Global Climate Change Mitigation: Strategic Incentives

Sigit Perdana[a] *and Rod Tyers*[b]

ABSTRACT

Central to global agreement on carbon emissions are strategic interactions amongst regions over abatement policy and the benefits to be shared. These are re-examined in this paper, in which benefits from mitigation stem from a meta-analysis that links carbon concentration with region-specific measures of economic welfare. Implementation costs are then drawn from a highly disaggregated model of global economic performance. Multiplayer games are then constructed, the results from which are sensitive to embodied temperature scenarios and discount rates but robustly reveal that the U.S. and China would be net gainers from unilateral implementation in net present value terms. The dominant strategy for all other countries is to free ride. Net gains to the three large economies are bolstered by universal adoption, which could be induced by affordable side payments. Yet the downside is that net gains to all regions are negative over two decades, rendering commitment to abatement politically difficult.

Keywords: Climate change, Carbon taxation, Global dynamic general equilibrium analysis

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1. INTRODUCTION

Even in countries that are signatories to the Kyoto Protocol and the more recent the climate convention on COP 21 Paris, policies restricting carbon emissions remain controversial (Cooper et al., 2016; Dimitrov, 2016). Indeed, current evidence suggests that these agreements have not been effective in mobilizing all signatories to reduce emissions. This ineffectiveness can be explained by disagreement over the scale of mitigation costs (Mahapatra and Ratha, 2017), the weakness of voluntary agreements in the presence of a "tragedy of the commons" (Fehr and Gächter, 2000; Clarke and Waschik, 2012), tardiness in some large economies in the implementation of emission controls (Falkner, Stephan and Vogler, 2010), strong political preferences to free ride (Hovi, Sprinz and Bang, 2010) and the issue of carbon leakage (Burniaux and Martins, 2012).

Yet all these perspectives rest on the presumption that, for no country or cohesive economic region is there a unilateral gain from mitigation policy. Moreover, even if the very large economies did perceive unilateral gains, those would not be large enough to justify side payments that might induce free riders to participate. These are empirical questions, answers to which this paper contributes.

a Corresponding author. Department of Economics, Business School University of Western Australia, Perth WA 6009, E-mail: sigit.perdana@research.uwa.edu.au. Laboratory of Environment and Urban Economics, Ecole Polytechnique Federale de Lausanne, Lausanne Switzerland 1015, E-mail: sigit.perdana@epfl.ch.

b Business School, University of Western Australia and Research School of Economics, Australian National University. E-mail: rod.tyers@uwa.edu.au.

The particular literature complemented is that addressing these strategic interactions, led by Nordhaus (2015) and the follow- up studies by Sælen (2016) and Hovi et al. (2017). Nordhaus uses the Coalition-DICE Model and an "evolutionary algorithm approach" to examine the potential for international "clubs" that implement uniform carbon taxes with target prices that range between 12.5 USD and 100 USD per ton of CO_2. A uniform carbon pricing regime without trade sanctions is shown to lead only to a non-cooperative equilibrium with minimal abatement. It is concluded that non-participation is the best strategy even for the larger key players: China, the United States (U.S.) and the European Union (EU). More generally, these studies suggest the need for penalties in the form of trade tariffs in order that stable coalitions should be formed.[1]

This paper commences with a detailed meta-analysis of benefits from mitigation that link carbon emissions to average surface temperature and then to region-specific changes in economic welfare. These results are then combined with region-specific mitigation costs that are calculated using a dynamic model of the global economy that is more highly disaggregated across products and regions than has been used in the previous studies. The level of disaggregation is particularly useful in capturing the interactions across regions that operate through changes in the terms of trade and the global distribution of investment that, in turn, stem from the implementation of mitigation policies alone. Net costs thus calculated are then combined with the results from the meta-analysis to construct matrices of regional payoffs in 2015 present values that are amenable to analysis as multi-player normal form games.

For reasonable ranges of parameters such as the discount rate, critical mass turns out to be smaller than the individual contributions of the two largest economies, the U.S. and China, so that they would be unilateral gainers from the adoption of carbon taxation. They contribute large enough shares of global carbon emissions that the gains from their abatement alone exceed their mitigation costs. It follows, then, that a "climate club" comprising the U.S., China, and Europe, would also be a unilateral gainer. Moreover, their collective net gains in present value terms prove sufficient to finance side payments that are would induce universal adoption. Nonetheless, the net gains do not turn positive in any region for two decades, rendering these policy outcomes politically difficult to achieve.

Section 2 briefly reviews the substantial prior literature on strategic interactions influencing potential agreement on climate policy and draws contrasts with the work to be presented. Section 3 introduces the global modelling of mitigation costs and their distribution and section 4 reviews studies that quantify the climate impacts of different levels of mitigation and their consequences for global economic welfare, combining these in a meta-analysis. Section 5 uses the results from the previous two sections to construct multiplayer normal form games and to derive policy-relevant equilibria. The section 6 then concludes and summarizes the research findings.

2. CLIMATE POLICY INTERACTION AND STRATEGIC BEHAVIOUR

The prior literature on the topic of this paper is both rich and vast. Here we mention only those studies most relevant to the research to be subsequently presented, with the purpose of clarifying our mission in the context of this literature and highlighting key points of difference. A major

1. Numerous alternative approaches have been offered that are not within our present scope. Aldy et al. (2003) provide a review. In particular, McKibbin and Wilcoxen (2002) offer a hybrid approach directed at tackling the inefficiency of the tradeable permit system and the political impracticability of an uncoordinated carbon price. Model regimes emphasising linkages and dominant factors are suggested by Stewart et al. (2013). Climate policy "clubs" that can be large enough to influence the global carbon price were initially suggested by Cooper (1998; 2001; 2007) and further examined by Weitzman (2015).

concern in studies like this is the prospect of regionally heterogeneous climate policies. Accounting for these is a herculean task for analysts and one that we will avoid, choosing instead to imagine that regional policies have equivalents in carbon taxation and that the policy choice is simply whether or not to implement a rate of US$ 20 per tonne.[2]

The most prominent work on strategic carbon abatement policy interactions at the global level is represented in the suite of articles by Nordhaus and Yang (1996), Nordhaus and Boyer (1999), Nordhaus and Yang (2006), Nordhaus (2010; 2011; 2014). It employs two models of the global economy, namely DICE, which is dynamic and global in scope but highly aggregated, and RICE, in which the world is divided into several regions. These models integrate the climate sector with the global economy, and each country is assumed to produce a single commodity for either consumption or investment, based on Cobb Douglas technology. Nordhaus (2015) assesses climate policy coalitions and examines the role of trade sanctions, imposed for stability, using the Coalition-DICE (C-DICE) model. In this work macroeconomic, bilateral trade and environmental data are used to determine each country's strategic incentive to join a coalition of countries adopting abatement policies. Payoffs are impacts on net national income and countries interact on carbon prices and punitive tariffs.

Sælen (2016) and Hovi et al. (2017) extend the work of Nordhaus by considering the potential of transfer payments to induce full participation. They use a simple and stylized binary decision model with empirical foundations, which includes population and GDP levels, associated emissions and vulnerability to climate change. Sælen's results indicate that there is substantial potential for side payments to facilitate an effective club. Hovi et al. extend Sælen's work and offer a more regionally disaggregated approach emphasising the importance of initiation by the large emitters, particularly the U.S. and the EU. They classify each country into two types, reluctant or enthusiastic, based on assumptions about intrinsic motivation to start a climate agreement.

A number of points of difference arise between these prior works and ours to follow. First, we follow the critique of Böhringer et al. (2017) and build on the innovative work of the Nordhaus team by using a model with fully endogenous financial flows and resulting capital growth paths and a level of disaggregation that enables the capture of both the leakage of emissions through trade in energy products and the effects of terms of trade changes due to carbon taxation in one region on the net gains achieved by others. One result of this approach is that the costs of participation differ significantly between regions and over time, as do the benefits at the regional level that are derived from our meta-analysis. We capture all the relevant dynamics and regional interactions but make the assumption that regional governments are able to pre-commit to mitigation policies at the outset, depending on their assessments of discounted net present values of economic gains over the coming 50 years.

