MEETING CONCENTRATION TARGETS IN THE POST-KYOTO WORLD: DOES KYOTO FURTHER A LEAST COST STRATEGY?

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Abstract. Preliminary analysis based on an aggregate model of global carbon emissions suggests that constraining emissions to the levels that would be imposed by compliance with the results of the Kyoto negotiations can increase the discounted cost of ultimately limiting atmospheric concentrations. Kyoto targets can be either too restrictive or too permissive depending upon the (currently unknown) trajectory of carbon emissions over the near- to medium-term *and* the (as yet unspecified) concentration target that frames long-term policy. The discounted cost of meeting low concentration targets like 450 ppmv. is diminished by allowing large sinks *and/or* by imposing more restrictive near-term emissions benchmarks (even if only Annex B countries are bound by the Kyoto accord). Conversely, the cost of achieving high concentration targets like 650 ppmv. is diminished by disallowing sinks *and/or* by imposing less restrictive emissions benchmarks. Intermediate concentration targets like 550 ppmv. look like high concentration targets (favoring no sinks and expanded near-term emissions) along low emissions paths; but they look like low concentration targets (favoring the opposite) along high emissions paths. Emissions trajectories that lie above the median, but not excessively so, represent cases for which adjustments in the Kyoto emissions benchmarks *and/or* negotiated allowances for sinks have the smallest effect on the cost of mitigation.

Keywords: climate change, concentration limits, discounted control costs, Kyoto Protocol

1. Introduction

The global change research community is beginning systematically to investigate the global and national cost implications of the Kyoto Protocol through the year 2010 and beyond. In the most general terms, meeting its objectives would require that Annex B countries as a group reduce their carbon equivalent emissions to 94.8% of 1990 levels by roughly 2010;[1] but the Protocol is more complicated than that. Indeed, many of the details of its implementation have not yet been worked out, and so the global and national costs of meeting even its general objectives cannot be estimated with any certainty. The Energy Modeling Forum (EMF) responded

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[1] The Annex B category includes most of the developed world. Wigley (1998) has reviewed the various commitments for Annex B countries in the Kyoto Protocol. He estimates that they, collectively, call for aggregate emissions to fall by 5.2% relative to 1990 levels over the 'commitment period' (2008–2012) – a figure consistent with Paragraph 1 of Article 3 of the Protocol that calls for a reduction of 'at least 5 percent'.

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to this uncertainty by issuing guidelines for a First Round Modeling Exercise in February of 1998 that was designed explicitly to focus attention on the implications of several of the major policy-design issues that are still pending (Weyant, 1998a). Modelers who chose to participate in this exercise began their work by updating their unregulated reference scenarios to incorporate new parameterizations of their models and to accommodate recent emissions experiences. They then turned to exploring scenarios that reflect selected combinations of four stylized views of how the post-Kyoto global policy environment might be structured:

- three alternative scenarios for (carbon) sink enhancement after 2010 (no enhancement, 16.7% of an estimated technical maximum, and 66.7% of this maximum estimated potential);[2]
- three alternative adjustments in Kyoto carbon targets derived from (more or less cost effective) reductions in other greenhouse gases that deviate from expectations (a 10% reduction in 2010 targets for carbon emissions, no change in 2010 targets, and a 10% increase in 2010 carbon emissions targets);
- four alternative structures for emissions-rights trading (no trading, limited Annex B trading, full global trading, and EU and 'rest of Annex B' trading bubbles); and
- two different post-2010 policies (freezing at the 2010 levels or moving from 2010 to limit atmospheric concentrations of greenhouse gases to 550 ppmv. with gradual non-Annex B participation).

The first three elements in this list reflect broad uncertainty about how the Protocol might be implemented; the last reflects uncertainty about what happens after 2010 given that the Framework Convention on Climate Change (FCCC) highlights concentrations and not emissions as the targets of mitigation policy. Each was thought to hold the potential of changing radically the dimension and distribution of the long-term cost of meeting the Kyoto objectives.

