THE VALUE OF COOPERATION IN ABATING CLIMATE CHANGE

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James Hammitt, John Adams

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INTRODUCTION

Climate change is usefully viewed as a long-term global commons problem. Because of the century-long atmospheric residence times of the major greenhouse gases (GHGs), large thermal capacity of the world oceans, and the multi-decade lifetimes of economic capital and technological systems, the effects of current activities on climate will persist for decades. Moreover, because the GHGs are well-mixed in the global atmosphere, the effects of anthropogenic emissions on climate do not depend on which nation emits them. Although a nation may bear all the costs of reducing its net GHG emissions, it cannot appropriate to itself all of the benefits; consequently, nations have inadequate incentives to reduce GHG emissions and greater-than-optimal emissions and climate change may ensue (Hardin 1968).

This paper provides insight into the significance of this commons aspect of climate-change decision making. Using an integrated assessment model to simulate the effects of near-term national decisions on the long-term costs of responding to climate change, it explores the economic and environmental outcomes associated with noncooperative and cooperative solutions. Quantitative assessment of welfare differences between solutions provides information about the potential magnitude of gains from near-term cooperation, as well as information about the possible distribution of gains among nations. Such information may be useful in developing effective measures for responding to the prospect of global climate change.

THE ABATEMENT-GAME ANALYSIS

The analysis is structured as a two-period game. In the first period (1990-2010), each of two world regions denoted North (industrialized nations) and South (developing nations) selects a GHG-abatement policy. In the second period (2010-2100) global emissions are limited to ensure that climate change, measured by the increase in global annual mean surface temperature above preindustrial levels (ΔT), does not exceed an exogenously determined climate target ΔT (the maximum value of ΔT is not always reached before 2100 but the emission scenarios are constructed so ΔT^* is never exceeded). The allocation of second-period emissions between regions is determined by an exogenously specified burden-sharing rule. In this analysis, the parties are assumed to have perfect information about abatement costs, climate sensitivity, the climate target, and other factors; in subsequent analyses, this condition will be relaxed. Each party's objective is to minimize the present value of its abatement costs, aggregated over the two periods. Alternative solutions to the game, including the noncooperative (Nash) equilibrium and efficient bargaining range are identified and the welfare gains (reductions in abatement costs) associated with movement from noncooperative to cooperative solutions are quantified.

Given this framework, a payoff matrix can be constructed. This matrix describes the welfare of each party as a function of first-period actions by North and South. Each party's payoff is defined as a constant (its welfare absent climate change) less the present value of its first- and second-period abatement costs. Using the payoff matrix, several interesting features of the problem, including the Nash equilibrium and welfare possibility frontier, can be characterized.

Figure 1 illustrates a hypothetical payoff matrix. The Nash equilibrium may be taken as the no-agreement solution (or threat point) because either party can withdraw from negotiations and guarantee itself the welfare associated with this outcome (unless the other party is willing to decrease its own welfare to "punish" the defector). In general, the Nash equilibrium is not Pareto

