Online Appendix to

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to Overcome Free Riding in International Climate Policy"

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Contents of Appendix

A. Representative Modeling Results of Climate Coalitions

A substantial literature has developed over the last four decades on the theory and modeling of global public goods with special attention to climate change. This section provides a review of some of the key studies with a focus on those that examine the game theory and modeling of coalitions of countries.

Carraro and Siniscalco (1993) examined the issue of free-riding in international environment agreements for global public goods. They showed that only a small number of countries would participate in their prototype agreements, but even those agreements would require the ability to make and enforce binding commitments. This was an early study finding the small coalition paradox.

Chandler and Tulkens (1995) provided an analysis of the potential for cooperative agreements in arrangements with global public goods. They find that it is not possible within their setup to have stable cooperative equilibria without transfers, although in limited cases efficient abatement can be obtained with transfers. However, their results depend upon the concept of a "γ core." This assumes that any single defection will lead to a complete disintegration of the coalition (called a "grim treaty" after grim trigger strategies), see Chandler (2007).

The assumption is therefore based on a kind of doomsday scenario that discourages defections from participation. Such a strategy is not renegotiation-proof because it harms the penalizer as well as the penalized and is therefore an unattractive agreement.

Yang (1999) examined the potential of technological transfers to induce cooperation. This study has a theoretical and empirical analysis of how transfers can improve the overall abatement. It finds that the non-cooperative outcome can be improved, although it requires substantial transfers from North to South to induce cooperation. Further studies of coalitions are in Yang (2008).

Bosetti et al. (2012) analyzed the coalition stability in the WITCH integrated-assessment model. This study concluded that only the coalition of all regions is able to attain the ambitious climate change objective of maintaining GHG concentration below 550 ppm CO_2-e. However, this coalition is unstable even with monetary transfers. The study found that smaller coalitions may be stable. The basic result – inability to find stable coalitions that can achieve significant emissions reductions in an agreement without penalties – is representative of models that find the small coalition paradox.

Similarly, Finus, Altamirano-Cabrera, and Van Ierland (2005) use a 12-region model to investigate potential climate treaties without penalties. They analyze "open" v. "closed" membership clubs in a one-shot game that covers 100 years. They find that no non-trivial coalition is stable with open membership. Similarly, a study of climate regimes by Weikard, Finus, and Altamirano-Cabrera (2009) confirms the potential for instability in climate agreements with transfers. They examined an integrated assessment model with 12 regions and six alternative sharing rules. They found that regimes have stable coalitions with only a small number of participants (generally two) and can attain only a small fraction of potential benefits, confirming the small coalition paradox. Moreover, the six sharing rules generate 18 different stable coalitions, and 14 of these are distinct. This shows dramatically how bargaining over the sharing rule can generate coalition instability.

A general survey of the economics of treaties with special reference to global public goods is Barrett (2003). This volume is especially valuable for a development of the theory and for case studies of the major international environmental agreements. It is not possible to summarize the major findings. Suffice it to say that this should be the starting point for those who are looking for the major issues and policies in this area.

B. Structure of the C-DICE Model and Model Analyses

This section describes the structure and the sources of the data for the Coalition-DICE, or C-DICE model. The modeling and calibration was undertaken with Paul Sztorc (hence "we" in this appendix), although Nordhaus takes responsibility for the procedures and results. Note that an early version of the model was called "TRICE," but the current name is more accurate.

I. Sources for the C-DICE model

All files and programs are contained in a zip folder labeled "ModelDetails-CDICE012015." This has three folders, "Excel," "Eviews," "Ossa," and "Appendix." The first two folders contain the models and a brief set of instructions. The third is the programs and description for use of the Ossa model. The last contains this appendix.

The basic source for the C-DICE model is an Excel spreadsheet. The public version for the published version is "aer-prog-simn15-102714c.xlsm." This program contains a sheet with instructions for operation.

The model was also programmed in Eviews. The program is "sim-0102714a.prg," while the inputs data called for in the program is "input-data-102714alt.xls." This can be used with any Eviews workfile. A simpler version that does not require the input data from the Excel file is "sim-0102714a-withdata.prg." This must be used with the Eviews file "res-sim15-ev-102714-withdata.wf1," which contains the input data.

Note that the two platforms give identical results except for unstable regimes.

II. Modeling structure

The basic C-DICE model is an Excel spreadsheet model that is run with a few simple macros. The structure is outlined in the main text. Here are the following major building blocks:

a. Macroeconomic and environmental data for 15 countries or regions.
b. Bilateral trade matrix for 15 x 15 regions.
c. Bilateral terms-of-trade gains or losses for 15 x 15 regions.
d. Efficiency losses for each element of the 15 x 15 elements of the trade matrix.
e. A routine to select randomly a sub-coalition from the 15 regions to see if they can improve their status by changing their participation status.
f. A routine to check whether the new pattern of incomes for the sub-coalition in (f) is weakly Pareto improving for its members.

g. A routine to substitute the new participation status from (f) if it passes the test in (f).

The model was also coded in EViews to check for coding and other errors. Both programs contained several errors in the initial round. After finding and removing the errors, they produced identical results (except for unstable regimes).

III. Major economic and policy parameters

The major input parameters for each regime are as follows:

a. The tariff rate associated with non-compliance (from 0 to 10%).
b. The global social cost of carbon ($12.5, 25, 50, and 100 per ton CO_2).
c. The international treaty carbon price (same as b).
d. The optimal tariff rate (% ad valorem).
e. The net output gain of the levying country associated with the optimal tariff (% of income).

IV. Damages and social cost of carbon

The estimates of the social cost of carbon by country are based on Nordhaus (2014). The following describes their derivation. Several models calculate the SCCs of different regions. These are the marginal impact of emissions on the economic welfare of a particular country or region. Table B-1 shows the estimates of regional SCCs for three widely used models that include damages, the DICE-RICE model, the FUND model, and the PAGE model. Damages are roughly proportional to discounted GDPs, with some countries deviating from this rule because of different climate-impact sensitivities. These numbers indicate that there is little consensus on the distribution of the SCC by region except that no region dominates the total. The different estimates reflect the poor understanding of the impacts by region. The derivation is described more fully in Nordhaus (2014).

Table B-2 provides the estimates of national SCCs used for the present model and two sensitivity analyses described below. The first column is the estimate based on national GDPs. The second column shows the estimates from the RICE 2010 model. The third column shows estimates based on the average of the three models shown in Table B-1. We have used the estimates in in the first numerical column but have conducted sensitivity studies with the alternative estimates.

V. Abatement costs

There are many studies of abatement costs, although the regional resolution outside the large high-income regions is generally poor because of lack of data or incomplete studies. Many models have several regions, but the reliability of the estimates is low. The latest estimates of mitigation costs by the IPCC (IPCC Fifth Assessment, Mitigation 2014) provided little guidance on regional mitigation costs.

The present estimates are based on a combination of detailed regional abatement cost estimates by McKinsey with aggregate estimates of abatement costs from the DICE-2013R model.

The first step was to determine the aggregate abatement cost function. For this purpose, I assumed that abatement cost is quadratic in the emissions reduction rate, as in the equation in the main text, $A = \alpha \mu^2 Q$, where A = abatement cost, Q = output, E = actual emissions, $\bar{E}$ = uncontrolled emissions, α is the abatement-cost parameter, and μ = emissions control rate $= (\bar{E} - E) / \bar{E}$. For this purpose, we calibrated the function at the carbon price (marginal cost of emissions reductions) of \$25 per ton CO_2. The result in the C-DICE model is a global 18% emissions reduction at a carbon price of \$25 per ton of CO_2.

The next step was to collect estimates of regional abatement costs from the study by McKinsey Company (2009). This study provided estimates of the cost and fractional reduction of CO_2 and other GHGs for 17 regions, including most of the ones included in the present study. It calculated the fractional abatement that could be attained for incremental costs of less than €60 in 2020 and 2030. The estimates are shown in Table B-3. From these estimates, I then obtain estimates for each region of the parameter of the abatement cost function shown in the last paragraph *(α)*. Table B-4 shows the estimated abatement cost parameters for the different regions calculated from the McKinsey study. The C-DICE model uses the estimates average for 2020 and 2030.

There have been many criticisms of the McKinsey approach as being overly optimistic – for example, ignoring embedded capital costs. For the present purposes, I assume that, while the estimates may be biased, there is no systematic bias across countries.

The final step is to adjust the McKinsey regional parameters to the estimates of the global abatement cost function. This is accomplished by scaling the regional parameters by a common factor to obtain the aggregate results from the DICE-2013R model described above. The scaling factor was 0.837. The interpretation is that the McKinsey cost curves overestimated abatement costs slightly relative to the DICE-model estimates.

Table B-5 shows the abatement cost parameters used in the study along with the carbon intensity of production. The interpretation of these is the following. For a given carbon price, the abatement-cost parameters are proportional to the carbon-output ratio because the higher that ratio, the more carbon there is to reduce at a given percentage reduction. The abatement cost parameters are inversely proportional to the percentage reduction that can be attained at a given carbon price. This indicates the "steepness" of the carbon abatement cost function.

Figure B-1 shows a scatter plot of the carbon intensity and the abatement cost parameter. Clearly, the carbon intensity is an important determinant in these estimates.

VI. Reduced-form tariff benefit function

a. *Basic analysis*

A key feature of the C-DICE model is the impact of tariffs on the net income of countries. For example, suppose that country A places a 1% ad valorem tariff on the imports of country B starting from a zero-tariff equilibrium. The impact will be efficiency losses in both countries from the price distortion caused by the tariff. Additionally, because countries have market power, prices will change. We would generally expect that country A would have an income gain from the terms-of-trade effect, while country B would have a corresponding loss.

