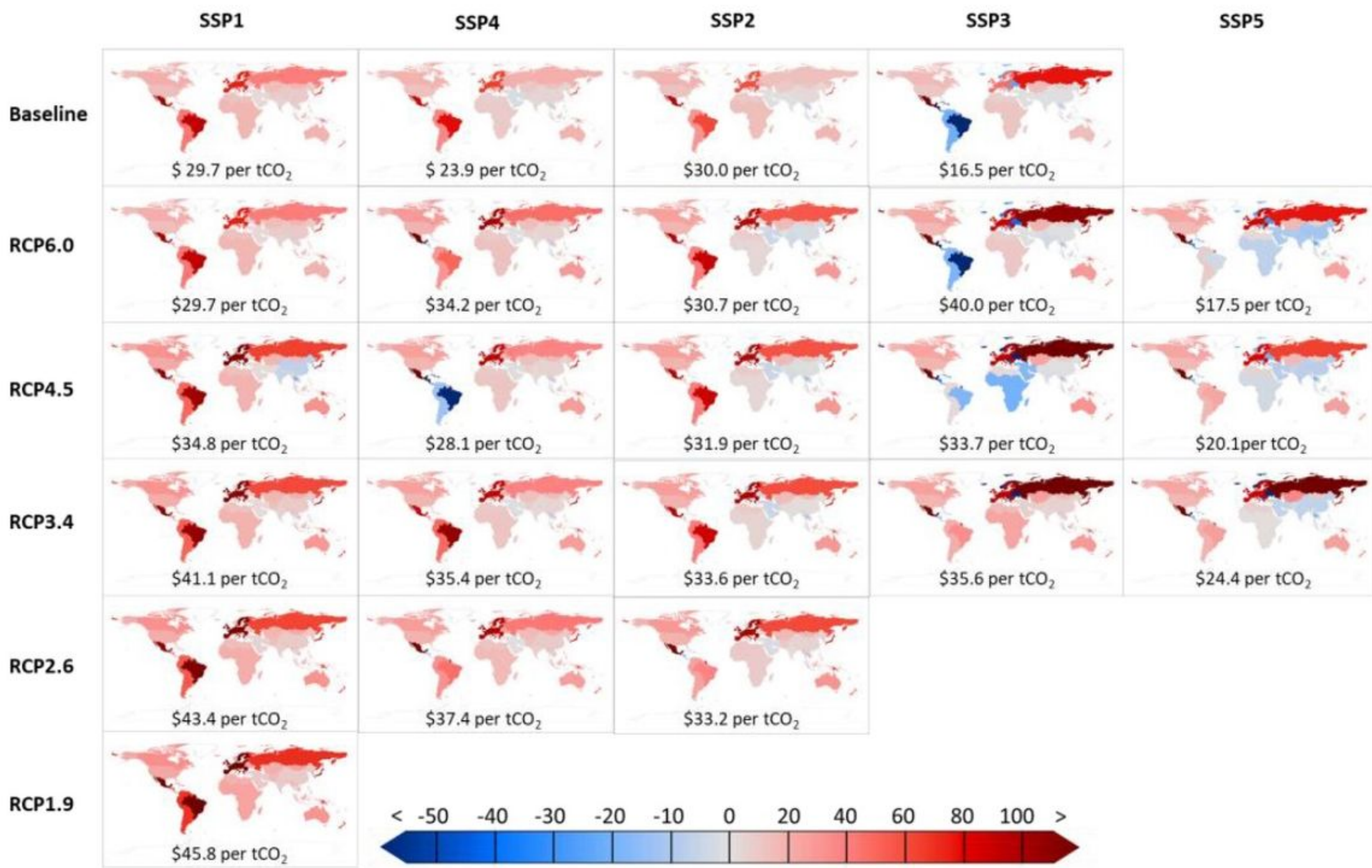