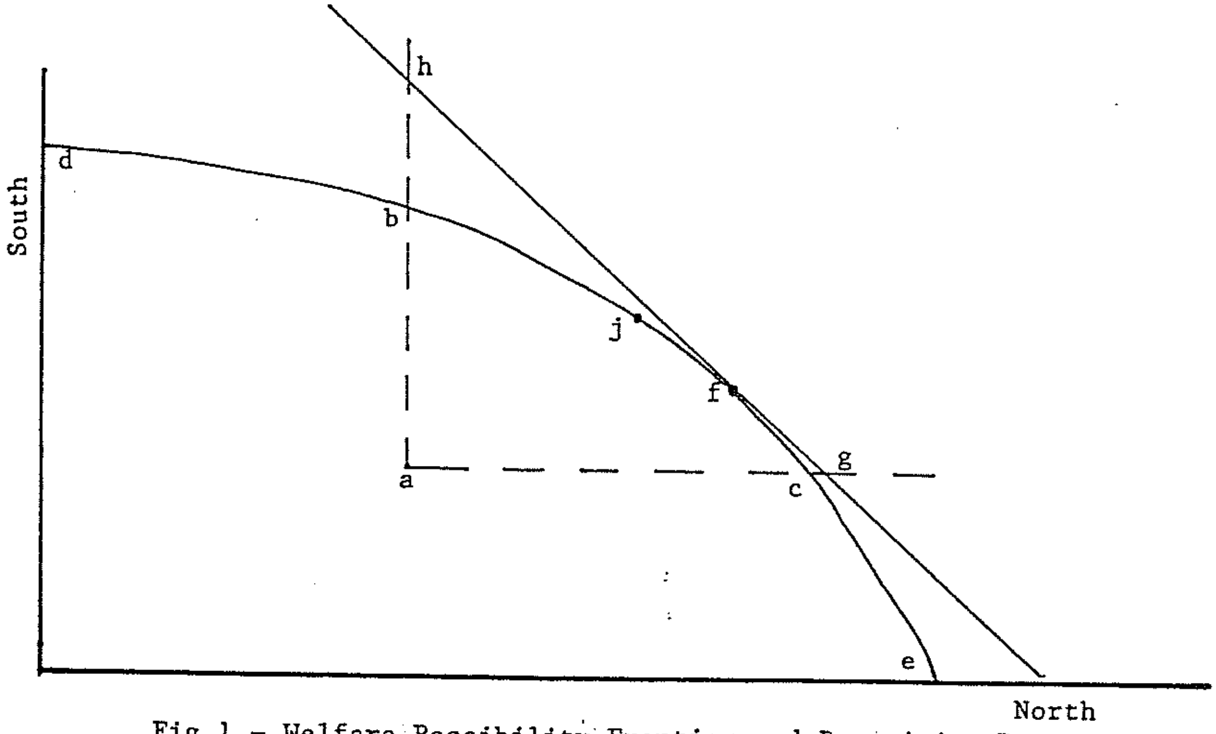

Fig.1 - Welfare Possibility Frontier and Bargaining Range

efficient; as illustrated in Figure 1, both parties' welfare would be improved if they could move from the Nash solution a to any point to its northeast. In particular, the segment b-c of the welfare possibility frontier d-e represents the efficient bargaining range, i.e., the set of efficient outcomes that are Pareto superior to the Nash equilibrium. The parties can achieve any point in this range by coordinated first-period actions. The resulting gains from cooperation range from zero to a-b for North and from zero to a-c for South.

If the parties can make side-payments (e.g., direct aid, initial allocation of tradeable emission permits), the range of feasible cooperative outcomes can be improved. The sum of the parties' welfare is maximized at point f in Fig. 1, where the slope of the welfare possibility frontier is -1. If welfare can be transferred without loss (e.g., if it is measured by GDP), all points on the tangent at f can be achieved by coordinating abatement actions to achieve f and transferring welfare between parties as appropriate. To achieve an outcome between f and h, the North would transfer resources to the South; to achieve an outcome between f and g, the transfer would go the other direction. (Note that point f may lie outside the range b-c; if so, all the points on the tangent that dominate the noncooperative solution require side payments in the same direction.) If such side payments are feasible, the efficient bargaining range is described by g-h and the possible gains from cooperation extend from zero to a-g for the North and zero to a-h for the South.

The parties' expectations about the division of second-period emissions are a central factor in formulating first-period strategies, as the share of second-period emissions a party expects to receive determines the extent to which it captures the benefit of its first-period emission reductions. A party that expects the other to absorb all the second-period abatement costs has no incentive to reduce its emissions in the first period; a party that expects to bear all the second-period costs will efficiently balance its abatement activities between periods.

Expectations about second-period allocations are incorporated by assuming a pre-specified burden-sharing rule. Several rules representing the range of foreseeable agreements are considered. Three of the rules are specified in terms of the rate at which a region must reduce its emissions, characterized by the fuel-switching half-life (r in eqn. 3 below). International agreements may plausibly take the form of schedules for emission reductions, and the transition half-life (which measures the time until a region reduces the carbon-intensity of its energy use by half) is a convenient index of the reduction rate. The three rules specify that fuel-switching rates are (a) equal, (b) proportional to emissions/capita, and (c) proportional to emissions/GDP. A fourth, least-cost, rule determines the second-period fuel switching rates that minimize the sum of North's and South's abatement costs.