The impacts of tariff changes are calculated in different international trade models, but including a full international trade model is unnecessarily complex for the purpose of calculating the impacts in a study of coalitions. Instead, I have calculated a reduced-form function that calculates the net economic impact on countries as a function of the tariff rates. The functions take the form:

Net impact = Efficiency impacts + terms-of-trade impacts

Based upon first-order impacts, I assume that the efficiency impacts are quadratic in the tariffs because the Harberger triangle efficiency losses are a function of the square of the tariff. Similarly, the terms-of-trade effects are assumed to be first-order or linear in the tariff. I therefore estimate the net impact on the income of region *i* of a tariff on country *j* as:

$$\Delta Y_{ij} = T_{ij}(\alpha_{ij}\tau_{ij} - \beta_{ij}\tau_{ij}^2)$$

Here, ΔY_{ij} = the net income gain by country *j*, τ_{ij} = the ad valorem penalty tariff rate levied by country *j* on country *i*, T_{ij} = the imports from country *i* into country *j* (in $), and α_{ij} and β_{ij} are parameters of the reduced-form tariff function. I determine the parameters of the tariff function by two values. The first is the optimal tariff level, and the second is the change in income of country *j* per unit tariff change, as discussed below. These two estimates uniquely determined the two parameters of the reduced-form function.

Estimates of the optimal tariff rate are currently poorly determined. Figure B-2 shows estimates from 3 different studies. Clearly, there are major disagreements depending upon the data and the methods. For the present study, I have taken the results of Ossa (2014). For a further discussion, see Costinot and Rodríguez-Clare (2014). The Ossa study indicates that the mean optimal tariff without lobbying is close to 60%, with an average own impact of 2.2% and an average impact on other countries of -0.7%. A sample of the results is shown in Table B-6. One surprising result of the Ossa study is that the optimal tariff is almost invariant to country size. The size of the optimal tariff may also surprise people, but it is actually the middle range of the three sets of estimates.

b. *Details of the calibration*

To calibrate the reduced-form trade model, Paul Sztorc and I calculated the two parameters using the trade-wars model of Ralph Ossa (2014), hence the use of "we" in this section. This note summarizes the calibration and the performance. Details on the modeling and the R code for making the estimates is contained in Sztorc (2014) and in the "Ossa" file of the online materials.

1. We first received the data and program from Ralph Ossa. This was implemented in MatLab. We replicated the Ossa results on the optimal tariffs and most other findings.
2. We next calculated the impact of alternative tariff structures by running the Ossa model. This involved estimating the impact on the net national income (NNI) of each region for a set of uniform additional or penalty tariffs ranging from 5% to 70% ad valorem. In all cases, the penalty tariffs were added to the existing tariff rates. Each calculation was done for all different combination of clubs (i.e., for each pair of countries and for each of the roughly 2^{15} coalitions. For example, we calculate the impact on the US of a 5% US import tariff when the US is in a club of 3 (say composed of US, EU, and Japan). Similarly, we calculate the impact when regions were not in the club for clubs of different sizes.
3. We then estimated a surface response function (SRF) of NNI for each country and club size. The SRF was quadratic in the tariff rates with the intercepts forced to be zero.
4. The next step was to determine which parameters in the C-DICE model would be adjusted. The C-DICE model reduced form function is of the form $\Delta Y_{ij} = T_{ij}(\alpha_{ij}\tau_{ij} - \beta_{ij}\tau_{ij}^2)$. In this equation, α_{ij} are the linear terms of the reduced-form function and β_{ij} are the quadratic terms of the function. The model is parameterized by two matrixes $[\alpha, \beta]$, where the α and β are 15x15 matrices of the two parameters. In the quadratic structure of the C-DICE model, the optimal tariff is equal to $\beta_{ij}/2\alpha_{ij}$.
5. To calibrate the model, we first set the optimal tariff at the level estimated by the Ossa model. Note that our estimates are different from those in Ossa

because we use uniform tariffs across industries. We then vary the income scaling parameter for each country ($\alpha_{1,1}$, α_{i2}, …, $\alpha_{15,15}$) while keeping the optimal tariff unchanged (and therefore keeping the ratio $\beta_{ij}/2\alpha_{ij}$) unchanged. Note that the $\alpha_{i,i} = 0$, which is correct for countries by not necessarily true for aggregates of countries.

6. We assume that the optimal tariff is the same when imposed by a country on other countries. In other words, the US optimal tariff is assumed the same for tariffs on Japan and Brazil.
7. To determine the scaling parameters, we calculated the average impact on each country of a 5% penalty tariff for clubs size 1 for in and (n-1) for out. This rate was chosen because the range of tariffs used in the model was between 0 and 10%, so we wanted to ensure that the reduced-form estimates were accurate in this tariff range. We calibrated the reduced form model so that it closely matched the estimates from the Ossa model at the 5% tariff for the "in" countries. In other words, the parameters for the US were set so that the impact on US NNI of a tariff of 5% on all other countries (other countries not responding) would be approximately equal in the C-DICE and the Ossa model.
8. We note that the estimated impact of a 5% tariff when the country is "out" is imperfectly estimated by this procedure, as discussed below.

The results were imperfect because we are selecting only one scaling factor for each region. The following shows the results of the calibration for two sets of tariff results. These are the effect of being in or out of the club for each of the seven Ossa regions. Figure B-3 illustrates the tariff function for tariffs imposed by the US on other regions in the Ossa model. The upper line shows the impact on US welfare, while the downward sloping lines at the bottom show the impacts on other regions. This graph illustrates clearly the optimal tariff structure.

c. *Results of the Calibration*

We next show the results of the calibration of the C-DICE model to the Ossa calculations. Figure B-4 shows the estimates of being in or out of the club for the C-DICE model as well as being in a club of 1 for the Ossa model. For each case, the impact is for a uniform tariff of 5%. The calculations show the impact of joining a club of 1 (the only participant) for the Ossa model and the C-DICE model, as well as being out of a club of 14 (the only non-participant) for the C-DICE model. The model is well-calibrated for all countries except Japan, which has very distorted tariff structure. The average impact of "in" for the six regions is identical at 0.335% for both the C-DICE and Ossa models. As a test, the estimate for the US for a 10% tariff in a club of 1 is virtually identical in Costinot and Rodríguez-Clare (2014), Figure 4.1.

There are many different comparisons possible with the Ossa/C-DICE models, indeed about 4500 region-club-size combinations. We tested the C-DICE model against the Ossa model for a few clubs of intermediate sizes to determine whether the calibration (to clubs of 1) was reasonably accurate for other clubs. The C-DICE model tends to underestimate the costs for solitary countries who are the only ones "out" of a grand coalition. For intermediate sized clubs, the model performed well. For example, for the Kyoto club (US, EU, and Japan), the C-DICE model predicted that the US would gain 0.37% of NNI, whereas the Ossa model calculated a gain of 0.42%, for a five basis-point error. The results for the EU for the two models were exactly the same to the one-basis-point level of accuracy, while those for Japan were off by 1 basis point. Since the Ossa model itself differs markedly from other estimates of the gains and losses from tariffs, we take the results for the intermediate sized clubs as essentially identical for the two models.

VII. *Implications of aggregation*

Note that the aggregation of countries into the regions such as Latin America will tend to increase slightly the non-cooperative carbon price and control rate. Additionally, it will simplify the bargaining because it excludes smaller states, which have much larger incentives to free-ride, from the bargaining calculations.

Side calculations indicate that the global Herfindahl index of GDP is overstated by around 2 percentage points as a result of aggregation, indicating that the aggregation error is small. This suggests that most of the results would be reproduced if sovereign countries or treaty-aggregates like the EU were taken to be the bargaining units. However, recall that the computational complexity is in the order of 2^n, where n is the number of regions.

VIII. *Sensitivity analysis*

It is useful to determine how sensitive the results are to alternative parameters. The study has emphasized the importance of the global SCC and the penalty tariff rate. Additionally, both theory and experimentation indicated three other parameters that might affect the outcome: the regional distribution of the global social cost of carbon, the abatement cost, and the optimal tariff rate. I discuss briefly the impact of changing these parameters on the results.

a. *Alternative regional SCCs*

Starting with the regional SCCs, I chose two alternatives: one from the RICE-2010 model and the other being the average of the three major models (see Table B-

2). The regional dollar values of the SCCs were scaled to total the global SCC for each of the four cases ($12.5, 25, 50, and 100 per ton of CO_2).

For the stable regimes, there were one or two changes in the numbers of participants, but the average was virtually identical. The insensitivity of results to regional SCCs is not surprising since it is the global total rather than the exact distribution of the global SCC that affects participation rates. The conclusion here is that for the major variables of interest, there was no appreciable impact of the alternative distributions of the SCC.

b. Abatement-cost parameter (ACP)

Next turning to the abatement-cost parameter, recall that the abatement-cost function is $A_i = \alpha_i \mu_i^2 Q_i = \alpha_i [(\bar{E}_i - E_i)/\bar{E}_i]^2 Q_i$. For the sensitivity analysis, the abatement-cost parameter (α_i) was varied by plus and minus 50% of the base parameter uniformly across all regions. This range represents the difference in estimates across different integrated assessment models.

The results showed moderate sensitivity to the abatement-cost parameter (ACP). The participation rate declined in some of the marginal cases for a lower ACP. For example, at the lowest tariff rates of 1% to 5% and a SCC of $25, the participation rate declined by from 1 to 5 regions. Examining stable regimes, for the lower ACP the average number of participants declined by 1.2, while the average carbon price declined by $4 per ton, or about 20%. There was much less sensitivity of higher ACP, however. For the higher ACP with changes in the outcome, the average number of participants rose by 0.7.

c. Optimal tariff rate

A final sensitivity experiment varies the optimal tariff rate (OTR). For this test, I varied the OTRs between 25% and 150% of the estimated level in the Ossa model, changing the OTRs uniformly for all regions. The lowest estimate is at the low end of the studies examined in the appendix. Additionally, other specifications (such as those with intermediate products and monopolistic competition) produce much higher gains from trade, and therefore presumably higher coefficients in the tariff function, but the tariff reduced forms have not been calculated for these models.