As to coalition stability, we recognise that self-enforcing structures (Barret 1994; 2003) are required. The more members the greater are the incentives to free ride.[3] If there are regions that derive unilateral benefits from implementing abatement policy but benefit further if other regions join, then coalition stability is readily retained by the conditionality of side payments.[4] We give emphasis to positive side payments, rather than punitive tariffs, following Sælen (2016) and Hovi et al (2017),

2. Support for this level of carbon taxation is offered by Shiller1981; Barrett (2002); Aldy et al. (2003); LeRoy (2005); Avi-Yonah and Uhlmann (2009), Cramton et al. (2015), and McKibbin, Morris and Wilcoxen (2008). Yet carbon taxes as abatement policy are not without their detractors. See, for example, Schmalensee (1998), who emphasises uncertainty and regional heterogeneity of outcomes, Bolton and Ockenfels (2000), and Kraft-Todd et al. (2015) who posit a coordination game structure in which first implementers lose.

3. This is a condition called the "small paradox" that makes free riding become inevitable (Carraro and Siniscalco, 1993).

4. Carraro and Siniscalco (1998); Martimort and Sand-Zantman (2015) and Caparrós and Péreau (2017).

but evaluate the affordability of side payments by comparing them with the measured present value of the net benefits from global abatement that accrue to the initiating region.[5] In the interests of analytical economy, however, we imagine that there is only one policy choice, as between the status quo and a US$20 carbon tax, and that governments commit as of 2015 to a once and for all policy choice based on the net present value of net regional benefits. We begin with the modelling of costs in the section to follow.

3. ESTIMATING THE FUTURE ECONOMIC COSTS OF CARBON ABATEMENT

This work proceeds in two phases. First, a dynamic model of the global economy is adapted to the assessment of carbon taxation at the regional level. We then describe the structure chosen and the database used. The first application is the construction of a baseline projection of global economic performance through 2050. In subsequent sections our analysis of the cost side is superimposes on this projection a number of alternative mitigation scenarios.

The model is an extension and adaptation of the Gdyn-E model of Golub (2013). The embodied dynamics accommodate current account imbalances, international capital mobility and capital accumulation via an adaptive adjustment theory of investment at the country or regional level. The database for the model draws on the Global Trade Analysis Project (GTAP-7). It includes five primary factors: land, natural resources, skilled and unskilled labor and capital. The full set of 57 commodities is condensed into 12, amongst which the energy sector consists of coal, crude oil, gas and petroleum products. The regional disaggregation is to 21, though in our strategic analysis we focus on outcomes for eight: Australia, China, Japan, and the U.S., the EU, Indonesia, and "other ASEAN", aggregating the other modelled regions into a rest of world group (ROW).[6]

As suggested in our review of the work by Nordhaus and others in the previous section, the particular advantages conferred by the adaptation of this particular model are first, that its commodity disaggregation allows sophisticated representation of the terms of trade effects of carbon abatement policy. These effects turn out to be significant, particularly for Europe and Japan, which have low emission rates and so benefit from the widespread implementation of abatement policies in other economies. Second, sectoral disaggregation enables better capture of the links between energy use and carbon emissions. And third, the model has open capital accounts with regional portfolio management that endogenizes the choice between the direction of home savings to investment domestically or abroad, based on expected net rates of return. The resulting financial flows greatly influence the emerging patterns of capital accumulation across regions.

Our applications require considerable recoding of the model and modifications to the original GDyn-E database, as well as the construction of a distinct baseline projection of the global economy that incorporates feasible demographic and technological scenarios. Critical to the scenarios constructed is the productivity performance of China, which is the single largest carbon emitter, and in the base period at least, the most rapidly expanding economy. This baseline reflects the recent and anticipated future slowdown in the rate of Chinese growth and so represents recent developments more precisely than Golub (2013).

5. We acknowledge numerous applications of Nash's restricted stability condition in climate conflict studies, such as those by Howard (1971), Selbirak (1994), Pittel and Rubbelke (2008), Decanio and Fremstad (2013), and Madani (2013).

6. A complete description of the adapted version of Gdyn-E, its aggregation and its database are provided in an accompanying appendix, which is available from the authors. Dynamic optimization featured in the model is considered as methodological advances in energy modelling (Griffin, 2006).

Among the 21 represented regions, the U.S. emitted the most CO_2 in 2015, followed by China and the European Union. The U.S. emitted around 7,348 million tonnes of carbon or 20 per cent of global emissions. China emitted 6,958 million tonnes or 18.6 per cent of the global total. These large shares ensure that the U.S. and China are the most significant regions in affecting carbon emission control. Europe collectively emitted 4,955 million tonnes or 13.3 per cent of global emission in 2015. Emissions released by countries such as Japan, India, Australia and Indonesia all contributed less than five per cent.

The model is solved over the period 2015–2050, firstly in the form of a baseline projection. This is designed to represent the path of the global economy with neither additional carbon taxation nor any other changes to government intervention.[7] It embodies exogenous projections of the growth rates of populations, labor forces and productivity at the sectoral level within each region. These exogenous projections are based on, and consistent with, those by the IMF (IMF, 2016) and the World Bank (2017).[8] Though changes in the relative sizes of economic regions do influence the global path of carbon emissions, this is of less importance than the interacting effects of carbon abatement policies and so these underlying behaviours are held constant throughout the subsequent analysis.

In it the overall Asian economy grows at around four to five per cent per year while advanced economies retain lower yet stable rates. China's growth rate declines from more than seven per cent per year in the early years to less than five per cent per year by 2050. Since this growth rate remains comparatively high, China is prominent throughout as carbon emitter. According to this projection, by 2020, it would surpass the U.S. as the biggest emitter in the world. By 2050, China would contribute 16.7 per cent of global emissions, followed by emerging India with 12.1 per cent.

Several carbon abatement scenarios are then constructed to examine the global and regional effects of abatement policy. Since GDP is a measure of the total income generated within an economy, the immediate cost of mitigation is calculated based on the deviation of regional real GDP from baseline levels—that is, the income foregone due to abatement.[9] To make the task manageable, the carbon tax rate considered in all regions is restricted to 20 USD per tonne. This rate is central among those discussed and it has been proven to be sufficient to achieve static targets in numerous countries, including China's 65 per cent declared reduction by 2030.[10]

When all regions in the world commit to the 20 USD carbon tax, there is a slight but widespread slowing of growth. Figure 1 exhibits these negative effects on the paths of real GDP. Economic restructuring occurs both regionally and globally (Ekins and Speck, 1999) and there are changes to each region's terms of trade and real exhange rate. Gains are enjoyed by some regions that more than offset the cost of implementing the tax. Japan and the European Union, in particular,

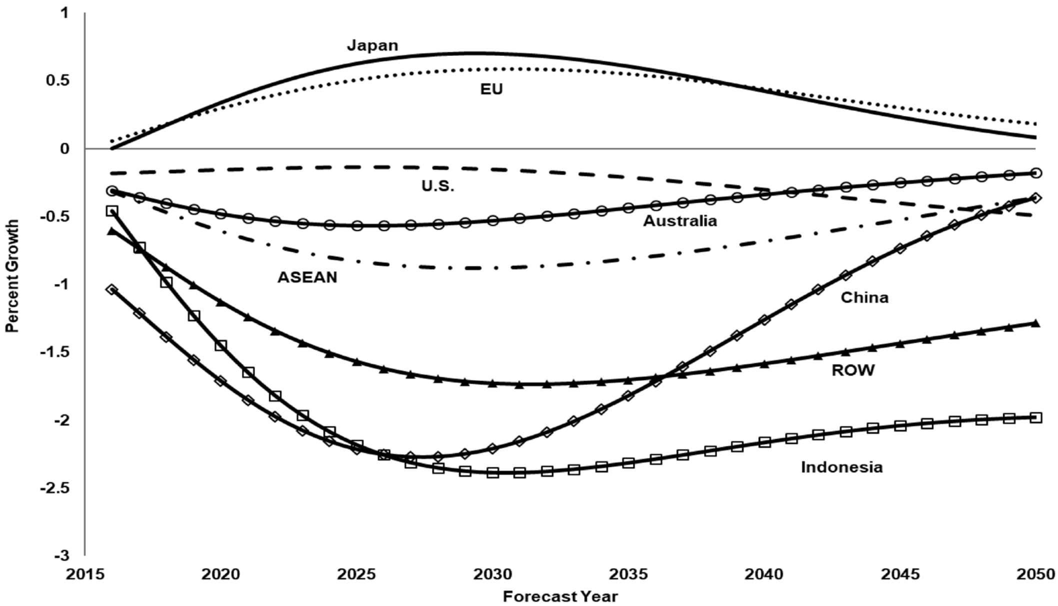
7. Recent emission mitigation action has taken the form of technological improvements in fossil fuel energy usage in the production process for several countries. Technical improvement rates are, accordingly, represented in our baseline simulation for the cases of Japan, the U.S. and EU, as well as China and India. The energy intensity rates used are based on the IEA ETP 2010 Report on each Region's energy intensity improvement from 1990–2007. The rates are in the appendix available from the authors.