Models that are capable of differentiating adequately in their cost calculations across the diversity of Annex B and non-Annex B countries tend to be large and complicated. They can be used to explore the cost implications of some of the 72 combinations of 'policy uncertainty' reflected in the First Round EMF Exercise along selected 'reference (unregulated) emissions scenarios', but they cannot

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[2] The February EMF memo (Weyant, 1998a) records maximum sink potentials for a variety of countries: 300 million metric tons of carbon for the United States, 150 million metric tons of carbon for the European Union/Western Europe, 240 million metric tons of carbon for Canada, Australia and New Zealand, 600 million metric tons of carbon for Eastern Europe and the Former Soviet Union, 300 million metric tons of carbon for China, 300 millions metric tons of carbon for India, 300 million metric tons of carbon for Mexico and OPEC, and 900 million metric tons of carbon for the rest of the world. These are obviously aggregate estimates for which little underlying detail is available. Supply curves for these sinks have not yet been estimated, for example. Their potential will, in the analysis presented here and elsewhere, be exploited under the assumption that they cost significantly less than alternative means of reducing net emissions. The alternatives posted by the EMF reflect three possible outcomes of both off-line cost analyses and associated international negotiations that have yet to be completed.

typically be applied across collections of emission trajectories that span the ‘not-implausible’ range of possible futures. Nor can they be expected to accommodate a range of alternative long-term concentration targets. Nonetheless, the cost of meeting the Kyoto objectives should be extremely sensitive to the choice of baseline emissions *and* to the selection of long-term concentration limits. There is, therefore, value in using a simpler model explore the cost implications of imposing various versions of how the Kyoto Protocol might be implemented across a range of emissions futures *and* with alternative long-term targets for concentrations. Such an exploration would, by design, miss the insight provided by the more complicated models, but it could easily identify trajectories and targets for which the more detailed analyses that these models can sustain could be expected to pay the largest dividends.

This paper reports the results of a preliminary exploration of control costs drawn from applying just such a simple global model across seven internally consistent and unregulated reference emissions scenarios that span upwards of 80% of the published range of emissions for the year 2100. As such, this paper reports the results of a cost study. It decidedly does not draw its insights from an integrated assessment of the Kyoto Protocol, and it makes no attempt to track the benefit side of alternative emissions trajectories with or without mitigation. Section 2 briefly reviews the model, characterizes the driving forces behind the seven unregulated carbon emissions trajectories, and offers model-specific estimates of their subjective likelihoods. Section 3 explains how the division between Annex B and non-Annex B emissions was accomplished and reports some comparative (discounted) control cost statistics when global policy takes the FCCC seriously and ultimately targets maximum concentrations at 550 ppmv. It compares minimum discounted control costs with and without the 2010 Kyoto emissions benchmarks along:

- all seven scenarios assuming global emissions-permit trading in each year after 2010 with
- the three alternative assumptions about post-2010 carbon sinks identified in (1) above or
- the three alternative Kyoto carbon emissions targets for 2010 noted in (2) above.

Relying on a global marketable permit regime means that cost minima are reported here; that is to say, cost estimates will include the cost-reducing power of the ‘when’ and ‘where’ efficiency displayed in Wigley, Richels and Edmonds (1996) when moving from 2010 to a 550 ppmv. concentration limit. Section 4 then broadens the focus slightly by contemplating long-term concentration limits that are higher and lower than 550 ppmv. Caveats, conclusions, and research recommendations are offered in Section 5.