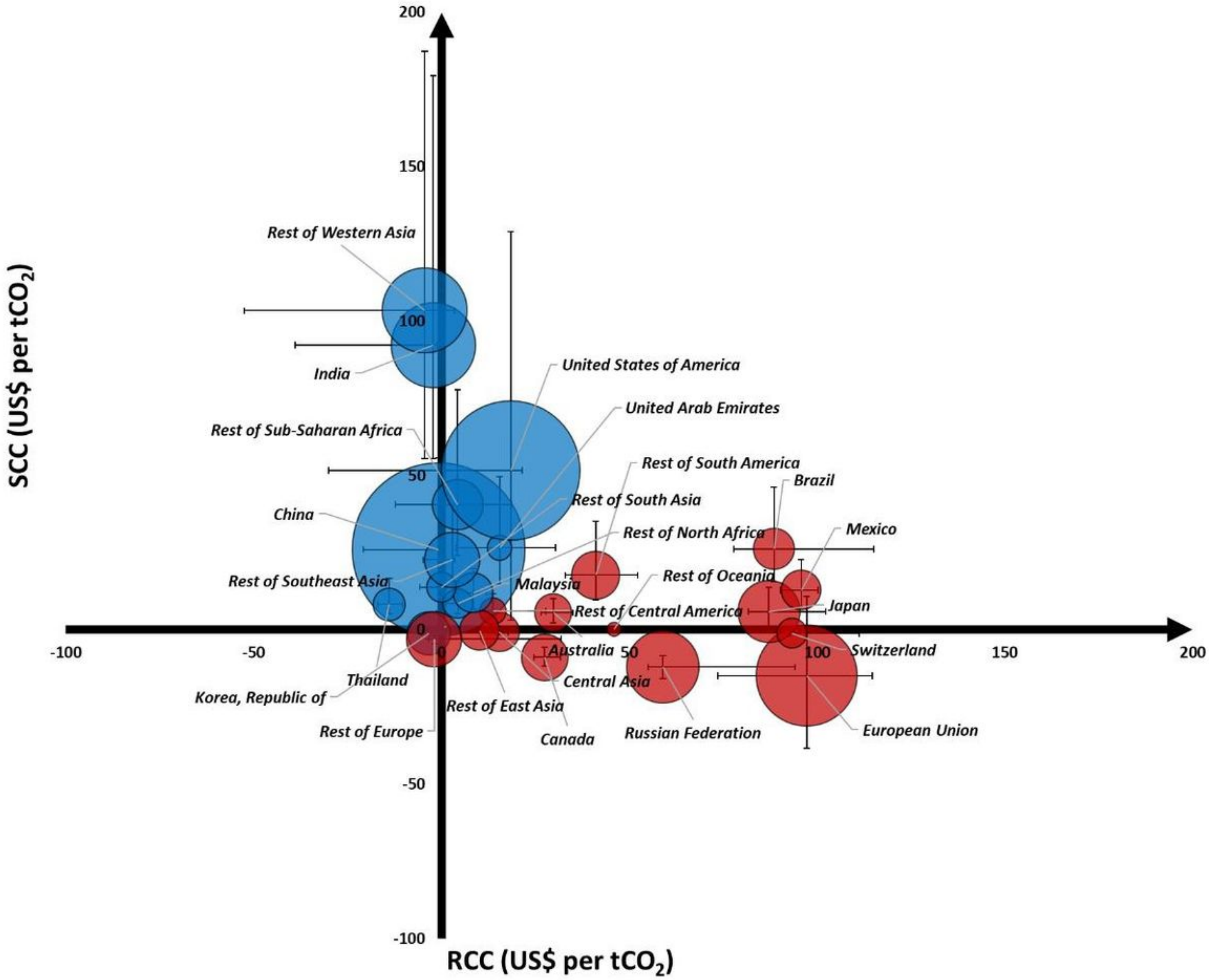