INTEGRATED ASSESSMENT MODEL

Regional abatement costs are simulated using a regionally disaggregated version of an assessment model which simulates globally aggregated GHG emissions, atmospheric concentrations, an index of climate change, and abatement costs (Hammitt et al. 1992, Hammitt and Lempert 1992). GHG fluxes (net emissions to the atmosphere) in year t, denoted F(t), are

$$F(t) = F_N(t) + F_S(t) \tag{1}$$

$$F_i(t) = B_i(t)\, I_i(t)\, E_i(t), \tag{2}$$

modeled as the sum of emissions from each region, where the regions are denoted by $i = N,S$, $B_i(t)$ is a reference emission trajectory, $I_i(t)$ is energy intensity (energy use per unit economic activity) and $E_i(t)$ is emissions intensity (GHG emissions per unit energy) in each region. (For simplicity, regional subscripts are dropped.) Abatement actions are represented through their effect on I(t) and E(t); in the absence of abatement action, $I(t) = E(t) = 1$ for all t. The model is based on the primacy of energy use among anthropogenic GHG sources--CO_2 is the dominant

GHG (e.g., it accounts for 72% of the increase in radiative forcing between 1990 and 2100 under the IPCC "business as usual" scenario SA90; Houghton et al. 1990) and energy transformation is the dominant anthropogenic CO_2 source (accounting for about 3/4 of current anthropogenic CO_2 emissions; Houghton et al. 1990). Other GHGs are incorporated by multiplying F(t) by 1.72 to approximate global emissions of the major GHGs in units of equivalent CO_2. This choice implies that emissions of the other GHGs can be limited at comparable marginal cost to CO_2 emissions. In an alternative case, the atmospheric concentrations of other GHGs are specified exogenously (the IPCC SA90 scenario) and are not affected by simulated abatement.

Atmospheric concentration is modeled using a linear impulse-response function for CO_2 that fit to the results of an ocean general circulation model (Maier-Reimer and Hasselmann 1987).

The difference between annual global mean surface temperature in year t and its preindustrial (1765) level, $\Delta T(t)$, is used as an index of climate change. Although the effects of climate change are likely to depend on regional and seasonal changes in temperature, precipitation, and other climate dimensions, the magnitude of such changes is likely to correlate with $\Delta T(t)$. It is possible that substantial regional and/or seasonal changes in climate could occur without a significant effect on ΔT, but existing GCM runs have not shown such effects (Schlesinger and Xiang 1991a,b). $\Delta T(t)$ is simulated using an energy-balance box-diffusion model (Schneider and Thompson 1981; cf. Cess and Goldenberg 1981, Hoffert et al. 1980, Siegenthaler and Oeschger 1984) calibrated to results of an upwelling-diffusion model (Schlesinger and Jiang 1990, 1991c). The climate sensitivity ΔT_{2x}, defined as the equilibrium increase in global annual mean surface temperature accompanying a doubling of CO_2, is the principal parameter by which uncertainties about climate change are summarized.

The damages associated with climate change are incorporated using a "climate target," ΔT^*, which represents a "maximum acceptable" value of $\Delta T(t)$ (Krause et al. 1992, Rijsberman and

Swart 1990, Swart and Hootsmans 1991, Wirth and Lashof 1990). Time paths of $\Delta T(t)$ that achieve the same maximum are assumed to impose the same environmental consequences. The climate target can be interpreted as the implicitly defined point at which marginal damages of the climate trajectory equal marginal abatement costs; alternatively, it can be interpreted as a level beyond which the risks of serious damages increase dramatically. The climate target ΔT^* and climate sensitivity ΔT_{2x} jointly constrain the allowable emissions so that $\Delta T(t)$ does not exceed ΔT^*.