With the exception of one regime, there were no changes in the outcomes of changing the OTR on participation in the stable regimes. The only sensitivity was at the highest target carbon price of $100 a ton and penalty tariffs of 5% and above. However, it is not possible to tell whether the impact of changing the OTR was because of the instability or because of the changed parameter. In the unstable regimes, the average participation rate was lower for the low OTR, which is intuitively clear since the terms-of-trade losses are smaller. There was no change in the participation rate for the higher OTR for any regime. So the summary is that the level of the optimal tariff makes no difference to the outcome in the range of from 25% to 150% of the central rate. However, it may tilt the equilibrium toward lower participation in unstable cases. The reason why changing the OTR has little difference is that the tariff function is close to linear over the range of penalty tariffs examined here.

In summary, the sensitivity analyses indicate that the major parameters that can affect the results are the global SCC and the abatement-cost parameter. All the other parameters tested had either no effect or an economically insignificant effect on the coalition size, the global carbon tax, or the gains from the club over the tested range.

IX. Testing and Reliability

A word about testing and reliability: The algorithm was initially written in Microsoft Excel and requires only a few simple macros. It contains approximately 4500 lines of code (that is, formulas in individual cells) for the Excel spreadsheet program and 50 lines of code for the macros.

Prior experience has shown that it is extremely difficult to root out errors in integrated assessment models (see Nordhaus and Sztorc 2013). A more robust procedure is to recode the problem independently in a different platform. We therefore recoded the model and algorithm in EViews 7.0. This provided less transparent output but it was also much faster and most important provided an independent check. The Eviews program contains approximately 270 lines of code. Both programs initially contained errors even after weeks of multiple careful checks. However, the errors were discovered by comparing the two sets of outputs, and the two platforms eventually provided identical results. (Different results were found for unstable coalitions, which provide different results for different starting points for each platform.)

An additional test is the sensitivity of the results as data are refined and updated. The results have shown small changes in the exact numbers, but the general patterns of participation and abatement are robust to changes.

To calculate the equilibria, with 4 SCC values x 11 tariff rates x 2 restarts x 20,000 iterations, the computations takes about 6 hours on a standard PC. However, for the stable regimes, the average number of iterations is around 200 for both Excel and Eviews, and the maximum is almost always less than 1000. Since stability can only be determined probabilistically, with 2^{15} coalitions, and in the worst case situation, we would need 300,000 iterations to reduce the probability of missing an alternative regime below 0.01%. Given that we have run approximately 50 million iterations without an examples of overturning a small number of iterations outside of unstable regimes, it is reasonable to conclude that the structure of the model is one in which the answer converges quickly on the stable coalition, if there is one, at a rate much quicker than the theoretical speed.

X. Kyoto Collapse

The main text discussed the evolution of the Kyoto Protocol using the structure of the C-DICE model. To test the coalition stability of the Kyoto Protocol, I formed a Kyoto club with the original Kyoto Protocol countries with emissions commitments in the Club; all other countries were outside the Club; and there with no penalties for non-compliance or non-participation. Starting from the original Kyoto coalition status, I then allowed combinations of countries to join or defect, as described above. Figure B-5 shows the evolution for 10 different simulations using the C-DICE model. They all collapse to the non-cooperative equilibrium, as the theory would predict.

XI. Voting Equilibrium

The calculations of the preferred carbon prices by regions were computed as follows. The SCC was set at $25 per ton, and the penalty tariff was set at 5%. This relatively high tariff level was set to avoid complexities that arise when participation changes and there are major trade effects. The coalitions were then calculated for international target carbon prices of $0 to $200 per ton. Full participation was achieved for prices up to $34 per ton of CO_2, which removed trade effects. The coalitions were stable except for several with carbon prices from $55 to $68 per ton. These were removed from the compilations.

For target carbon prices with full participation, the net benefits were close to quadratic, and the maximum was generally in the full-participation regime. Some regions had net benefits at higher levels with partial participation, but these were generally excluded. Instead, I chose the *lowest* preferred price if there were multiple local equilibria.

The breakeven carbon prices were generally unambiguous. However, for countries with high preferred prices, the breakeven sometimes came with 0 participation (the NC equilibrium), which occurred at around $100 per ton C. There were instabilities in the range of $60 to $100 per ton, so we truncated the breakeven at $60. This choice affected the mean but not the medians of any calculations.

XII. Background Data

Tables B-7 through B-10 provide the numerical data behind the figures in the main text. Note that unstable regimes are approximations based on quasi-stable coalitions. For example, for the regime with a SCC = $50 and a tariff rate of 3%, 10 cold restarts give three different quasi-stable coalitions; the runs have an average number of participants of 8.6, with a minimum of 6 and a maximum of 9 regions.

Region	Emissions (Billions of tons CO2, 2005)	SCC (2015)	RICE 2010	FUND 2013	PAGE 2011
			Percent of global SCC		
US	6.11	1.94	10	17	7
EU	4.14	2.32	12	24	9
Japan	1.28	0.43	2	3	na
Russia	1.54	0.18	1	10	na
Eurasia	0.92	0.16	1	na	na
China	6.14	3.02	16	8	11
India	1.48	2.21	12	5	22
Middle East	2.14	1.89	10	na	na
Africa	0.69	2.09	11	6	26
Latin America	1.54	1.30	7	na	11
OHI	1.93	0.74	4	na	na
Other	1.38	2.29	12	na	na
Weighted country average		1.92			
Global	29.30	18.6	100	100	100

Table B-1. Estimate of the Regional Social Cost of Carbon

Source: Nordhaus (2014)

Region	Proportional to GDP by region	RICE 2010 model	Average of three models
Brazil	3.1	2.4	2.9
Japan	4.8	2.3	2.4
EU	18.5	12.1	13.8
SSA	2.3	7.2	7.4
Canada	1.6	0.9	1.0
US	17.0	10.2	10.6
LatAm	5.6	4.4	5.2
ROW	6.2	9.7	10.0
SEAsia	7.3	12.1	12.5
Mideast	6.5	6.4	6.5
Russia	3.5	3.4	3.5
India	6.5	11.6	11.7
Safrica	0.7	0.7	0.7
China	14.8	15.8	11.0
Eurasia	1.6	0.9	0.9
WORLD	100.0	100.0	100.0

Table B-2. Assumptions about SCC by region for C-DICE model and two alternatives for sensitivity analysis

GtCO$_2$e per year		BAU Emissions			Abatement potential	
Region Cluster	Country/region	2005	2020	2030	2020	2030
North America	Canada	0.6	0.8	0.9	0.2	0.4
	United States*	6.8	7.7	8.3	2.0	4.7
Western Europe	France	0.5	0.6	0.6	0.1	0.3
	Germany	1.0	1.1	1.1	0.2	0.4
	Italy	0.6	0.6	0.6	0.1	0.2
	United Kingdom	0.6	0.6	0.6	0.1	0.2
	Rest of EU27	2.2	2.4	2.6	0.7	1.6
	Rest of OECD Europe	0.4	0.5	0.6	0.1	0.3
Eastern Europe	Russia	2.4	2.9	3.0	0.7	1.5
	Rest of Eastern Europe	0.7	0.9	0.9	0.2	0.5
OECD Pacific	Japan	1.3	1.5	1.4	0.3	0.6
	Rest of OECD Pacific	1.1	1.3	1.4	0.4	0.8
Latin America	Brazil	2.7	3.1	3.3	1.9	2.4
	Mexico	0.5	0.7	0.8	0.2	0.4
	Rest of Latin America	1.7	2.3	2.7	0.8	1.7
Rest of developing Asia	Rest of developing Asia	6.8	7.9	8.6	3.9	5.7
Africa	South Africa	0.4	0.6	0.7	0.2	0.5
	Rest of Africa	2.7	3.2	3.5	1.3	2.4
China	China	7.6	13.9	16.5	3.5	8.4
India	India	1.8	3.3	5.0	1.0	2.7
Middle East	Middle East	1.6	2.6	3.2	0.6	1.4
Global Air & Sea Transport	Global Air & Sea Transport	1.8	2.6	3.3	0.3	0.8
	Total	**45.9**	**61.2**	**69.9**	**18.9**	**38.0**

Table B-3. Estimates of Business-as-Usual (BAU) Emissions and Abatement Potential

Estimates are the abatement potential for different regions at a cost of less than €60 per ton of CO_2-equivalent of reductions. These use the standard bottom-up McKinsey technique. GtCO$_2$e is billions of tons of CO_2 equivalent emissions per year.

Source: McKinsey (2009).

	Unadjusted alpha			
Region	2020	2030	average	C-DICE
Brazil	0.00880	0.00583	0.00716	0.00599
Japan	0.05056	0.01797	0.03014	0.02523
EU	0.03671	0.01439	0.02299	0.01924
SSA	0.01066	0.00461	0.00701	0.00587
Canada	0.05828	0.03020	0.04195	0.03512
US	0.04931	0.02144	0.03251	0.02721
LatAm	0.02932	0.01408	0.02032	0.01701
ROW	0.01617	0.00969	0.01252	0.01048
SEAsia	0.02655	0.01490	0.01989	0.01665
Mideast	0.06951	0.03703	0.05073	0.04246
Russia	0.08906	0.03637	0.05691	0.04764
India	0.04744	0.02728	0.03597	0.03011
Safrica	0.08199	0.02987	0.04949	0.04142
China	0.10036	0.03559	0.05977	0.05003
Eurasia	0.10829	0.03194	0.05882	0.04923

TRICE scaling parameter = 0.837

Table B-4. Abatement cost parameters for regions from McKinsey study

The first two columns show the estimates are for two years and calculate the implicit abatement cost parameters in equation (3). The model uses the average of the two years, shown in the third column, as these are likely to correspond to the assumptions of the integrated assessment models. The last column shows the parameter adjusted to scale to the global reduction rate from the DICE-2013R model. The last column is used in the C-DICE model.