8. World Bank National Account Data. available at: https://data.worldbank.org/indicator/NY.GDP.MKTP.CD

9. The C-DICE model of Nordhaus (2015) assumes the emission intensities and damage-output ratio are identical for all countries, and countries only differ in their sizes, recalling that their particular model has a single commodity for consumption or investment supplied via Cobb Douglas technology and trade is ignored. This means that, unlike our work below, the quantum of a region's emissions does not depend on the composition of production or trade and that the leakage of emissions via trade and changes in the terms of trade do not enter the analysis.

10. A 20 USD per tonne CO_2 tax rate could meet Indonesian's ambitious target of 26–41 per cent, based on Unilateral Carbon Taxation in Indonesia: Economic Implications (Perdana and Tyers 2016).

Figure 1: Real GDP Annual Growth Rate Deviations, Due to Abatement Policy Adoption (% Change from the Baseline)



Source: Simulations of the model described in the text.

enjoy expansions in their GDP levels, relative to the baseline.[11] This departs from what would be observed had either region implemented the tax unilaterally, in which case their real GDP growth would be curtailed relative to the baseline. The difference is due in part to their comparatively strong baseline emission controls, which reduce the burden of the eventual tax and to their assumed relative productivity performance paths in energy-intensive industries. These cause the rate of return on future investment in these regions to grow relative to other regions subject to the tax and so they enjoy faster capital growth.

4. ESTIMATING BENEFITS FROM CLIMATE CHANGE MITIGATION

It is impossible to evaluate the strategic interaction between regions over mitigation policies without consideration of the benefits that might be expected from the associated levels of climate stabilization. Notwithstanding a large literature devoted to such benefits, the results have considerably greater variance than the more readily modeled economic costs of mitigation (Böhringer et al., 2006). One of the reasons for this is that the benefits are public—non-rival and non-excludable. Another is that they rely on at least three research links, each of which carries uncertainty, namely the link between fossil fuel burning and atmospheric carbon, that between atmospheric carbon and temperature change and that between temperature changes and economic welfare. Here we rely on a survey of the literature that covers these links and a meta-analysis to quantify them. In the subsection to follow, we draw on available information to establish the link between carbon emissions and the climate-related impacts on global GDP. In the next subsection, we investigate divergences in these impacts across regions.

11. This proves to be consistent with Nordhaus (1996) finding as regards energy efficiency in Japan and Europe.

4.1 Emissions, Climate and Global GDP Effects

The relationship we address is between total carbon emissions (in Gigatonnes, or GT) and the average global surface temperature (in °Celsius) via the atmospheric concentration of greenhouse gas (parts per million, or ppm). The projected level of total carbon emissions is linked to average surface temperature using the 2000–2100 global temperature scenarios of the Intergovernmental Panel on Climate Change (IPCC). Each carbon taxation scenario from our model yields a separate simulated trajectory for carbon emissions. The IPCC temperature estimates are based on GHG Emissions (CO_2 combined with other greenhouse gases, including Methane, CFC and Nitrous Oxide). Because the relative contribution of CO_2 is about 80 per cent (Nordhaus, 1991), for the purposes of this analysis we measure emissions in terms of tonnes of carbon and assume the contributions and impacts of the other gasses are proportional.

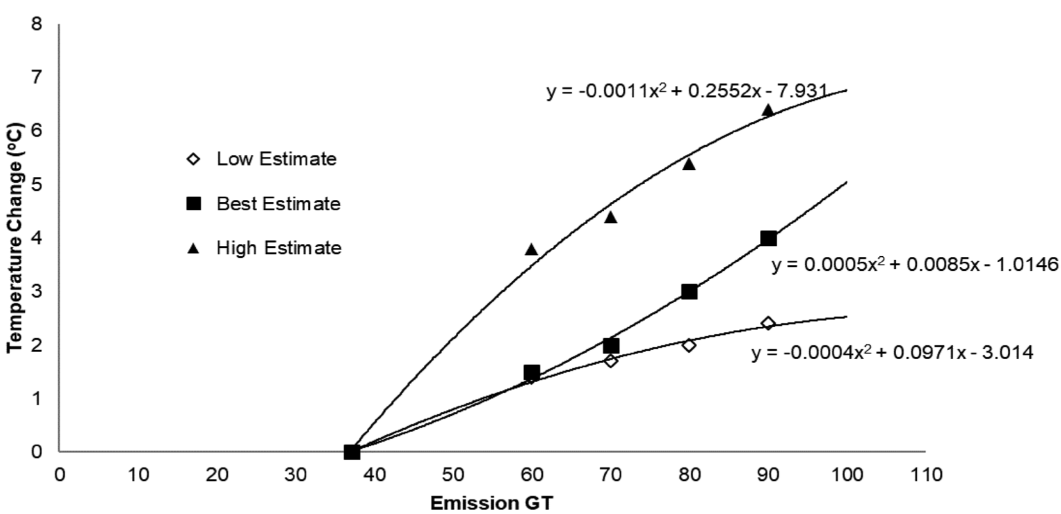
The associated rises in average global surface temperature are taken from IPCC scenario ranges (Table 1) which are projected through 2090 from the year 2000 with a very wide error band. For this reason, we adopt IPCC terminology and construct three different temperature scenarios: "low", "best" and "high". Total emissions and temperature estimates under these three IPCC scenarios are illustrated in Figure 2.

Table 1: IPCC Temperature Scenarios and Estimated Temperature Changes

Emission (GT) in 2050/ Lower Border	IPCC (GHG scenario)	IPCC Atmospheric Concentration (PPM)	IPCC Best Temperature Estimate (°C)	IPCC Likely Uncertainty Range (°C)	Developed Temperature Estimate Low Estimate (°C)	Best Estimate (°C)	High Estimate (°C)
90	A1F1	660–790	4.0	2.4–6.4	2.4	4.0	6.4
80	A2	570–660	3.0	2.0–5.4	2.0	3.0	5.4
70	A1B	485–570	2.8	1.7–4.4	1.7	2.0	4.4
60	A1T	440–485	2.4	1.4–3.8	1.4	1.5	3.8
37.2	—		—	—	0.0	0.0	0.0

Source: IPCC (2007).

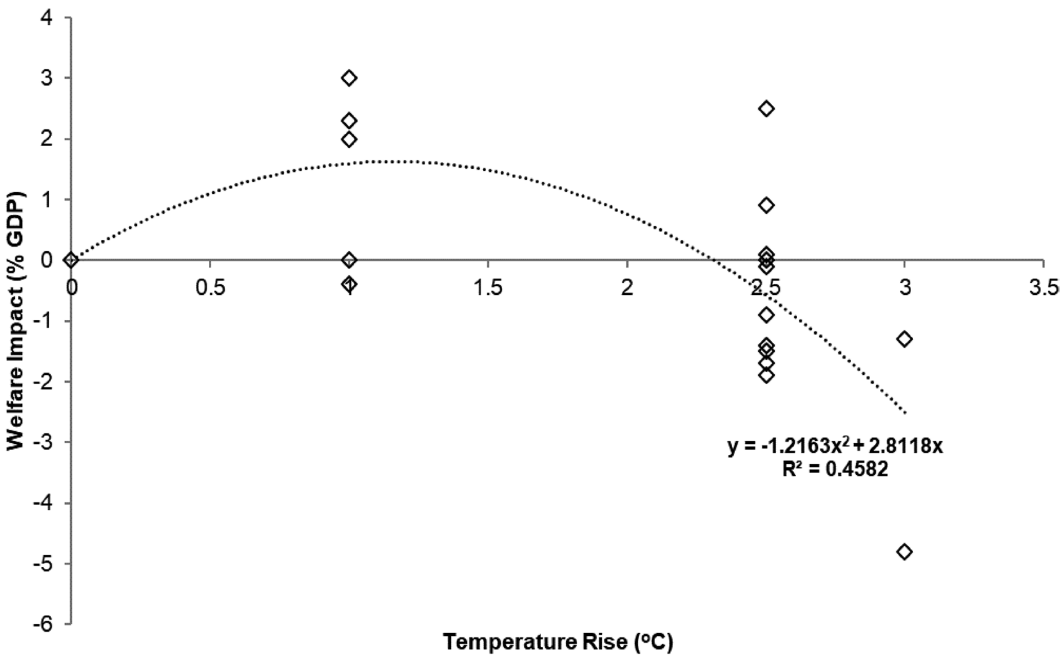
Figure 2: Emissions and Global Temperature Changes (IPCC Scenarios)



Source: IPCC cases and fitted relationships (IPCC 2007).