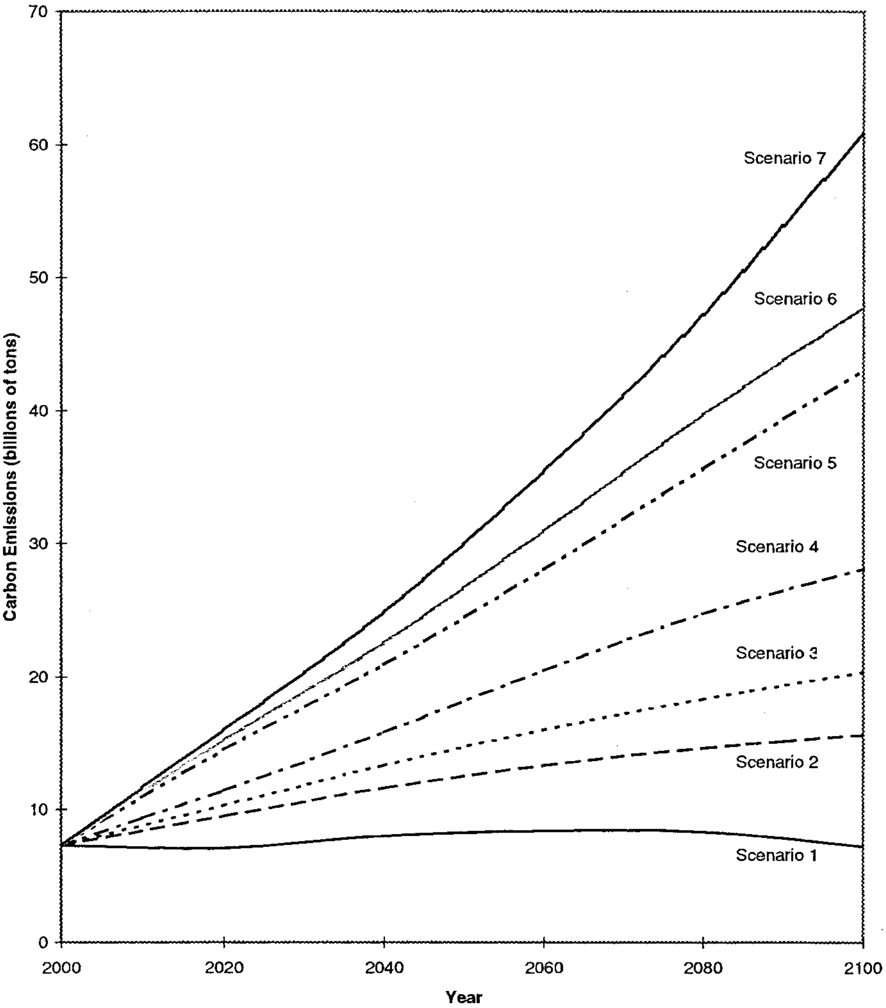

Figure 1 – Panel A. Alternative and representative carbon emissions trajectories derived from the global model.

2. The Model and the Representative Reference Scenarios

The results reported here are drawn from seven representative global emissions scenarios that were derived from the latest variant of an iterative global model designed to accommodate monte carlo simulation over multiple sources of uncertainty. Its details are reported in the appendix to Yohe et al. (1998).[3] The analysis that produced these seven representative scenarios focused on the four parameters

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[3] Readers familiar with the lineage of integrated assessment models will recognize the model as a combination of the probabilistic global emissions model published by Nordhaus and Yohe (1983) and the more recent DICE construction by Nordhaus (1994). The model variant employed

TABLE I

Characterization of the representative scenarios

Panel A: Scenario definition[a]

Scenario	Subjective likelihood	Population growth	Technological change	Depletion	Substitution elasticity
(S1)	0.27	L	H	H	H
(S2)	0.13	L	M	M	H
(S3)	0.23	M	L	L	H
(S4)	0.19	M	M	L	M
(S5)	0.09	H	L	H	L
(S6)	0.05	H	L	M	L
(S7)	0.04	H	L	L	L

Panel B: Scenario outcomes – carbon emissions in 2100[b]