Region	Abatement cost parameter	Carbon intensity
Brazil	0.00599	0.167
Japan	0.02523	0.285
EU	0.01924	0.239
SSA	0.00587	0.144
Canada	0.03512	0.376
US	0.02721	0.365
LatAm	0.01701	0.272
ROW	0.01048	0.245
SEAsia	0.01665	0.364
Mideast	0.04246	0.367
Russia	0.04764	0.589
India	0.03011	0.365
Safrica	0.04142	0.786
China	0.05003	0.702
Eurasia	0.04923	0.695
Global	0.03337	0.380

Table B-5. Abatement cost parameters by region for C-DICE model

Table shows the estimated abatement-cost parameters. These are proportional to a region's carbon intensity and inversely proportional to the cost of reducing a given unit of emissions.

	Change in welfare		Optimal tariff
	Own	Other	(median)
Brazil	1.1%	-0.1%	56%
China	1.8%	-0.6%	59%
EU	1.9%	-1.0%	61%
India	1.7%	-0.1%	54%
Japan	4.0%	-0.3%	60%
RoW	2.9%	-1.7%	62%
US	2.3%	-0.9%	60%
Mean	2.2%	-0.7%	59%

Table B-6. Estimates of optimal tariff and welfare changes from Ossa

These are the estimates excluding lobbying. Source: Ossa (2014).

	Externality	Benefit of in for club of 1 (2% tariff)	Cost of out for club of 15 (2% tariff)
Region	Billions of US $ per year		
Brazil	3.84	1.20	1.16
Japan	4.00	4.33	8.47
EU	10.45	22.27	21.13
SSA	2.22	1.18	2.75
Canada	1.73	5.03	5.41
US	16.37	22.70	10.21
LatAm	6.15	5.18	6.50
ROW	8.94	9.77	8.19
SEAsia	14.30	17.19	15.45
Mideast	5.14	5.00	11.18
Russia	6.83	0.47	1.99
India	7.18	1.33	-0.05
Safrica	2.82	-0.08	-0.32
China	30.20	2.75	8.70
Eurasia	4.26	0.11	0.81
World	124.43	98.44	101.59

Table B-7. Estimates of Externalities as well as Benefits and Costs of Club Membership

Number of participanting regions

Tariff rate	International target carbon price ($/tCO2) 13	25	50	100
0%	0	0	0	0
1%	15	9	0	0
2%	15	13	3	0
3%	15	15	7	0
4%	15	15	9	0
5%	15	15	12	1
6%	15	15	13	1
7%	15	15	13	2
8%	15	15	13	3
9%	15	15	14	3
10%	15	15	14	6

Actual global average carbon price (2011$/t$CO_2$)

Tariff rate	International target carbon price ($/tCO2) 12.50	25.00	50.00	100.00
0%	1.41	2.82	5.65	11.30
1%	12.50	15.01	5.65	11.30
2%	12.50	23.19	14.10	11.30
3%	12.50	25.00	21.37	11.30
4%	12.50	25.00	30.03	11.30
5%	12.50	25.00	46.38	12.81
6%	12.50	25.00	46.38	12.81
7%	12.50	25.00	46.38	22.32
8%	12.50	25.00	46.38	25.75
9%	12.50	25.00	49.31	25.75
10%	12.50	25.00	49.31	52.02

Table B-8. Participants and carbon price by regime

These provide the data for Figures 3 and 4 in the text.

Global net benefit (billions of US$ per year, 2011$)

Tariff rate	International target carbon price ($/tCO2)			
	12.50	25.00	50.00	100.00
0%	3.96	15.85	63.40	253.58
1%	19.52	50.34	63.40	253.58
2%	19.52	72.97	97.39	253.58
3%	19.52	78.06	155.22	253.58
4%	19.52	78.06	199.45	253.58
5%	19.52	78.06	289.56	266.70
6%	19.52	78.06	291.47	266.39
7%	19.52	78.06	291.20	343.64
8%	19.52	78.06	290.88	368.82
9%	19.52	78.06	306.17	368.82
10%	19.52	78.06	306.06	664.29

Gain as share of potential gain (cooperative v non-cooperative)

Tariff rate	International target carbon price ($/tCO2)			
	12.50	25.00	50.00	100.00
0%	0.000	0.000	0.000	0.000
1%	1.000	0.554	0.000	0.000
2%	1.000	0.918	0.137	0.000
3%	1.000	1.000	0.369	0.000
4%	1.000	1.000	0.547	0.000
5%	1.000	1.000	0.909	0.013
6%	1.000	1.000	0.917	0.013
7%	1.000	1.000	0.915	0.090
8%	1.000	1.000	0.914	0.116
9%	1.000	1.000	0.976	0.116
10%	1.000	1.000	0.975	0.413

Table B-9. Participants and carbon price by regime

These provide the data for Figures 5 and 6 in the text.

Impacts by regime for 11 selected regimes
Net benefit (billions of US$ per year, 2011$)

Regime	Brazil	Japan	EU	SSA	Canada	US	LatAm	ROW	SEAsia	Mideast	Russia	India	Safrica	China	Eurasia	Sum
Tar=3%; SCC=$12.5	0.56	1.12	4.54	0.51	0.32	3.03	1.07	0.89	0.47	1.54	0.31	1.25	-0.12	0.06	0.00	**15.55**
Tar=3%; SCC=$25	2.25	4.49	18.17	2.03	1.27	12.14	4.29	3.57	1.90	6.14	1.25	4.99	-0.49	0.23	-0.01	**62.21**
Tar=6%; SCC=$25	2.25	4.49	18.17	2.03	1.27	12.14	4.29	3.57	1.90	6.14	1.25	4.99	-0.49	0.23	-0.01	**62.21**
Tar=2%; SCC=$50	1.60	2.30	9.12	0.60	2.86	5.91	3.00	-1.39	1.46	-1.48	-0.13	3.90	0.26	6.14	-0.14	**33.99**
Tar=3%; SCC=$50	4.23	4.30	28.66	1.53	6.39	16.72	7.80	-1.14	-1.17	5.97	1.54	9.51	0.37	6.62	0.49	**91.82**
Tar=4%; SCC=$50	4.71	9.07	46.48	4.07	2.19	18.46	7.13	4.61	5.89	12.73	2.76	13.96	0.49	2.49	1.03	**136.06**
Tar=6%; SCC=$50	7.93	16.20	67.47	8.05	4.53	43.07	15.02	13.17	6.59	23.76	3.61	23.13	0.36	-4.16	-0.66	**228.08**
Tar=8%; SCC=$50	7.93	16.20	67.47	8.05	4.53	43.07	15.02	13.17	6.59	23.76	3.61	23.13	0.36	-4.16	-0.66	**228.08**
Tar=8%; SCC=$50	8.00	16.29	68.27	8.32	4.56	43.59	15.08	13.64	7.23	24.36	3.63	19.64	-0.67	-3.81	-0.64	**227.48**
Tar=8%; SCC=$50	8.00	16.29	68.27	8.32	4.56	43.59	15.08	13.64	7.23	24.36	3.63	19.64	-0.67	-3.81	-0.64	**227.48**
Tar=10%; SCC=$100	19.84	9.95	141.13	10.07	5.05	31.47	11.31	10.76	4.68	33.00	17.16	51.89	4.14	52.52	7.76	**410.71**

Table B-10. Impacts by region and regime for selected regimes

These provide the data for Figure 7 in the text.