Next, we investigate the global welfare impacts of changes in average surface temperature. Our meta-analysis of the economic welfare impacts of warmer temperatures draws on the survey by Tol (2009), which covers 15 sources offering measured impacts.[12] These include enumerative studies based on natural experiments as well as statistical analyses. In the enumerative approach, the welfare estimates are extrapolated from selected individual locations to the global scale and from the immediate past to the distant future. The statistical studies rely on uncontrolled experiments and measured differences across regions in climate and income. Despite the differences in analytical approach, these studies tend to agree that a rise in the average surface temperature by a single degree Celsius would actually benefit the global economy on average. Rises above two degrees are injurious, however. The resulting fitted relationship between the aggregate welfare impact (average global GDP loss) and the corresponding global average surface temperature rise is shown in Figure 3.

Figure 3: Temperature Changes and Welfare Consequences

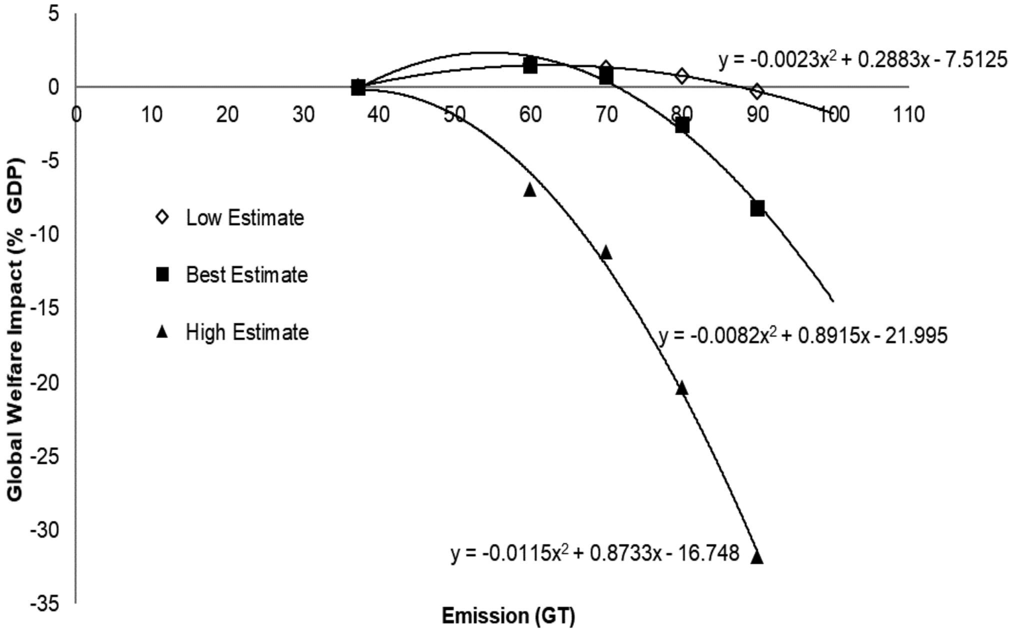


Source: Based on estimated economic welfare measures from 15 sources, as compiled by Tol (2009).

The final step in estimating the benefits from global mitigation involves calculating the economic welfare impacts of changes in global emissions, for each of the three IPCC scenarios. This is done by combining the fitted polynomial functions illustrated in Figures 2 and 3. The global welfare reduction per gigatonne of emissions is derived as shown in Figure 4. The high variance of the IPCC temperature scenarios results in considerable divergence in welfare reduction estimates. The low-temperature scenario embodies the least economic risk, though our focus will mostly be directed at the IPCC "best", or most likely, scenario.

12. The surveyed estimates offer economic evaluations of temperature rises from one to three degrees Celsius. Toll's cited impacts range from negative 4.8 percent of GDP for 3 degrees Celsius, to positive 3.0 percent of GDP for one degree Celsius.

Figure 4: Global Emissions and Global Economic Welfare (GDP)



Source: Authors' estimates as described in the text.

4.2 Causal Factors Affecting Regional Divergences in GDP Effects

There is considerable evidence that warming will not affect all regions equally. Climate change impacts depend on variations in temperature that depend in turn on geographical location, altitude, geology, and micro-climate. Here we account for these variations. To quantify different climate impacts for each region identified in our study, we draw on the integrated assessment study of Roson and Sartori (2015) of six climate impacts based on their own meta-analysis sourced in the scientific and economic literature. Our focus in accounting for this regional variability is on four climate indicators: sea level rise (SLR), agricultural output, impacts of heat on labour productivity and the human health effects of climate.[13]

Roson and Sartori first calculate the SLR impacts as the percentage losses due to changes in endowments of productive land. The results suggest considerable regional variation in endowment loss that is particularly large for small island states, Central America and Asia but may be negative for arctic states. The impact on agriculture is based on effects on the output of the staples, maize, wheat, and rice. Their conclusion accords with the findings by Schlenker and Roberts (2009). The most modest impacts turn out to be at the highest latitudes, particularly in Europe and North America.

The effect on labour productivity is estimated by the change in the wet bulb globe temperature (WBGT) per degree Celsius, since this appears to diminish effective working hours. They generalize based on a minimum threshold from Kjellstrom (2009), with rising temperatures impairing labour productivity in agriculture, manufacturing and services. The agricultural labour productivity is reduced most by temperature rise and the effect is largest in the humid tropics. Additionally, the vector-borne, heat-related diseases are also more destructive the higher the temperature climbs.

13. Here we omit climate impacts on tourism and household energy demand which require secondary feedbacks associated with mitigation benefits that are not captured in our modelling.

The estimation of this effect relies on the earlier work of Bosello et al. (2006) and the 2014 IPCC Assessment Report.

4.3 Region Specific Climate Benefit Factors

We estimate ratios of the regional to the average global climate benefits in two steps. In the first, the per-region net effects on GDP are estimated for all the causal factors outlined in the previous section. Second, for each region the four GDP effects are multiplied by their respective GDP shares and added. More specifically, region-wide effects of agricultural output changes are approximated by multiplying by agriculture's value-added share; labour productivity effects due to heat stress and disease incidence are estimated via the product of the sectoral productivity effect and the ratio of sectoral labor income to total GDP. Finally, for SLR, estimated changes of land productivity are multiplied by the share of land rent in total GDP. The addition of these causal effects yields the region-specific GDP incidence per degree increase in the average surface temperature.[14]

The second step is to construct the regional benefit ratio, with numerator and denominator measuring the percentage change in GDP. If the global benefit (per cent change in global GDP) per degree reduction in average surface temperature is $\bar{B}_W$ and the corresponding regional benefit is B_i, the ratio of regional to global benefit is $B_i / \bar{B}_W$, which must be normalised to satisfy:

$$\bar{B}_W = \sum_{i=1}^{n}\left(\frac{Y_i}{\sum_j Y_j}\right)B_i \text{ or } \sum_{i=1}^{n}\left(\frac{Y_i}{\sum_j Y_j}\right)\left(\frac{B_i}{\bar{B}_W}\right)=1$$

To be consistent with the three different IPCC temperature scenarios introduced in section 4.1, the regional benefit ratio is calculated for temperature rises of between one and five degrees Celsius. An average is then taken across five sets of estimates, as indicated in Table 2.

5. ANALYSIS OF STRATEGIC INTERACTIONS

The payoffs for each region are based on comparisons of the benefits from the implementation of mitigation policies at the regional level, derived from the previous section, with the associated mitigation costs, calculated using the model described in Section 3. Net global and regional gains are calculated for each year from 2015 to 2050. The global scale of these gains depends, however, on the mix of regions participating. Moreover, the results arise in triplicate given the three IPCC temperature scenarios discussed previously. The costs (positive or negative) facing regions that do not participate stem only from changes in the paths of their terms of trade, real exchange rate and investment that are due to the implementation of the tax by other regions. These costs also vary depending on the mix of regions participating. For regions that do participate, these are added to those stemming directly from their implementation of the tax. The mitigation costs, thus augmented, are then deducted from region-specific gains due to moderated temperature changes at both the global and regional levels.