Two classes of abatement activity are included that differ in cost per unit emission reduction, capacity, and rate of implementation. "Energy conservation" represents a class of activities that are relatively inexpensive, quickly implemented, and limited in scope. Conservation is represented by:

$$I(t) = (1 - \gamma) + [\gamma/(1 - \epsilon)][1 + e^{(\rho (t - t_0 - r)}]^{-1}, \tag{3}$$

where γ is a capacity limit, representing the asymptotic fraction of energy that may be conserved and r is a transition half-life that describes the rate of implementation. (The parameters $\epsilon = 0.01$ and $\rho = -(1/r) \ln[\epsilon/(1 - \epsilon)]$ are needed to produce $I(t_0) = 1$.) The logistic decline is characteristic of technological diffusion (Fisher and Pry 1971, Hafele 1981, Laurmann 1988, Mansfield 1961, Marchetti 1975, Marchetti and Nakicenovic 1978). Costs are assumed to be incurred in the year of operation and are linear in energy savings:

$$K_c(t) = \sigma B(t) \, [1 - I(t)] \tag{4}$$

where σ is the cost-effectiveness of conservation.

Additional emission reductions require "fuel switching," which represents a set of higher-cost, more slowly implemented actions. Cost and effectiveness are simulated assuming that all emissions are produced by long-lived capital equipment using either emitting (e.g., fossil fuel) or non-emitting (e.g., nuclear, solar, biomass) technologies; for both technologies, construction and operating periods are 10 and 30 years, respectively. The fraction of energy use accounted for by emitting technologies is E(t) which is constrained to follow a logistic path (eqn. 3) where the transition half life r is a choice variable and complete substitution is possible ($\gamma = 1$).

The incremental cost due to fuel switching is the difference between policy-induced and base-case expenditures on capital equipment. Fuel switching is divided between low-cost and high-cost components, reflecting increasing marginal abatement costs. E(t) can be reduced from 1 to 1/2 using only low-cost non-emitting capital; additional reductions require high-cost non-emitting equipment as well. Annual costs are given by:

$$K_f\ (t) = \sum_{j=0}^{2} \left[\sum_{i=-9}^{2} \kappa_j\ n_{ji}(t) + \sum_{i=1}^{30} \sigma_j\ n_{ji}(t) \right] \tag{5}$$

where $n_{0i}(t)$, $n_{1i}(t)$, and $n\backslash_{2i}(t)$ are, respectively, the energy used by emitting, low-cost and high-cost non-emitting equipment of age i in year t ($-9 \leq i \leq = 0$ indexes equipment in construction), σ_j are annual operating costs and $10\kappa_j$ are total capital costs, allocated uniformly over the construction period. Sufficient capital equipment to satisfy increased demand and to replace equipment that will retire a decade later is assumed to enter construction each year, with the appropriate share of non-emitting capital to satisfy the desired trajectory for E(t). If necessary, emitting equipment is retired prematurely, oldest first.

ESTIMATION OF REGIONAL COST PARAMETERS

Cost parameters for each region are estimated by calibrating to the results of two of the models that provided results for the EMF scenarios, Edmonds/Reilly (ER) and Global 2100 (G2100). These are the only models of those participating in EMF that provide sufficient regional detail and a distant horizon required for this analysis. The cost fitting incorporates two steps. First, parameters are estimated so that the emission model approximates the emission trajectories calculated by the ER and G2100 models for the six EMF-12 scenarios (Reference, Stabilization by 2000, 20% reduction by 2010, 50% reduction by 2050, 2%/yr reduction, and Phased-in carbon tax). Second, cost parameters are estimated such that the average cost of emission reduction calculated by the model approximates the average cost calculated by the ER and G2100 models. For both steps, parameter values are obtained using nonlinear least squares regression, taking each year as an independent observation. Emission and GDP loss figures for each year are obtained by linearly interpolating between the values at the years reported to EMF.

Separate estimates are obtained for each region for the ER and G2100 models. The regions are constructed by aggregating the five regions for which EMF results were reported so that the emission constraints defined by each EMF scenario are common to each component of the aggregate regions: North (USA, Other OECD, USSR) and South (China, Rest of World).