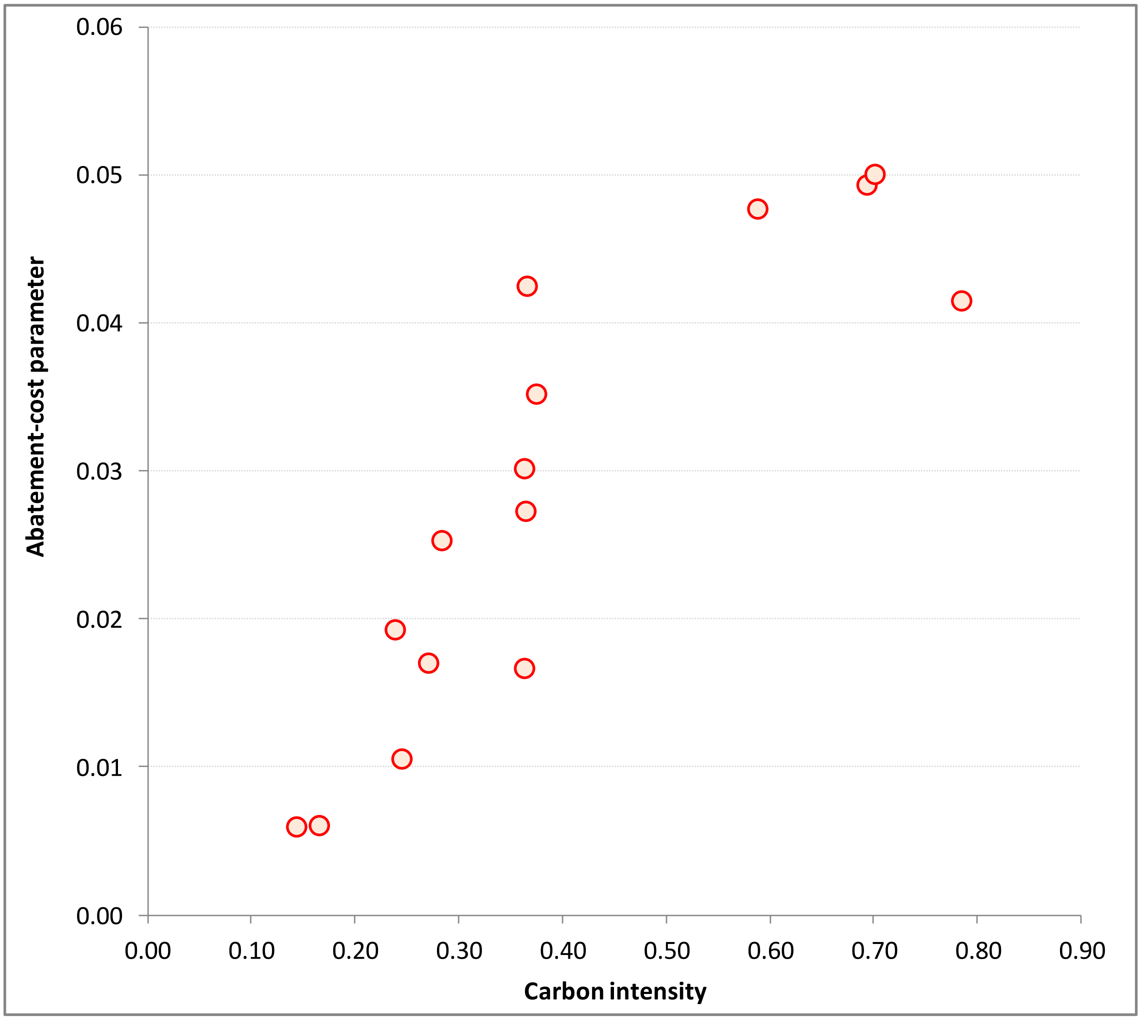

Figure B-1. Carbon-intensity and abatement-cost parameter for different regions of C-DICE model

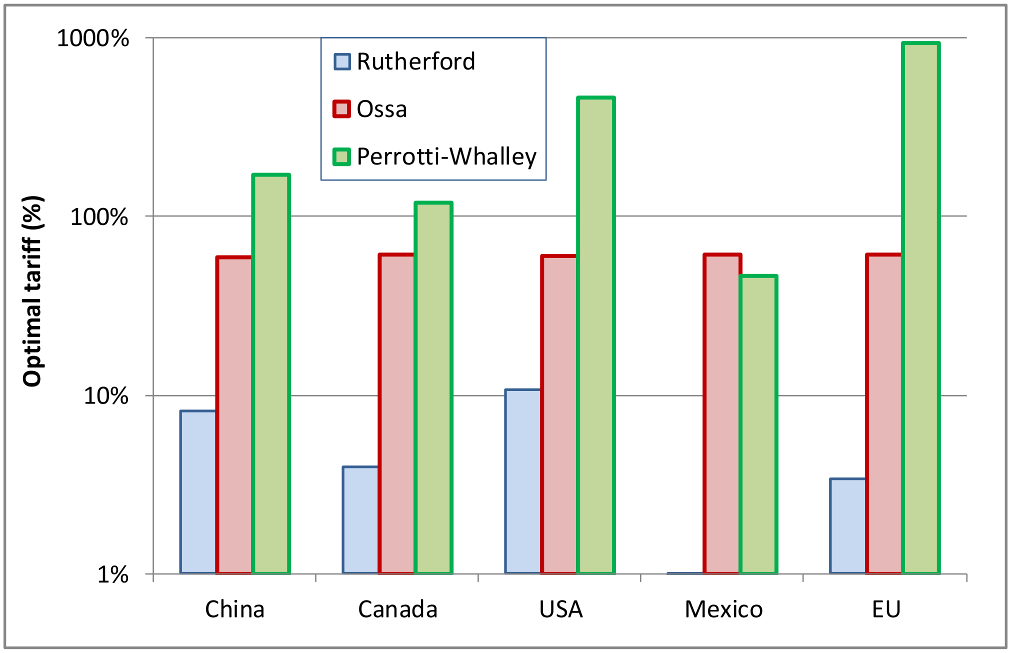

Figure B-2. Alternative estimates of the optimal tariff from three studies

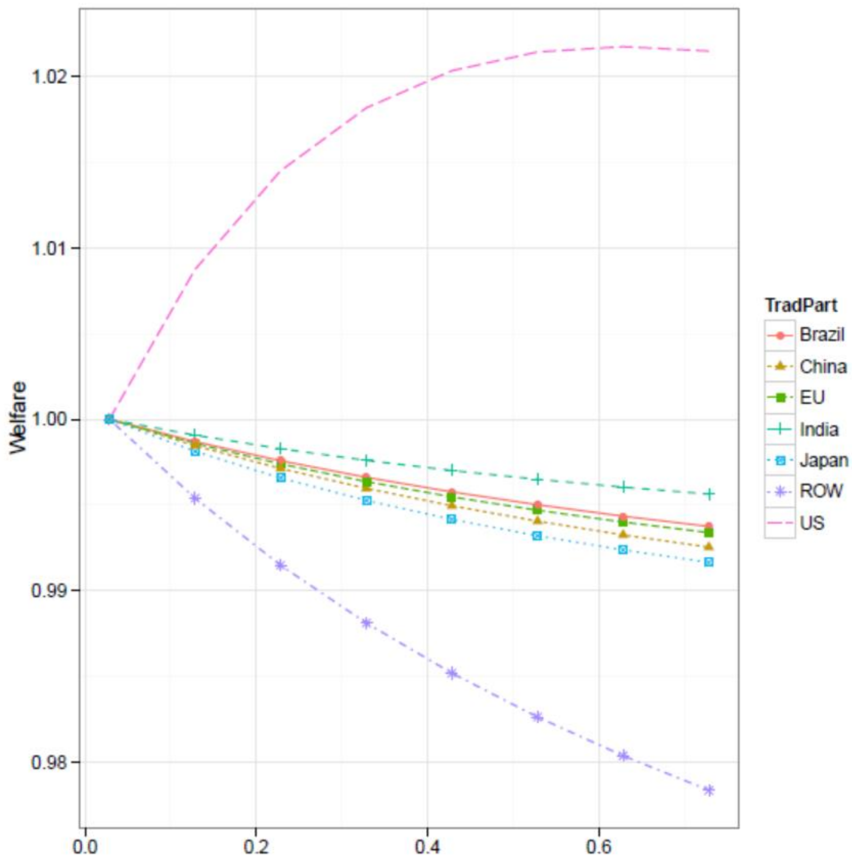

Figure B-3. Tariff function for the US

The figure shows the estimated impact of a uniform tariff levied on all other countries by the US. This is a “club of 1.” Tariff rates go from 0 to 70% on top of existing tariffs. Welfare is normalized at 1 for the base. Note that the US welfare is maximized at approximately a 60% tariff. Other regions are all harmed.

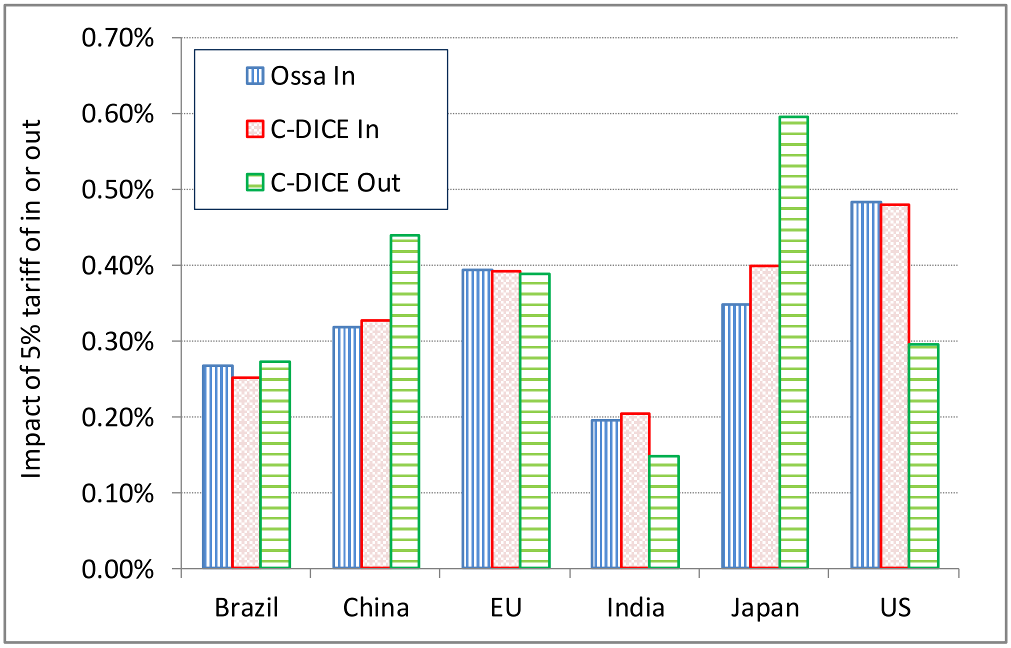

Figure B-4. Impact of 5% tariff for “In” and “Out” for six regions

Results of calibration of C-DICE to Ossa model. Bars show the impact on country for a 5% penalty tariff when a country is the only in country (“In”) or the only out country (“Out”), as well as calculation from the Ossa model for “In.”