5.1 Intertemporal Analysis and Discounting

The net payoffs for each region are 2015 discounted net present values of net economic welfare effects in 2015 US$, constructed over the period 2016 to 2050. The net welfare effect for each year is derived by multiplying the net percentage change in projected GDP for each region by its corresponding level and discounting the result to 2015 at the 2017 U.S. 10-year Treasury bond

14. These results are summarised in Table A7 of the accompanying appendix, available from the authors.

Table 2: Regional to Global Benefit Ratios

No	Country/Region	Temperature Rising					Average
		+1°C	+2°C	+3°C	+4°C	+5°C	
1	Indonesia	0.36	0.82	1.14	1.10	0.98	0.88
2	Singapore	0.08	0.14	0.18	0.17	0.15	0.14
3	Malaysia	0.19	0.32	0.41	0.38	0.34	0.33
4	Other ASEAN	0.33	0.57	0.73	0.70	0.63	0.59
5	Other Asia	0.88	1.16	1.34	1.29	1.21	1.17
6	Australia	0.20	0.23	0.25	0.25	0.25	0.24
7	New Zealand & Oceania	0.09	0.07	0.07	0.07	0.07	0.07
8	China (PRC)	3.97	3.82	3.79	3.79	3.80	3.83
9	Japan	0.76	0.77	0.85	0.94	1.02	0.87
10	Korea	0.18	0.18	0.18	0.20	0.21	0.19
11	India	1.74	2.32	2.68	2.52	2.31	2.32
12	Brazil	0.37	0.58	0.75	0.81	0.81	0.66
13	U.S.	2.76	2.50	2.34	2.29	2.35	2.45
14	Canada	0.41	0.17	0.01	0.04	0.09	0.14
15	Other America	0.85	1.64	1.87	1.88	1.75	1.60
16	EU	4.70	2.75	1.50	1.70	2.16	2.56
17	Russia	0.62	0.28	0.05	0.08	0.16	0.24
18	FTA Europe	0.15	0.08	0.04	0.04	0.06	0.07
19	Ex. Soviet Union & Other EU	0.43	0.29	0.20	0.21	0.24	0.27
20	Middle East	1.24	1.15	1.10	1.07	1.06	1.13
21	Africa	0.69	1.18	1.53	1.47	1.35	1.24

Source: Estimation as described in the text.

yield of 2.35 per cent. We realise that this rate high compared to the less than one per cent value chosen for the Stern Review (Stern 2006). A tendency toward a declining social discount rate is proposed by Weitzman (2001), Gollier and Weitzman (2010), Gollier (2012) and Arrow et al. (2014). Yet rates up to seven per cent were central to the attitude of the U.S. government at the time of its decision to withdraw from the Paris Agreement.[15] We follow Heal (2017), who sees discount rate choice as central to difficulties in arriving at Pareto efficient paths given the nature and extent of climate change externalities and so offer an analysis of sensitivity to this value in Section 5.6.

5.2 Game Structures

Our starting hypothesis has been that these payoffs would form a coordination game, with multiple Nash equilibria and with regions facing transition penalties for unilateral moves from low-level to high-level equilibria. Under this scenario the mix of current policies would leave the world in an inferior equilibrium from which no region would gain by moving unilaterally and a transition to a superior equilibrium would require a "critical mass", of countries and regions to act together. Under these conditions, Schelling (1980) had identified "focal points" as means to help resolve the coordination problem, an idea that favours the constant-rate carbon tax as a device for simplifying the interaction choice (Avi-Yonah and Uhlman, 2009). Our analysis tests this hypothesis and finds it wanting, in that at least some of the very large emitting regions derive sufficient net benefit, in present value terms, from implementation that abatement policy is unilaterally advantageous even if no other regions join them.

Significant emission contributions from China, the U.S., and the EU distinguish these large, regions from the others. For this reason, the first scenario considered focusses on these three regions. Other regions are assumed to free ride (not to participate in carbon taxation and hence abatement).

15. We thank an anonymous reviewer for pointing this out.

Since there are more than two players, the normal form game requires more than four combinations of decision options. These follow Pascal's triangle, where the number, k, of combinations of n elements is the sum of the *n-th* row of the binomial coefficients.[16]

$$\sum_{0\le k\le n} c_k^n = \sum_{0\le k\le n} \binom{n}{k} = 2^n$$

And the number of subsets in each combination is obtained by calculating the whole number between 1 and n, where $n, k \in R$, or:

$$\sum_{0\le k\le n} \binom{n}{k} = \frac{n!}{k!(n-k)!}$$

It follows that the game between the three largest players (the U.S., China and Europe), each facing just the two options (participate in the carbon tax program or defect), has eight strategic combinations, which comprise one zero-participation subset, three subsets where one country participates, three subsets where two countries participate and one subset in which three countries participate. The static, normal form game analysis for this case is illustrated in Figure 5 and discussed in the following subsection. In the subsection to follow that we consider a game with five active regional players.

5.3 Strategic Analysis: The Big Three (China, U.S, EU)

This analysis is undertaken for each of the three IPCC temperature scenarios. We take them in turn.

The IPCC "low temperature" case:

The payoffs, in this case, prove inconsistent with the hypothesized coordination game. A single Nash Equilibrium appears and it combines defection by all three regions. In this case, the global welfare losses due to average surface temperature changes are very modest and so there is a disincentive to participate for all regions. Further investigation (Table 3) reveals that, even if all three regions were to participate, estimated global emissions would be reduced to 87.35 GT in the year 2050, suggesting a welfare gain of only 0.16 per cent of global GDP. By comparison, China's participation cost would be 2.76 per cent of its projected GDP. The calculus is similar for the U.S. and the EU.

In this case, the dominant strategy to defect yields the best economic outcome, at least for China and the U.S. The option of all participating offers no superior outcome. With defection, China avoids a present value loss amounting to three trillion USD while the U.S. enjoys a slightly higher benefit. By contrast, despite the fact that the EU's best individual strategy is to defect, it would be better off if all three were to choose mitigation.

The "best" IPCC temperature scenario:

In this case, while a coordination game is not evident, it is distinctive that the U.S. and China now have unilateral incentives to participate. The Nash equilibrium has the U.S. and China implementing mitigation policy while Europe is better off free riding. Decisions to defect or partici-

16. The number, k, of combinations given set ,S, with n elements is denoted as C_k^n. Alternatively, $\binom{n}{k}$ is read as n chose k.

Figure 5: Normal Form Static Games on 2015 Present Values for Three Regions (The U.S., China, EU)

LOW Scenario (in Trillion USD)

EU Participate

U.S	China: Participate (U.S.)	China: Participate (China)	China: Participate (EU)	China: Defect (U.S.)	China: Defect (China)	China: Defect (EU)
Participate	10.11	3.66	*14.02*	9.04	8.58	*11.92*
Defect	13.86	2.99	*12.81*	11.73	7.20	*9.58*

EU Defect

U.S	China: Participate (U.S.)	China: Participate (China)	China: Participate (EU)	China: Defect (U.S.)	China: Defect (China)	China: Defect (EU)
Participate	9.90	3.25	*17.85*	8.29	7.79	*15.13*
Defect	13.38	2.41	*16.34*	10.73	6.25	*12.49*

*All Defect

BEST Scenario (in Trillion USD)

EU Participate

U.S	China: Participate (U.S.)	China: Participate (China)	China: Participate (EU)	China: Defect (U.S.)	China: Defect (China)	China: Defect (EU)
Participate	-2.57	-6.40	*0.30*	-16.18	-11.50	*-15.52*
Defect	-3.65	-11.07	*-6.14*	-20.92	-18.67	*-26.04*

EU Defect

U.S	China: Participate (U.S.)	China: Participate (China)	China: Participate (EU)	China: Defect (U.S.)	China: Defect (China)	China: Defect (EU)
Participate	-5.17	-8.81	*1.54*	-20.66	-15.21	*-16.42*
Defect	-7.15	-14.09	*-5.93*	-26.27	-22.96	*-27.94*

**EU Defect

HIGH Scenario (in Trillion USD)

EU Participate

U.S	China: Participate (U.S.)	China: Participate (China)	China: Participate (EU)	China: Defect (U.S.)	China: Defect (China)	China: Defect (EU)
Participate	-114.52	-88.47	*-124.34*	-164.20	-118.48	*-180.74*
Defect	-132.55	-104.72	*-149.88*	-187.24	-138.14	*-211.88*

EU Defect

U.S	China: Participate (U.S.)	China: Participate (China)	China: Participate (EU)	China: Defect (U.S.)	China: Defect (China)	China: Defect (EU)
Participate	-125.82	-96.83	*-132.90*	-178.07	-128.61	*-192.21*
Defect	-145.05	-113.88	*-159.80*	-202.26	-149.04	*-224.67*

***All Participate

Notes: U.S. outcome to participate and to defect is underlined while EU´s is in italic style. Shading area indicate the strategic choice. Source: Simulation results and meta-analysis benefits calculated as described in the text.

pate are influenced by China. Once China participates, the EU's best strategy is to defect and hence to free ride on mitigation by the U.S. and China.