EMISSION TRAJECTORIES

For each model/region pair, B(t) is set equal to Reference scenario emissions; by letting I(t) = E(t) = 1 for all t, the model reproduces the EMF-12 reference case emissions.

Parameters of the conservation and fuel-switching processes are modeled assuming a two-period abatement strategy. The period boundaries are 1990-2010 and 2010-2100. Conservation, represented by changes in I(t), can begin in either period. Once initiated, I(t) is determined by eqn. (3) with specified transition rate and asymptote and t_0 equal to the date at which conservation begins, 1990 or 2010. Fuel switching (changes in E(t)) can also begin in either period; if begun in the first period, the transition half-life can change at the start of the second period but the asymptote is common to both periods. Because fuel switching requires construction of new energy-using equipment, E(t) is determined by eqn. (3) with t_0 equal to the date at which the period begins plus the 10 year construction period (i.e., $t_0 = 2000$ for the first period, 2020 for the second). If the transition half life changes between periods, E(t) is continuous but its derivative is discontinuous at 2020.

Parameter values are estimated using nonlinear least squares regression. The results indicate that parameter values for conservation can be made common across scenarios, models, and regions without significantly compromising the fitted emission levels. The common values are $t_0 = 1990$, $r = 10$ years and $\gamma = 0.2$. Fuel switching parameter values, reported in Table 1, differ by model and region.

Table 1. Fuel Switching Emission Parameters

	Global 2100			Edmonds/Reilly		
	T1	T2	A	T1	T2	A
North						
Stabilization	25	80	.57	inf	35	.29
20% Reduction	20	213	.80	28	297	1.0
50% Reduction	21	37	.76	31	44	.68
2%/yr Reduction	22	166	1.0	20	150	.95
Phase-in tax	50	40	1.0	inf	41	.77
South						
Stabilization	140	42	.88	97	39	.78
20% Reduction	inf	38	.87	97	39	.78
50% Reduction	140	42	.88	86	39	.78
2%/yr Reduction	22	159	.98	22	163	1.0
Phase-in tax	inf	30	.95	44	81	1.0

Notes: T1 = 1st period transition half life
T2 = 2d period transition half life
A = asymptote (γ)
inf = infinity

COST PARAMETERS

Values are estimated for three cost parameters, representing the annualized cost of conservation, low-cost and high-cost non-emitting equipment. Costs are measured as a multiple of the cost of CO_2-emitting energy-using equipment, in dollars per ton avoided carbon emissions. Cost parameters are constrained as follows: $0 \leq$ conservation $\leq$ low-cost non-emitting equipment $\leq$ high-cost non-emitting equipment. The annualized cost of emitting equipment is \$380/t emitted carbon, calculated assuming capital costs of \$0.015/kwh, operating costs of \$0.025/kwh, and emissions of 7.2 t C/10^5 kwh equal to the ratio of fossil fuel C emissions to world primary energy use (Hammitt et al. 1992) and using a 5% discount rate.

Capital costs are divided uniformly across the 10 year construction period and operating costs are incurred in each year of operation. Because simulated conservation can be undertaken with no construction lag, conservation costs are modeled as if all costs are operating costs. This structure leads to simulated large negative costs in early years as conservation is adopted and less energy-using equipment need enterconstruction (which are offset in later years by the higher operating cost of conservation relative to emitting equipment).

Parameters are estimated by fitting predicted average costs at year t to average costs at t calculated by the ER and G2100 models, where average cost is the GDP loss in year t divided by the difference in emissions between the reference and specified scenario. Between reporting years, average costs for the ER and G2100 models are calculated as the ratio between linearly interpolated values of GDP loss and emission difference. Parameters are estimated using ER and G2100 results for the period 2010-2100 so that values would not be influenced by the large negative costs in early years; estimates using the period 2000-2010 are not seriously different.

Cost parameters are estimated independently for each region/model/scenario. Within a region/model pair, there is no systematic relationship between estimates and scenario. The median values across scenarios for each region/model pair, reported in Table 2, are selected as final estimates.