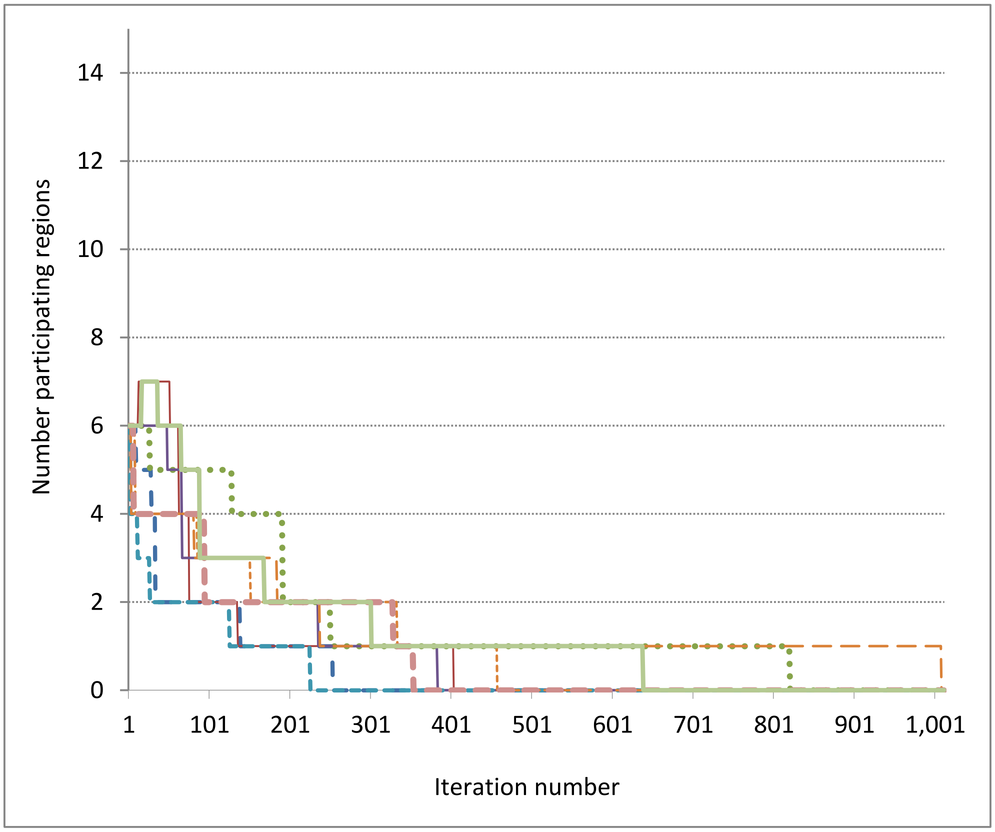

Figure B-5. Simulated Collapse of the Kyoto Protocol

Starting from the coalition structure of the Kyoto Protocol with no penalties for non-participation, the coalition gradually disintegrates because of the lack of incentives to cooperate.

C. Analysis of Bottom-Up Coalitions Using a C-DICE-type structure.

An empirical example was developed to test coalition stability in bottom-up coalitions using the structure of costs, damages, and emissions intensities assumed in equations (1) to (5) of the main text. The only assumptions that enter into the stability are the abatement cost function and the relative size of countries. In addition, we add the assumption that where there is a tie, the smaller number in the coalition wins.

The parameters of the model are world GDP, the number of countries, the parameters of the abatement cost function (described in the next paragraph), the global social cost of carbon, and global CO_2 emissions. The abatement cost function is of the general form $A_i = \alpha \mu_i^{\beta} \theta_i Q_w$. The C-DICE model assumes that $\beta = 2$, or that the function is quadratic.

The number of countries in the stable coalition is independent of all parameters except β. If countries are identical and $\beta > 2$, then the number of countries in the coalition is 2, while for $\beta < 2$, then the number of countries in the coalition is 3. When $\beta = 2$, as in the C-DICE model, both 2 and 3 are stable.

An interesting twist is the equilibrium with countries of different sizes. With different sized countries that approximate the distribution of country GDPs today, the number of countries in the coalitions is stable at 2 for all plausible values of β. The stable coalitions are EU and US, China and Japan, Brazil and Russia, India and Canada, and so forth. This is the best that can be done without any penalties for non-participation or other top-down features such as are introduced in the C-DICE model.

D. Analysis of Coalitions Using Carbon Duties Instead of Uniform Tariffs

As mentioned in the text, an alternative approach to penalties is the use of carbon duties. These are duties which are levied on the carbon content of imports. Modeling these in the C-DICE model is more difficult for two reasons. First, the trade elasticities of energy products tend to be quantitatively different from those of most other traded goods.

Second, it will prove difficult to measure the carbon content of trade for goods other than fossil fuels. For example, given that automobiles have an extensive fraction of their content in different countries, an accurate measure of that content is difficult. This second factor will lead countries to include only a fraction of imported embodied carbon in goods subject to carbon duties.

To get a rough estimate of the effectiveness of carbon duties as a mechanism to induce participation, I built a version of the C-DICE model using countervailing duties as a sanction. For this version, we assumed: (1) that exports have the same carbon-intensity as domestic production, (2) that 50% of trade could be captured by the sanctions mechanism (this being the fraction of EU emissions covered by the EU-ETS), and (3) the penalty rate was the difference between the cooperative carbon price and the non-cooperative carbon price calculated in the standard C-DICE model time the carbon intensity of products.

Preliminary modeling of this simple example indicates that a carbon duty approach appears much less able to promote effective abatement than the uniform tariff approach. Table D-1 shows the results for global SCC from $6.25 to $200. For SCC of $12.5 and above, the tariff is insufficient to induce significant participation. Note also that the effective carbon price is either low or at the non-cooperative level. The reason is that the effective tariff rate is much too small since it is levied only on the carbon context of part of imports.

SCC	Number participants	Average carbon price	
		Non-cooperative	Club
6.25	13	0.50	5.80
8.84	13	0.71	8.21
12.50	2	1.41	1.00
17.68	2	2.00	1.41
25.00	2	2.82	5.58
35.36	0	3.99	3.99
50.00	0	5.65	5.65
70.71	0	7.99	7.99
100.00	0	11.30	11.30
141.42	0	15.98	15.98
200.00	0	22.59	22.59

Table D-1. Results of Climate Club using duties on carbon content of imports

This table shows estimates of the participation rate when the tariff is calculated as the carbon duties divided by total imports. The tariff rate is usually in the order of 0.15% of trade. For this reason, it is too low to induce participation except at the lowest levels of the cooperative carbon tax (for SCC and cooperative carbon tax less than $10 per ton CO_2).

E. Major data and programs for C-DICE model

Appendices E through G contain three parts. Tables E-1 through E-3 provide the major input data for the C-DICE model for the 15 regions. E-4 shows the major countries in each of the regional aggregates along with their share of the region's GDP. Appendix F provides the Eviews code to run the evolutionary program. Appendix G provides the input data for the Eviews program (it is also available as an Excel file).

Region	GDP	Pop	per capita GDP ($)	Trade/GDP (%) [World Bank]	[UNCTAD]	Trade ($)
Brazil	2,816	197	14,301	10.6	8.6	242
Japan	4,386	128	34,316	14.1	18.4	805
EU	16,906	506	33,409	34.9	13.0	2,192
SSA	2,096	776	2,699	31.2	12.3	258
Canada	1,419	34	41,333	26.1	31.3	445
US	15,534	312	49,855	12.0	11.7	1,810
LatAm	5,065	394	12,865	19.7	13.6	688
ROW	5,660	893	6,341	22.7	19.9	1,127
SEAsia	6,676	390	17,114	28.2	28.8	1,922
Mideast	5,954	337	17,674	23.8	14.7	878
Russia	3,227	143	22,570	21.5	11.6	373
India	5,963	1,221	4,883	21.1	6.0	359
Safrica	614	52	11,910	27.3	16.4	101
China	13,496	1,344	10,041	23.5	12.8	1,734
Eurasia	1,434	143	10,061	33.2	14.8	212
WORLD	91,247	6,869	13,284	25.4	19.8	13,146

Note: GDP and trade in billions of international US $; population in millions. All pertain to 2011.
Trade data from World Bank and UNCTAD.

Table E-1. Macroeconomic Data

Region	CO2 (mt)	CO2/GDP	Social cost of carbon (% of world)	($/t at $25/t global	Optimal tariff	Abatement parameter
Brazil	470	0.167	3.1%	0.77	0.45	0.00599
Japan	1,250	0.285	4.8%	1.20	0.48	0.02523
EU	4,048	0.239	18.5%	4.63	0.55	0.01924
SSA	302	0.144	2.3%	0.57	0.53	0.00587
Canada	533	0.376	1.6%	0.39	0.53	0.03512
US	5,671	0.365	17.0%	4.26	0.59	0.02721
LatAm	1,378	0.272	5.6%	1.39	0.53	0.01701
ROW	1,389	0.245	6.2%	1.55	0.53	0.01048
SEAsia	2,433	0.364	7.3%	1.83	0.53	0.01665
Mideast	2,182	0.367	6.5%	1.63	0.53	0.04246
Russia	1,900	0.589	3.5%	0.88	0.53	0.04764
India	2,174	0.365	6.5%	1.63	0.30	0.03011
Safrica	483	0.786	0.7%	0.17	0.53	0.04142
China	9,480	0.702	14.8%	3.70	0.47	0.05003
Eurasia	997	0.695	1.6%	0.39	0.53	0.04923
WORLD	34,690	0.380	100.0%	25.00		0.03337

Note: CO2 in millions of metric tons. All pertain to 2011. Optimal tariff from Ossa model (2014). Abatement-cost parameter by author based on DICE, other models, and McKinsey study.