The IPCC "high" temperature scenario:

The mitigation gains are more significant in this case. All three regions choose to participate. The benefits far exceed the economic costs of mitigation and so all three participate and hence impose the carbon tax.

Table 3: Estimated Average Global Welfare Effect from Emission Abatement by Regions and Regional Groupings, Percentage of GDP Deviation

No	Selected Scenario Carbon Tax Implementation	Global Emission (GT)	PV of Global Welfare Impact (% Global GDP Baseline)[a]			PV Participation Cost (% Country GDP Baseline)[b]		
			Low	Best	High	CHN	U.S.	EU
1	Global (All Countries)	64.90	2.02	1.77	–11.40	–0.84	–0.57	0.19
2	U.S., China, EU (Big Three)	87.35	0.16	–8.96	–37.80	–2.76	–0.64	–0.17
3	U.S. China	89.18	–0.12	–10.33	–40.64	–3.04	–0.70	0.42
4	China and EU	90.08	–0.28	–11.03	–42.07	–3.13	0.04	–0.45
5	U.S. and EU	95.01	–1.18	–15.17	–50.36	0.65	–0.62	–0.31
6	China	92.65	–0.72	–13.12	–46.29	–3.41	–0.02	0.14
7	U.S.	96.80	–1.55	–16.79	–53.55	0.37	–0.68	0.28
8	EU	98.47	–1.92	–18.38	–56.62	0.28	0.06	–0.59
9	NONE	100.28	–2.32	–20.18	–60.05	0.00	0.00	0.00

[a] These effects stem from reduction in global surface temperature change, due to mitigation.
[b] The cost the implemented mitigation policy is a USD 20 Uniform Carbon Tax. Positive rate reflects benefit rate as free rider.
Source: Estimation as described in the text.

5.4 Strategic Analysis: Five Countries

In the three-region analysis and the "best" and "high" temperature cases, each region's contribution to the abatement of global emissions plays a critical role in determining its incentive to participate. It is therefore likely that strategic incentives differ for regions with smaller emissions. Here we add to the analysis two smaller regions that, nonetheless, generate high emissions per capita, namely Indonesia and Australia.[17] With five regions the game has 32 combinations (2^5), including the subsets in which either no regions or all regions participate in implementing the tax. There are also five subsets pairing one region with four and ten pairing two and three. The payoff matrices for this multi-player game are summarized and illustrated in Figure 6.

The IPCC "low temperature" case:

Given that the large regions all defect in the three-player game it is not surprising that no regions participate in this variant. All face dominant non-participation strategies. For the two smaller regions the cost of mitigation is comparatively high compared with their share of the global benefits that would accrue from it. Implementing unilaterally would, for Australia and Indonesia, cause 2015 present value GDP losses of 0.28 and 0.26 Trillion USD respectively, yielding no abatement action. This dominant strategy, for all to defect, is also not consistent with a prisoner's dilemma, in that participation by all does not confer net benefits for all regions.

The IPCC "best" temperature scenario:

As in the three-player case there is no coordination game. Except for the U.S. and China, all regions choose to free ride. The costs the other regions face in implementing the tax are set against comparatively small increments to shared global welfare from the resulting mitigation. By

17. We recognise that this choice of smaller regions to add is arbitrary and made in our case for reasons unrelated to the mission of this paper. Smaller economies in Asia, Latin America or Africa would serve this purpose too, though they are here consolidated into a "rest of world" group as likely free riders. Yet these chosen small open economies do have high emissions per capita and serve to illustrate the incentives to free ride faced by all such regions.

Figure 6: Normal Form Static Games on 2015 Present Values for Five Regions

LOW SCENARIO (TRILLION USD)

NO	COUNTRY	PARTICIPATION	
		PARTICIPATE	DEFECT
1	US	8.29	10.73
2	China	2.41	6.25
3	EU	9.58	12.49
4	Indonesia	-0.26	0.14
5	Australia	-0.28	0.06

BEST SCENARIO (TRILLION USD)

NO	COUNTRY	PARTICIPATION	
		PARTICIPATE	DEFECT
1	US	-20.66	-26.27
2	China	-14.09	-22.96
3	EU	-26.04	-27.94
4	Indonesia	-0.91	-0.54
5	Australia	-0.51	-0.17

HIGH SCENARIO (TRILLION USD)

NO	COUNTRY	PARTICIPATION	
		PARTICIPATE	DEFECT
1	US	-178.07	-202.26
2	China	-113.88	-149.04
3	EU	-211.90	-224.69
4	Indonesia	-3.74	-3.43
5	Australia	-1.59	-1.27

Source: Simulation results and meta-analysis benefits calculated as described in the text.

contrast with the "low" scenario, and consistent with the earlier unilateral analysis, the U.S. and China enjoy unilateral gains from abatement even when, because other regions defect, no other region contributes to that abatement. This finding emphasizes the central role of these big two emitters in global climate change abatement.

The IPCC "high" temperature scenario:

This yields a more striking result. The two smaller economies that consider investment in abatement, Australia, and Indonesia, still choose to free ride. Even with larger benefits from abatement, the implementation cost is too high to justify participation by these small emitters. The accumulated present value of their net impact is negative if both commit to the tax.

While in this case universal participation does yield net benefits at the global level, the free riding incentives are shown to prevent participation by all regions, even in this "high" scenario. If the free rider losses are smaller than the collective welfare or revenue gains by the larger regions that would participate, then this excess gain could feasibly finance side payments to induce universal participation. The following subsection assesses the potential affordability of such side payments, as a means to overcome this free rider problem.

5.5 Free Riding and the Potential Affordability of Side Payments

We have seen that the U.S. and China consistently derive net gains from bearing the cost of abatement in both the "best" and the "high" IPCC temperature scenarios, while the EU is a net gainer from unilateral implementation only in the "high" scenario. In these cases, the three largest economies taken together (the "big three") would implement carbon taxation irrespective of the behavior of other regions. Yet this raises difficult politics. It is easier to advocate the implementation of a tax that is costly in the short term if other regions are committed to it. Free riding therefore remains a political stumbling block.

Importantly, however, if the rest of the world were also to implement the tax the global gains from mitigation would be substantially increased and the implementation cost would be smaller for the big three. The question then arises as to whether they would be made better off by more than it would cost to induce participation by the others via side payments. Were this to be the case then the side payments would be both affordable and, notwithstanding the additional fiscal burden, they would be net welfare improving for the big three.[18] Thus, the affordability of side payments can be considered in terms of the accumulated present value of net future benefits. If the additional net benefits that arise from global abatement are sufficient to more than compensate for the losses in other regions then side payments are affordable and yield net benefits to the big three, even though this would require considerable intertemporal redistribution due to the costs arising before the benefits are seen.[19]

Our first step is to measure the present value of the stream of global welfare improvements, relative to a no-abatement case, for each carbon tax implementation (Table 4). Then this number is adjusted by each region's benefit share and its mitigation cost in terms of the present value of their projected GDP. This yields the net welfare effect of carbon mitigation, both in regions that implement the tax and those that do not. We calculate the present value of the stream of extra benefits gained by the big three carbon taxing emitters (China, the U.S., and the EU) when all the otherwise free-riding regions also implement the tax. This extra benefit arises both from reduced global surface temperature and from terms of trade changes due to taxation in the other regions. We then estimate the present value of actual net losses that would be incurred by the previously free-riding regions, due to their switch to abatement policy.