Figure 2

Substantial cross-regional disparity in cost of carbon mitigation. The RCC for each region under each scenario (unit: US$ per tCO2). Note: The designations employed and the presentation of the material on this map do not imply the expression of any opinion whatsoever on the part of Research Square concerning the legal status of any country, territory, city or area or of its authorities, or concerning the delimitation of its frontiers or boundaries. This map has been provided by the authors.



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Contrast between costs and benefits of carbon mitigation for individual emitters. The RCC and SCC for each country/region under SSP2-RCP4.5. The size of the dots denotes the magnitude of regions' CO2 emissions. Regions with higher SCC than RCC are shown with the blue color, and regions with higher RCC than SCC are shown with red color. The vertical error bar represents the 66% CI of SCC. The horizontal error bar represents the maximum and minimum RCC values based on results from five IAM models.

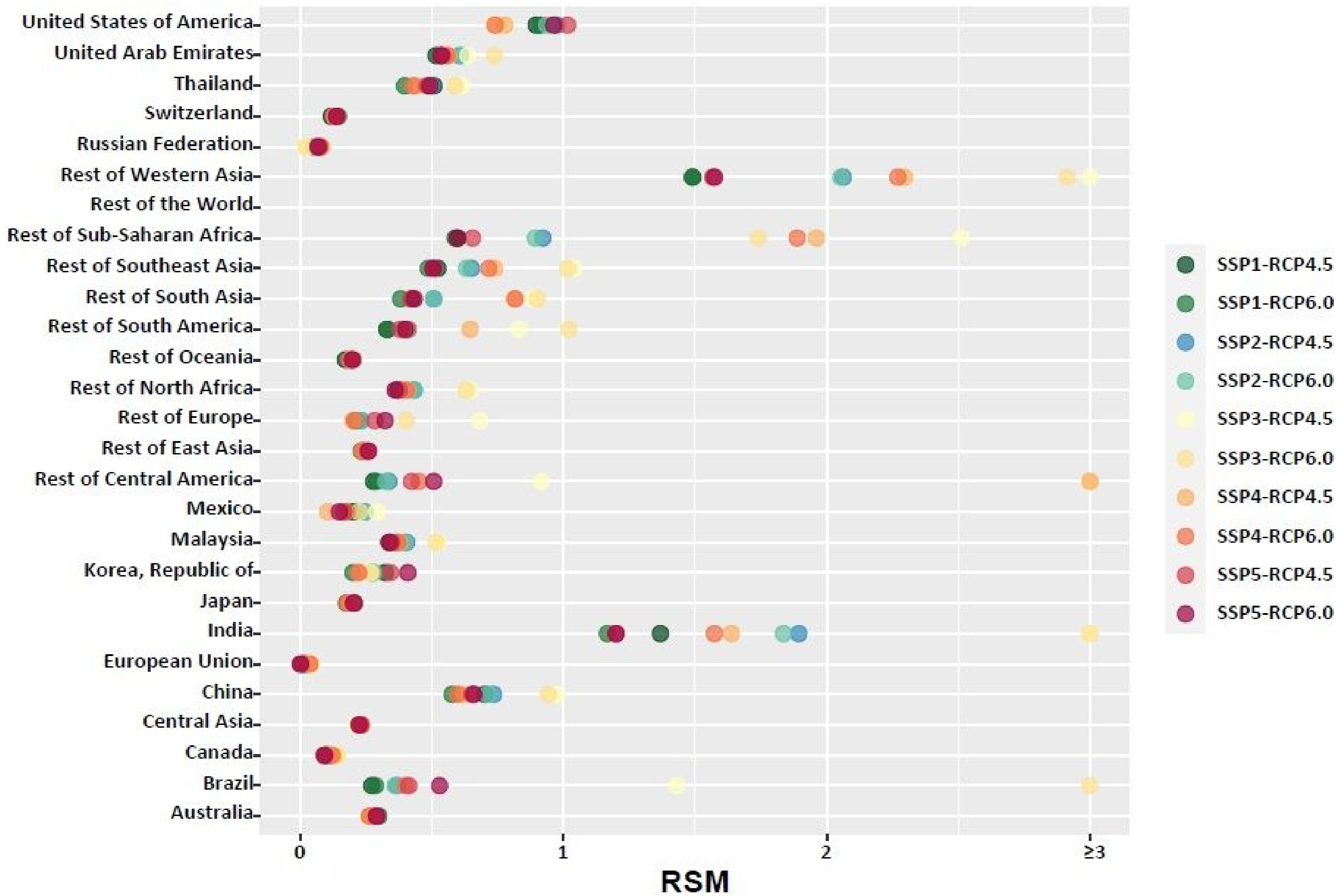

Figure 4

Substantial cross-regional disparity in suitability of carbon mitigation. RSM for each region under each scenario.

Supplementary Files

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