Table E-2. Emissions and other environmental data

Bilateral trade matrix — Importing region

Exporting region		Brazil	Japan	EU	Tropical Africa	Canada	US	Latin America	ROW	SouthE Asia	Mideast	Russia	India	South Africa	China	Eurasia	***Total exports***
	Brazil	-	9	53	5	3	26	52	16	18	14	4	3	2	44	1	250
	Japan	6	-	96	6	9	128	35	48	284	21	12	11	4	162	2	823
	EU	50	69	-	63	42	372	88	473	244	200	149	56	35	192	59	2,092
	Tropical Africa	11	4	89	-	8	68	3	17	19	4	1	25	11	43	1	304
	Canada	3	11	40	1	-	332	10	11	16	4	2	3	1	17	0	450
	US	43	66	270	13	281	-	308	97	205	49	8	22	7	104	4	1,478
	Latin America	38	17	84	2	23	393	-	26	39	9	4	12	2	55	1	705
	ROW	8	62	432	14	12	107	14	-	156	72	15	35	6	82	13	1,027
	SouthE Asia	23	219	265	25	18	236	61	214	-	73	19	76	13	660	7	1,908
	Mideast	10	155	197	13	12	96	3	98	314	-	1	129	10	111	3	1,155
	Russia	2	14	231	1	1	16	4	36	23	12	-	5	0	35	65	444
	India	5	6	55	13	2	33	5	39	49	51	2	-	4	17	1	283
	South Africa	1	7	20	15	1	8	1	7	8	2	0	5	-	19	0	93
	China	32	148	358	38	25	325	86	118	556	80	39	51	13	-	28	1,898
	Eurasia	2	1	102	1	3	5	1	30	5	9	47	3	0	29	-	238
	Total imports	234	788	2,291	213	439	2,143	672	1,228	1,936	601	302	435	109	1,570	186	

Table E-3. Bilateral trade matrix

Group	Country	Share of group GDP
EU	Germany	20%
	France	16%
	United Kingdom	14%
Eurasia	Kazakhstan	27%
	Ukraine	24%
	Azerbaijan	10%
Latin America	Mexico	37%
	Argentina	14%
	Colombia	11%
Mideast	Saudi Arabia	24%
	Islamic Republic of Iran	19%
	United Arab Emirates	13%
Southeast Asia	Australia	30%
	South Korea	24%
	Taiwan	9%
Tropical Africa	Nigeria	29%
	Angola	12%
	Sudan	8%
Rest of World	Indonesia	24%
	Turkey	22%
	Switzerland	19%

Table E-4. Major countries in aggregated regions

F. Program for Eviews evolutionary algorithm (sim-102714a.prg)

Note: To run the program, you will need to set up an Eviews workfile with 10,000 observations. Note that the important control variables are under "DEFINE SCOPE." It also requires loading a data file, input-data-072514.xls. The file is available in the data zip files, but the data used are contained in Appendix G below, with the different sheets of the file labeled. Users will need to study the Eviews programming language to operate the program.

```
==========================

' Control program to calculate the climate coalition
' Current version is October 27, 2014
' Includes calc file in the program
' Filename sim-0102714.prg
' This subroutine contains the declarations and parameters
' Note that need input data file.

'PART I. SETUP OF MODEL
' DEFINE SCOPE
'Need to open a file, but can create a dummy that will work.
'wfopen sim15-ev-102714.wf1

!numiter=5000
!numberrepeats=1
!numbertariffs=11
!numberctax=4
!sizematrix=!numberrepeats*!numbertariffs*!numberctax
'Careful here that size matrix is sufficient if do alternative runs
!sizematrix=44
'Parameters
!Alphascaling=0.837

'Define and read macro data
vector(15) vgdp
vector(15) veco2
vector(15) vpop
vector(15) vpcgdp
matrix(15,15) mwelf

vector(15) vifin
vector(15) vmcalpha
vector(15) vcorrmcalpha
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vector(15) vco2intense
vector(15) percentscc
vector(15) scc
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matrix(15,15) trfquad
matrix(15,15) trade
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matrix(15,15) welftradelin
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vector(15) netbenefitsifchange
vector(15) vifrand
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vector(15) vpertradeimpact
vector(15) testifin
scalar minchange
scalar ifnewbest
scalar iteration
vector(15) bestcprice
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scalar globbestcprice_baseemis
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scalar svalitermaxchange
scalar maxchange
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matrix(15,15) mtheta2
vector(15) vwelf

welftradelin.fill(l) 0
welftradequad.fill(l) 0
welftradetot.fill(l) 0
dolwelftradelin.fill(l) 0
dolwelftradequad.fill(l) 0
dolwelftradetot.fill(l) 0
testvtradeimpact.fill(l) 0
vpertradeimpact.fill(l) 0
vone.fill(l) 1
matrix(15,15) moptimaltariff

' Make sure you have the input data file. Must be "*.xls" format.
vgdp.read(b2,s=col) input-data-102714.xls
veco2.read(d2,s=col) input-data-102714.xls
vpop.read(c2,s=col) input-data-102714.xls
mwelf.read(a1,s=welf) input-data-102714.xls
vmcalpha.read(a3,s=mkk) input-data-102714.xls
vcorrmcalpha=vmcalpha*!Alphascaling
percentscc.read(e2,s=col) input-data-102714.xls
trade.read(a1,s=trade) input-data-102714.xls
vco2intense=@ediv(veco2,vgdp)
voptimaltariff.read(a1,s=opttar) input-data-102714.xls
vwelf.read(a1,s=vwelf) input-data-102714.xls

for !ncol= 1 to 15
for !nrow= 1 to 15
moptimaltariff(!nrow,!ncol)=voptimaltariff(!ncol)
mtheta1(!nrow,!ncol)=vwelf(!ncol)
```

```
next
next

mtheta2=@ediv(mtheta1,moptimaltariff)/2

smpl 1 1
'Trade reduced form matrices
newtrflinear = mtheta1
newtrfquad = mtheta2

' For results routine
!p=0
' END PARAMETER SUBROUTINE

'START LOOPS FOR CALCS
for !repeat=1 to !numberrepeats
 for !tar = 1 to !numbertariffs
  for !tax = 1 to !numberctax

'reset highest iteration change
svalitermaxchange=1.1

!carbontax=   12.5*2^(!tax-1)
!globalscc=!carbontax
!penaltytariff=(!tar-1)/100
scc=percentscc*!globalscc
nashcprice=scc

' This parameter controls the randomization
!prand=0.1

'PART II. STARTING VALUES
'vifin=0
'vifin(1)=1
 for !m=1 to 15
 vifin(!m)=@rbinom(1,!prand)
 next
testifin=vifin
bestifin=vifin
bestnetbenefits=-9999
bestcprice=0
besteco2=veco2
```

```
' Cooperative and Nash policies
  for !m=1 to 15
nashmiu(!m)=(scc(!m)*vco2intense(!m))/(2*vcorrmcalpha(!m))/1000
coopmiu(!m)=(!carbontax*vco2intense(!m))/(2*vcorrmcalpha(!m))/1000
coopcprice(!m)=!carbontax
nashabateratio(!m)=vcorrmcalpha(!m)*nashmiu(!m)^2
coopabateratio(!m)=vcorrmcalpha(!m)*coopmiu(!m)^2
coopabatecost(!m)=coopabateratio(!m)*vgdp(!m)
nashabatecost(!m)=nashabateratio(!m)*vgdp(!m)
  next

' ITERATION LOOP
        for !kk= 1 to !numiter

' GENERATE NEW RANDOM CHANGE COALITION
  for !m=1 to 15
'vifrand=0
vifrand(!m)=@rbinom(1,!prand)
if bestifin(!m)+vifrand(!m)=2 then testifin(!m)=0
else testifin(!m)=bestifin(!m)+vifrand(!m)
endif
  next

'THIS IS THE CALCULATION FILE
'CALCULATE VALUES

'Calculate tariff rate as function of in and out
tariffrate.fill(l) 0
 for !n=1 to 15
   for !m=1 to 15
if  testifin(!m)=1 and testifin(!n)=0  then
tariffrate(!n,!m)=!penaltytariff
else
endif
    next
 next
'Calculate welfare effects for ins
  for !n=1 to 15
    for !m=1 to 15
welftradelin(!n,!m)=tariffrate(!n,!m)*newtrflinear(!n,!m)
welftradequad(!n,!m)=-tariffrate(!n,!m)^2*newtrfquad(!n,!m)
welftradetot(!n,!m)=welftradelin(!n,!m)+welftradequad(!n,!m)
```

```
dolwelftradelin(!n,!m)=welftradelin(!n,!m)*trade(!n,!m)
dolwelftradequad(!n,!m)=welftradequad(!n,!m)*trade(!n,!m)
dolwelftradetot(!n,!m)=welftradetot(!n,!m)*trade(!n,!m)
    next
  next

'Calculate welfare effects for outs
   for !n=1 to 15
    for !m=1 to 15
if  testifin(!m)=0 and testifin(!n)=1  then
dolwelftradelin(!n,!m)=-dolwelftradelin(!m,!n)
dolwelftradetot(!n,!m)=dolwelftradelin(!n,!m)
else
endif
    next
  next

'Trade effects
  for !n=1 to 15
vector vvv = @columnextract(dolwelftradetot,!n)
testvtradeimpact(!n)=@sum(vvv)
  next

vpertradeimpact=@ediv(testvtradeimpact,vgdp)

'MAJOR RESULTS ON PRICES AND BENEFITS

'Cost etc for ins and outs
   for !m=1 to 15
if  testifin(!m)=1  then
testabatecost(!m)=-coopabatecost(!m)
testmiu(!m)=coopmiu(!m)
testcprice(!m)=coopcprice(!m)
testabateratio(!m)=coopabateratio(!m)
else
testabatecost(!m)=-nashabatecost(!m)
testmiu(!m)=nashmiu(!m)
testcprice(!m)=nashcprice(!m)
testabateratio(!m)=nashabateratio(!m)
endif
   next

'Actual emissions
```

```
oneminusactmiu=vone-testmiu
testeco2=@emult(veco2,oneminusactmiu)

'Emissions -- best and actual
!baseglobemis=@sum(veco2)
!actglobemis=@sum(testeco2)

'Damages
    for !m=1 to 15
testdamages(!m)=(!baseglobemis-!actglobemis)*scc(!m)/1000
    next

'Net benefits
testnetbenefits=testdamages+testabatecost+testvtradeimpact

'END OF THE CACLUATION FILE

' These statements define the change coalition
   for !m=1 to 15
if bestifin(!m)=testifin(!m) then ifINchange(!m)=0 else ifINchange(!m)=1 endif
  next

'Estimate diff in net benefits
changenetbenefits=testnetbenefits-bestnetbenefits

'Estimate benefit change for change coalition
netbenefitsifchange=@emult(changenetbenefits,ifINchange)

'Calculate whether there is a Pareto improvement for the change coalition
minchange=@min(netbenefitsifchange)
maxchange=@max(netbenefitsifchange)

' Then change the best results if Pareto improving for the new coalition
if minchange<0 then ifnewbest=0 else ifnewbest=1 endif
if minchange=0 and maxchange>0  then svalitermaxchange=!kk endif
if ifnewbest=1 then bestnetbenefits=testnetbenefits endif
if ifnewbest=1 then bestifin=testifin endif
if ifnewbest=1 then bestcprice=testcprice endif
if ifnewbest=1 then besteco2=testeco2 endif

'if !kk=30 then stop else endif
iteration=!kk
'next for !kk
```

```
next

'Results
globbestcprice_actemis=@inner(bestcprice,besteco2)/@sum(besteco2)
globbestcprice_baseemis=@inner(bestcprice,veco2)/@sum(veco2)
matrix(!sizematrix,50) results
results(!tax +!p ,1)=svalitermaxchange
results(!tax+!p ,2)=iteration
results(!tax+!p ,3)=@sum(bestifin)
results(!tax+!p ,4)= globbestcprice_baseemis
results(!tax+!p ,5)=@sum(bestnetbenefits)
results(!tax+!p ,6)=globbestcprice_actemis
results(!tax+!p ,7)=!penaltytariff
results(!tax+!p ,8)=!carbontax
results(!tax+!p ,9)=!globalscc
   for !ppp=1 to 15
results(!tax+!p,9+!ppp)=bestifin(!ppp)
   next
results(!tax+!p ,25)=@sum(bestifin)
   for !ppp=1 to 15
results(!tax+!p,25+!ppp)=bestnetbenefits(!ppp)
results(!tax+!p ,41)=@sum(bestnetbenefits)
   next

'Next for loops
' Next for number repeats
next
!p=!p+4
' Next for number tariffs
next
'Next for number carbon prices
next
==========================
```