Should the present value of the extra gains by the top three exceed the present value of aggregate incremental losses by these regions, there is room for side payments while still incentivising the big three to commit to abatement. For parsimony, we limit the side payment analysis to only the "best" temperature scenario, where in that case, and the "high" temperature scenario, the free riding and the prisoner's dilemma structure are clearest. Table 5 summarizes the total extra benefit accruing to the big three emitters from full global implementation, and the aggregated losses borne by other regions due to their switching from free riding to implementation. The present value of the additional net welfare benefits to China, the U.S., and the EU, which arise from the implementation of the tax by all other regions, is estimated roughly at 27 trillion USD. This is sufficient to compensate for the present-value incremental net loss of 15 trillion USD in the other regions.

18. This approach is consistent with the Carraro and Siniscalco (1993) definition of stable transfer payments. To achieve a stable coalition, where there are no incentives to free ride, the total transfers should be lower than the gain the committed member would obtain from the expanding coalition, But must be larger on net than the potential member's net loss associated with joining other regions in adopting abatement.

19. One practical way to model side payments would be based on receipts from carbon taxation, since these would be readily available for redistribution. In our model, however, expenditure by governments on transfers abroad are not distinguishable from private net factor income flows, which are driven by foreign investment patterns and not by aid policy.

Table 4: Present Value of Improvement Relative to No Abatement Case

No	Selected Scenario Carbon Tax Implementation	Global Emissions (GT)	PV Global Welfare Impact (Trillion USD)			Percentage Improvement from "No Abatement" Case Relative to Baseline GDP Value		
			Low	Best	High	Low	Best	High
1	None (No Abatement)	100.28	–1.41	–12.24	–36.43	0.00	0.00	0.00
2	Global (All Countries)	64.90	1.23	1.08	–6.92	4.34	21.95	48.65
3	U.S., China, EU (Big Three)	87.35	0.10	–5.44	–22.93	2.48	11.21	22.25
4	Big Three + Indonesia	86.42	0.18	–5.03	–22.08	2.62	11.87	23.65
5	Big Three + Other ASEAN	86.66	0.16	–5.14	–22.30	2.59	11.70	23.29
6	Big Three + Australia	86.84	0.15	–5.21	–22.46	2.56	11.58	23.02
7	Big Three + Japan	86.91	0.14	–5.24	–22.53	2.55	11.53	22.92
8	Big Three + India	80.42	0.65	–2.71	–16.98	3.39	15.71	32.06
9	Big Three + Russia	84.32	0.36	–4.17	–20.22	2.91	13.31	26.72
10	Big Three + Middle East	85.22	0.29	–4.53	–21.01	2.79	12.70	25.42
11	Big Three + New Zealand	87.31	0.10	–5.42	–22.90	2.49	11.24	22.31
12	Big Three + Brazil	87.21	0.11	–5.38	–22.80	2.50	11.31	22.46
13	Big Three + Korea	86.80	0.15	–5.20	–22.43	2.56	11.61	23.08
14	Big Three + Canada	86.93	0.14	–5.25	–22.55	2.54	11.51	22.89
15	Big Three + Latin Americas	86.25	0.20	–4.96	–21.93	2.65	11.99	23.91
16	Big Three + Other Asia	85.90	0.23	–4.81	–21.61	2.70	12.24	24.43
17	Big Three + FTA Europe	87.32	0.10	–5.42	–22.90	2.49	11.23	22.30
18	Big Three +Ex. Soviet Union	86.14	0.21	–4.91	–21.83	2.66	12.07	24.07
19	Big Three + Africa	85.04	0.30	–4.46	–20.85	2.82	12.83	25.68

Source: Estimation as described in the text.

Table 5: Cumulative Discounted Dollar Value of Net Welfare Benefit or Loss due to Uniform Tax (2015 US$ Trillions)

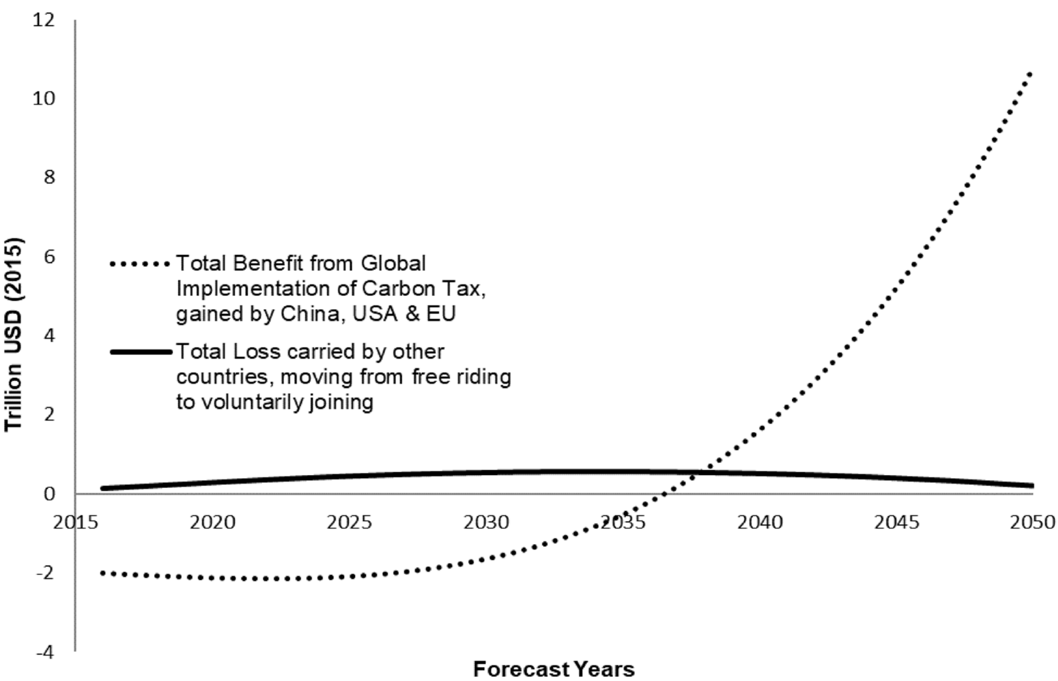
Regions (A)	Unilateral Implementation (B)	"BIG Three" Implementation (C)	Universal Implementation (D)	Extra Benefit by Universal Implementation (D-C)
China	21.37	16.56	26.68	10.12
U.S.	13.63	23.70	31.36	7.60
EU	5.23	28.23	37.58	9.35
Total "Big Three"		**68.48**	**95.62**	**27.14**

Regions (A)	"BIG Three" Implementation/ Benefit as Free Rider (B)	Joining "Big Three" (C)	Effect of Altering Mitigation Strategy (C-B)
Indonesia	0.59	0.20	–0.39
Other ASEAN Countries	0.64	0.17	–0.47
Australia	0.35	0.00	–0.35
Japan	4.12	3.37	–0.75
India	4.74	3.54	–1.20
Russia	0.01	–3.26	–3.27
Middle East & North Africa	2.37	–0.51	–2.88
New Zealand & Oceania	0.06	0.00	–0.06
Brazil	0.83	0.53	–0.30
Korea	0.50	–0.06	–0.56
Canada	0.35	–0.14	–0.49
Latin America	4.49	2.47	–2.02
Other Asia	1.58	1.05	–0.53
FTA Europe	0.15	0.05	–0.10
Ex. Soviet Union	0.32	–0.75	–1.07
Africa	1.58	0.89	–0.69
Total	**22.66**	**7.53**	**–15.12**

Source: Estimation as described in the text.

If this analysis is implemented on an annual basis, rather than in present value terms, there are years in which the capacity for compensation is sufficient and years in which it is too small.[20] Sadly it is during the early years that the compensation would be inadequate. Indeed, considered annually, the extra benefit gained by the big three would not be sufficient to compensate the total loss carried by other regions, at least until the year 2035. As illustrated in Figure 7, the total loss due to switching from free riding to the implementation of the tax in the smaller regions is stable throughout the simulation period at something under 0.5 trillion USD per year. For the big three, however, the net gains are negative throughout the first two decades. Indeed, as Figure 8 shows, within the first two decades, the big three would experience net negative benefits from carbon abatement, substantial for China and the U.S. yet comparatively modest for Europe. The turning point would be two decades after the tax is first implemented. While this is consistent with our finding that both the U.S. and China are net gainers from unilateral tax implementation, the task is made politically difficult due to the need to wait almost an entire generation for the net gains to begin to flow.