Table 2. Cost Parameters

	Global 2100		Edmonds/Reilly		Hammitt et al.
	North	South	North	South	Global
Conservation	0	74	0	52	5
Low-cost non-emitting	230	110	320	130	50
High-cost non-emitting	399	334	999	570	200

OBSERVATIONS

Estimated cost parameters are substantially larger than the values used by Hammitt et al. (1992) and substantially larger than the backstop costs of Global 2100 (~$200/t C). The high costs relative to the backstop have been noted in EMF working group meetings and attributed to the rapid emission reductions required by these scenarios.

The estimated costs of conservation are lower in the North than the South, but the costs of fuel switching are lower in the South. This suggests that the North is the low-cost emission avoider in the short term (during which conservation is the only mechanism with significant effect), but the South is the low-cost avoider over the longer term (when conservation reaches its asymptotic level and incremental reductions are based on fuel switching). The features of the ER and G2100 models that produce this result have not been identified.

Cost parameters estimated from the ER model are generally greater than those estimated from G2100 (conservation being the exception). The estimated zero cost of conservation (for all model/region pairs except ER/South) should interpreted carefully, as the conservation and low-cost non-emitting cost parameter estimates are closely correlated. This correlation is less significant for predicting abatement costs, which is of interest here.

THE GAME PAYOFF MATRIX

Payoff matrices can be generated for each game described by an exogenously specified set of possible first-period abatement actions by each region, a second-period burden sharing rule, climate and cost parameters. For illustration, the effect of varying the burden-sharing rule is analyzed for a fixed specification of cost, climate, and other parameter values.

The following cases all correspond to the cost parameters estimated using the Edmonds/Reilly model, a climate sensitivity of 2.5° C, and a climate target of 1.5° C. In the first period, each region is assumed to adopt conservation and adopts fuel switching with a half-life of 20, 40, or 100 years.

The payoff matrices for three burden-sharing rules are presented in Fig. 2. The rows and columns correspond to first-period fuel-switching half-lives in the North and South, respectively. Within each cell, the left number is the annualized (at 5%) abatement cost summed over the two periods (1990-2100) for the North; the right number is the corresponding cost to the South, and the number at the bottom of the cell is the sum of the regional abatement costs.

The payoff matrix for the burden-sharing rule that imposes equal fuel-switching rates in the second period (which corresponds to equal percentage emission reductions from the level at the end of the first period at any subsequent date) is shown by Panel A. Let Ni, Sj and (Ni, Sj) denote the strategies (first-period abatement actions) of each party and the cell defined by the specified strategy pair, where i and j represent first-period fuel-switching half-lives for N and S, respectively. The noncooperative (Nash) equilibrium is (N100, S100), which corresponds to the slowest possible abatement by both regions in the first period. That this cell represents a Nash equilibrium can be readily verified: N100 is a dominant strategy for N (i.e., whatever strategy S chooses, N cannot do better than to choose N100); the best response for S to N100 is S100. Note that S100 is not a dominant strategy for S; its best response to N20 is S40. Consequently,

Figure 2. Panel A
Payoff Matrix Equal Second Period Transition Rate Burden-Sharing Rule

South's
First Period Strategy

North's
First Period Strategy

	20	40	100
20		north 720 south 150 total 870	north 820 south 150 total 870
40	north 200 south 530 total 550	north 360 south 220 total 580	north 420 south 180 total 600
100	north 180 south 410 total 590	north 330 south 220 total 510	north 330 south 220 total 550

this payoff matrix does not correspond to a particularly severe form of a commons problem, the prisoners dilemma, in which the equilibrium strategies are dominant for both players.

The least-social-cost solution (point f in Fig. 1) for this game is (N100, S40), for which the social cost (510) is about 7% smaller than the social cost of the Nash equilibrium. If side payments between the parties are feasible, the bargaining range is defined by the difference in payoffs between the Nash and least cost solutions. In this case, movement to the least cost solution saves N 80 and costs S 40, for a net gain of 40; both regions would benefit if S increased its first-period abatement to S40 and N paid it between 40 and 80.