G. Screen shots of pages of input data sheet for Eviews program

If you are unable to find the Excel input sheet for the Eviews program, the following are screenshots of the different pages. These are read by the Eview program above.

Sheet "col"

	A	B	C	D	E
1	Country	GDP	Pop	CO2	SCC
2	Brazil	2,816.37	196.94	470.18	0.03087
3	Japan	4,386.18	127.82	1,249.71	0.04807
4	EU	16,906.11	506.03	4,048.34	0.18528
5	SSA	2,095.59	776.45	302.18	0.02297
6	Canada	1,419.49	34.34	533.31	0.01556
7	US	15,533.95	311.58	5,670.81	0.17024
8	LatAm	5,064.79	393.70	1,378.25	0.05551
9	ROW	5,660.44	892.61	1,388.93	0.06203
10	SEAsia	6,676.37	390.11	2,433.17	0.07317
11	Mideast	5,953.54	336.86	2,182.07	0.06525
12	Russia	3,226.53	142.96	1,899.86	0.03536
13	India	5,962.91	1,221.16	2,173.76	0.06535
14	Safrica	614.31	51.58	482.55	0.00673
15	China	13,496.41	1,344.13	9,479.96	0.14791
16	Eurasia	1,434.18	142.55	996.52	0.01572
17	WORLD	91,247.15	6,868.80	34,689.59	1.00000
18					
19					
20					

col / trade / welf / ifin / mkk / sens / opttar / vwelf

Sheet "trade"

	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O
1	-	9.473	53.209	4.889	3.130	25.943	51.533	15.547	17.657	14.480	4.216	3.201	1.681	44.315	0.879
2	6.207	-	95.945	6.086	8.909	127.675	34.566	47.614	284.217	20.710	11.813	11.078	4.317	162.035	1.937
3	49.570	69.360	-	62.588	41.704	372.313	87.875	473.133	244.369	200.072	148.802	56.137	35.012	192.068	58.840
4	11.116	4.209	89.336	-	7.808	67.819	3.479	16.661	18.754	3.739	0.841	24.596	11.161	43.147	0.884
5	2.869	10.776	40.348	1.187	-	331.755	10.347	10.963	15.517	4.276	1.512	2.655	0.690	16.985	0.403
6	42.943	66.160	269.648	13.293	280.710	-	308.094	96.526	205.464	49.398	8.285	21.628	7.294	103.878	4.498
7	37.757	16.696	84.012	2.427	22.988	393.176	-	26.113	38.672	8.943	3.623	11.998	1.652	55.162	1.460
8	8.026	61.581	431.700	14.425	12.264	106.672	13.697	-	155.760	72.406	15.246	34.507	6.143	81.720	12.823
9	23.221	218.630	264.799	25.071	18.108	235.514	60.615	213.768	-	72.968	18.589	76.288	13.058	660.432	6.677
10	10.431	154.781	197.238	13.440	11.705	95.639	3.218	98.148	314.472	-	1.475	129.013	10.341	111.483	3.138
11	2.103	14.235	230.540	1.411	0.537	15.626	4.386	36.262	23.085	11.737	-	4.666	0.115	34.692	65.027
12	5.391	5.593	54.733	12.924	1.877	32.919	5.141	38.959	49.480	51.356	1.894	-	4.320	16.718	1.260
13	0.741	6.727	20.348	15.284	0.603	7.535	0.912	6.516	7.857	1.775	0.297	5.300	-	18.564	0.108
14	31.837	148.269	357.766	38.453	25.267	325.011	86.470	117.781	556.158	80.207	38.903	50.536	13.362	-	28.227
15	1.75	1.33	101.76	1.17	3.23	5.43	1.26	29.65	4.51	8.82	46.73	3.31	0.11	28.67	-

col / trade / welf / ifin / mkk / sens / opttar / vwelf

Sheet "welf"

	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P
1	0.68	0	0	0	0	0	0	0	0	0	0	0	0	0	0	
2	0	0.41	0	0	0	0	0	0	0	0	0	0	0	0	0	
3	0	0	0.61	0	0	0	0	0	0	0	0	0	0	0	0	
4	0	0	0	0.55	0	0	0	0	0	0	0	0	0	0	0	
5	0	0	0	0	0.68	0	0	0	0	0	0	0	0	0	0	
6	0	0	0	0	0	0.73	0	0	0	0	0	0	0	0	0	
7	0	0	0	0	0	0	0.63	0	0	0	0	0	0	0	0	
8	0	0	0	0	0	0	0	0.59	0	0	0	0	0	0	0	
9	0	0	0	0	0	0	0	0	0.64	0	0	0	0	0	0	
10	0	0	0	0	0	0	0	0	0	0.64	0	0	0	0	0	
11	0	0	0	0	0	0	0	0	0	0	0.65	0	0	0	0	
12	0	0	0	0	0	0	0	0	0	0	0	0.59	0	0	0	
13	0	0	0	0	0	0	0	0	0	0	0	0	0.62	0	0	
14	0	0	0	0	0	0	0	0	0	0	0	0	0	0.58	0	
15	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.61	
16																
17																
18																
19	0.682	0.410	0.611	0.549	0.685	0.733	0.626	0.591	0.641	0.642	0.654	0.585	0.623	0.581	0.614	

Sheet "ifin"

	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R	S	T	U
1	1	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
2	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
3	1	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
4	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
5	1	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0
6	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0
7	1	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0
8	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0
9	1	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0
10	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0
11	1	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0
12	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0
13	1	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0
14	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0
15	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0

Sheet "mkk"

	A	B	C	D	E	F
1	McKinsey					
2	alpha					
3	0.00716					
4	0.03014					
5	0.02299					
6	0.00701					
7	0.04195					
8	0.03251					
9	0.02032					
10	0.01252					
11	0.01989					
12	0.05073					
13	0.05691					
14	0.03597					
15	0.04949					
16	0.05977					
17	0.05882					
18	**0.03012**					
19						
20						

col / trade / welf / ifin / **mkk** / sens / opttar / vwelf

Sheet "sens"

	A	B	C	D
1				
2				
3		average	RICE	
4	TRICE regions			
5	Brazil	2.88%	2.43%	
6	Japan	2.40%	2.28%	
7	EU	13.91%	12.22%	
8	SSA	7.39%	7.18%	
9	Canada	0.98%	0.94%	
10	US	10.72%	10.25%	
11	LatAm	5.24%	4.42%	
12	ROW	11.17%	10.85%	
13	SEAsia	10.95%	10.63%	
14	Mideast	6.38%	6.20%	
15	Russia	3.59%	3.49%	
16	India	11.78%	11.67%	
17	Safrica	0.68%	0.66%	
18	China	11.04%	15.93%	
19	Eurasia	0.89%	0.87%	
20		100.00%	100.00%	
21				

col / trade / welf / ifin / mkk / **sens**

Sheet “opttar”

	A
1	0.45
2	0.48
3	0.55
4	0.53
5	0.53
6	0.59
7	0.53
8	0.53
9	0.53
10	0.53
11	0.53
12	0.3
13	0.53
14	0.47
15	0.53

col / trade / welf / ifin / mkk / sens / **opttar** / vwelf

Sheet “vwelf”

	A
1	0.682
2	0.410
3	0.611
4	0.549
5	0.685
6	0.733
7	0.626
8	0.591
9	0.641
10	0.642
11	0.654
12	0.585
13	0.623
14	0.581
15	0.614

col / trade / welf / ifin / mkk / sens / opttar / **vwelf**