Figure 7: Side Payments from China, the U.S., and the EU Sufficient to Induce Universal Participation



Source: Estimation as described in the text.

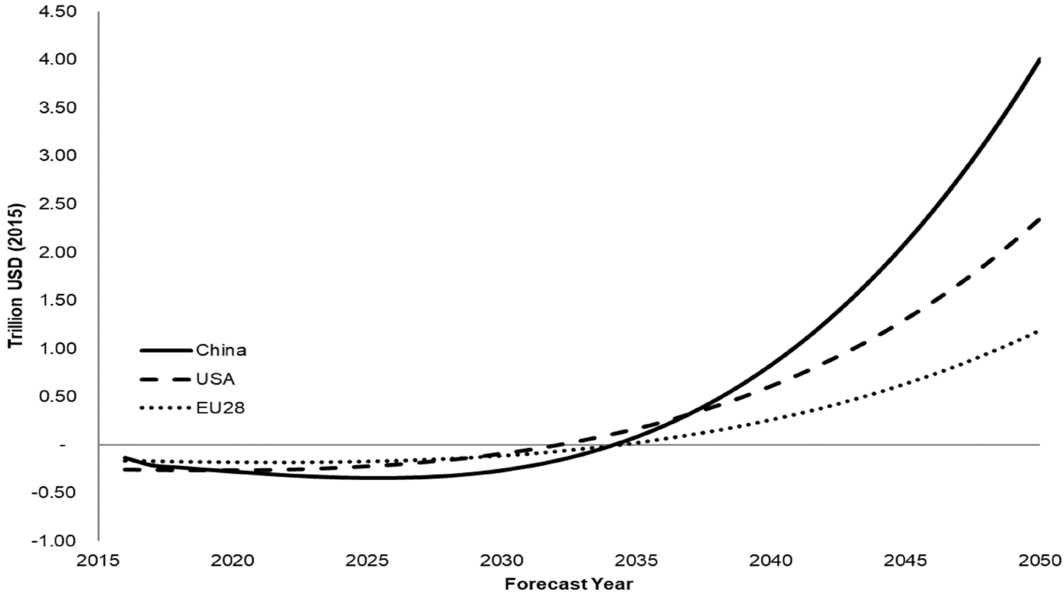
5.6 Sensitivity Analysis: Discount Rate

While there are many facilitating assumptions required for this analysis,[21] we regard the rate at which future benefits and costs are discounted to be the strongest of these and so it is impor-

20. There is clearly a time consistency issue with this analysis in that it is our assumption that regional governments can pre-commit to 35 years of future climate policy as of 2015. Dealing with the possible failure of this assumption is necessarily the subject for further research.

21. Beyond the structural assumptions embodied in our modelling of costs, there is our omission of risk preferences from the analysis and our assumption that, while regional impacts of warming and of abatement are unequal, the effects of abate-

Figure 8: Estimated Net Welfare Benefit due to Unilateral Implementation of Abatement Policy by China, the U.S., and EU



Source: Estimation as described in the text.

tant that the associated sensitivity of results should be explored. Here we consider the 10-year U.S. Treasury bond rate to be at the low end of a possible range, given that abatement policies are to be implemented in economic environments where the opportunity cost of capital depends on commercial financing rates, and particularly those in the energy and electricity sectors. We therefore consider two additional discount rates: five per cent captures the cost of equity in commercial activity in open economies generally. We also consider a rate of 7.2 per cent to represent cost of capital in energy and energy intensive industries.[22]

With these different discount rates, the game theoretic results from all scenarios confirm the previous findings, for almost all regions. Variations are, nonetheless, of particular interest. In the "best" temperature scenario, we find that the choices of the U.S and China are sensitive to the discount rate. At the five per cent rate, the U.S. participation strategy becomes less dominant, yet the equilibrium still has unilateral participation of both the U.S. and China.

At 7.2 per cent, China and the U.S. are highly interactive. Two equilibria emerge in which either China or the U.S. participates, but they do not do so together. The best reaction of the U.S. is now to defect if China commits and to participate if China defects. China's optimal reactions are the converse, highlighting the strong incentives for members of the big three to free ride once another large emitter decides to commit.

As to the affordability of side payments, under the "best" temperature scenario, at the higher discount rates, the big three would not be able to afford compensation sufficient to induce universal implementation. In the "high" temperature scenario, however, the total discounted value of the larger benefits to the big three from temperature stability would still be more than sufficient

ment depend on global rather than regional emissions. We also neglect the role of green industrial policy motives (Rodrik, 2014), focusing instead on narrow economic implications. These clearly matters for further work.

22. For consideration of the discount rate as the cost of capital see Nordhaus (2007) for an evaluation of the cost capital facing US industries. See: http://www.stern.nyu.edu/~adamodar/New_Home_Page/data.html.

to finance the necessary transfers, albeit with yet more considerable intertemporal wealth transfers domestically.

6. CONCLUSION

The ineffectiveness of the Kyoto Protocol and the constraints facing the success of the Paris Accord arise from hesitation among nations in the face of costly mitigation actions, combined with incentives for smaller regions to free ride on the commitments of larger ones. Because the uniform carbon taxation scheme offers a simple and internationally transparent negotiation target on the one hand and a comparatively efficient economic policy measure on the other, we adopt it as a policy model to explore and quantify these strategic issues.

The effects of varying numbers and sizes of regions that might commit to such a tax are considered by conducting simulations of a global economic model and combining these with the results from a meta-study of the temperature and economic welfare impacts of alternative levels of global carbon emission. Three IPCC temperature rise cases are considered: “low”, “best” and “high”. These yield quite different economic gains from moderating the rise in average global surface temperature. In the “best” case, the results suggest that the absence of further carbon mitigation will see the average surface temperature rise by four degrees Celsius, bringing with it a loss to the global economy of 15 per cent of its GDP. In the IPCC “high” temperature case this impact is almost doubled. More modest results emerge in the “low” temperature case. When mitigation is added via carbon taxation at 20 USD per tonne, five key conclusions emerge.

First, the more widespread is the implementation of the tax the more the global terms of trade is shifted in favour of just a few comparatively energy-efficient regions, including the EU and Japan. Gains to these regions stem both from the abatement and hence lower temperatures as well as from these terms of trade improvements. Second, in the “best” and “high” IPCC temperature scenarios, in present value terms the U.S. and China would derive positive net economic gains from their unilateral implementation of the tax, irrespective of the behaviour of other regions.

Third, in the “best” scenario, the large carbon-emitting regions, namely the U.S., the EU, and China, have sufficient individual effects on the global climate that the gains each would derive from their joint implementation of the tax, and hence their unilateral effects on the global surface temperature, exceed their collective economic costs of implementing it. Together, they face a purely economic incentive to implement the carbon tax that does not depend on whether other regions choose to do so. This finding contradicts the analysis using the DICE-Coalition model by Nordhaus (2015), with their pessimistic result ruling out a coalition without penalties. It does, however, confirm the “small paradox” theory of Barrett (1994; 2003). It also highlights the crucial role of China, rather than Japan, in global climate policy.

Fourth, in the “best” IPCC temperature scenario, were they able to coordinate, China, the U.S. and the EU would choose to implement the tax collectively. The question then arises as to whether the additional gains they would derive (via lower temperatures and further terms of trade changes) were the remaining regions also to implement the tax would be sufficient for them to afford side payments large enough to induce the other regions to do so. Our results show that, so long as future benefits and costs are discounted at the 2017 ten-year Treasury bond yield, their additional gains are quite sufficient to finance such side payments. At higher rates of discount, only the IPCC “high” temperature scenario yields net gains to the big three that are large enough to compensate other regions for participation. Indeed, at these higher discount rates, strategic interaction between the U.S. and China is heightened in the “best” temperature scenario, with only one facing unilateral net gains from implementation. When one commits to abatement policy the other will free ride.

Fifth, and finally, it is shown that carbon abatement policies will be politically difficult to implement by all countries, even the U.S. and China, which are the only unilateral gainers under the "best" temperature scenario. This is because the annual net gains do not turn positive for at least two decades. This finding suggests pessimism about the potential for implementation in the "anchor" regions but, moreover, since no side payments would be affordable in the first two decades, the potential for wider coalition building also looks bleak. Nonetheless, even though net benefits are negative in the early decades, implementing regions would be generating considerable public revenue from the taxes and these could be a source of inducement through global redistributions. Yet, even this would require strong forward-looking behaviour by governments.

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