An alternative burden-sharing rule imposes second-period fuel-switching rates proportional to regional emission/GDP ratios in 2010. This rule favors the region that is more "GHG efficient" in the sense of generating greater GDP per unit emissions. For the Edmonds/Reilly reference case, 2010 CO\d2\u emissions/GDP for N is about 0.6 times as large as for S, so the second-period half-life for S is 0.6 times the value for N. (Because it imposes a faster response on S than N, this rule is not likely to be adopted.)

Payoffs under the GDP rule are shown in Panel B of Fig. 2. As for the equal-rate case, (N100, S100) is a Nash equilibrium. N100 weakly dominates N40 (the two are equally good responses to S20) and S100 is not dominant (S40 is the best response to N20). Unlike the equal-rate case, the Nash equilibrium is also the least-social-cost solution, which suggests there is no benefit to inter-regional coordination in this case. The bargaining range includes only the single point (N100, S100).

A third burden-sharing rule is the least-cost rule, by which it is presumed the parties agree in advance to choose whatever pair of second-period fuel-switching rates minimize the sum of their second-period abatement costs (conditional on first-period choices). The payoff matrix for this rule is shown in Panel C of Fig. 2. As in the previous cases, N has a dominant strategy but

Figure 2. Panel B
Second Period Rate Proportional to Emissions/GDP Burden-Sharing Rule

		South's First Period Strategy		
		20	40	100
North's First Period Strategy	20		north 670 south 160 total 830	north 720 south 160 total 880
	40	north 170 south 370 total 540	north 290 south 250 total 540	north 350 south 210 total 560
	100	north 170 south 440 total 610	north 220 south 310 total 530	north 250 south 270 total 520

Figure 2. Panel C
Payoff Matrix Least-Cost Burden-Sharing Rule

	South's First Period Strategy		
North's First Period Strategy	20	40	100
20		north 670 south 160 total 830	north 670 south 160 total 830
40	north 180 south 360 total 540	north 180 south 320 total 500	north 170 south 320 total 490
100	north 210 south 340 total 550	north 240 south 260 total 500	north 250 south 270 total 520

in this case it is N40. S40 and S100 are about equally good responses to any of N's options. There is a Nash equilibrium, at (N40, S100). As for the GDP-based rule, this equilibrium is also the least-social-cost solution, so cooperative first-period solutions cannot improve on the noncooperative equilibrium.

CONCLUSIONS

The potential gains to inter-regional coordination of near-term climate-change abatement policies have been analyzed as a simple game with payoffs to each region simulated using an integrated assessment model with costs calibrated to the Edmonds/Reilly model. The regions' near-term emission reductions depend on their expectations regarding longer-term allocation of the burden of abating climate change. These expectations have been represented by alternative burden-sharing rules. For the exogenously specified first-period strategies considered here, the Nash and cooperative solutions coincide under two of the burden-sharing rules (least-cost and emission reductions tied to emissions/GDP). For the third rule (equal proportional reductions), the cooperative solution allows a reduction in total abatement costs of about 7% of the abatement costs of the noncooperative solution.

The least-cost solution is also sensitive to the burden-sharing rule, differing for each of the three rules considered. The associated cost, however, is only moderately sensitive to the burden-sharing rule (differing by only 4%). For the GDP-based rule, the least-cost solution requires minimal first-period abatement (100 year half life) by both regions. The least-cost and equal-rate rules require stronger abatement (40 year half life) by North and South, respectively.

Cost parameters estimated from the Edmonds/Reilly and Global 2100 results suggest that near-term abatement may be less expensive in the North than the South, and that long-term abatement is less expensive in the South. Despite this finding, the GDP-based burden-sharing rule has a more expensive minimum-cost solution than the equal-rate rule, even though it shifts imposes more of the second-period burden on S. However, the lowest cost of all the solutions examined (the least-cost solution with the least-cost burden-sharing rule) is consistent with this result: first-period fuel-switching rates are 40 and 100, and second-period rates are 100 and 20, for North and South, respectively.

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