Scenario	Partition	Representative	Low boundary	High boundary
(S1)	I	7.2	3.1	7.4
(S2)	II	15.6	7.6	17.5
(S3)	III	20.3	17.5	23.1
(S4)	IV	28.1	23.1	34.4
(S5)	V	43.1	34.6	45.2
(S6)	VI	47.8	45.3	52.2
(S7)	VII	60.8	52.5	69.9

[a] The subjective likelihoods reported emerge from the representative scenario selection process described in the text. H, M, and L reflect high, medium, and low assumptions about the indicated random variables. ‘H’ (‘L’) in the technological change column signifies that the real price of energy increases (decreases) over time. ‘H’ (‘L’) in the depletion column signifies that the price of carbon-based fuel reflects depletion by significant (small) increases in its real price; and ‘H’ (‘L’) in the substitution elasticity indicates large (small) abilities to substitute between carbon-based and noncarbon-based fuel.

[b] The emissions reported here are denominated in Gt of carbon. The representative scenarios are used to represent trajectories that are contained in the indicated partitions; their relative likelihoods are computed as the sum of the subjective weights of the scenarios whose emissions in 2100 lay between the lower and upper boundaries recorded in the third and fourth columns, respectively. The emissions trajectories, as well as their associated likelihoods, are clearly dependent upon the simple aggregate model from which they were drawn.

that were found to contribute most significantly to the range of emissions through the year 2100:

- the rate of technological change in the supply of energy (as reflected by the secular trend in the real price of energy),
- the rate of growth of population,

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here replaced the DICE representation of the carbon cycle with the Maier-Reimer and Hasselmann (1987) model as calibrated by Hammit et al. (1992) for their equation (2).

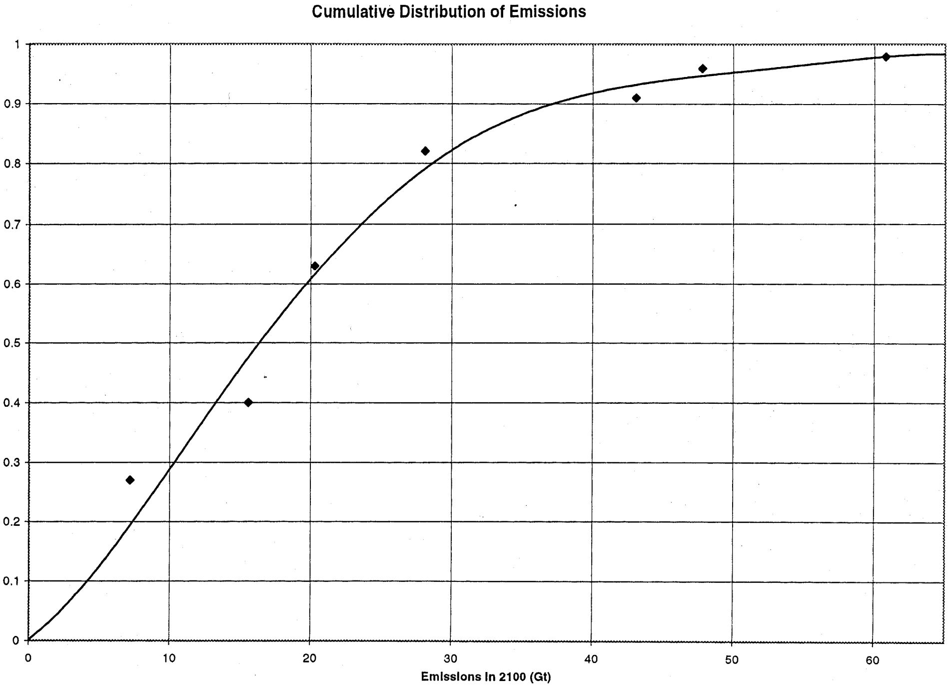

Figure 1 – Panel B. Cumulative distribution of representative carbon emissions derived from the global model for the year 2100.

- the degree to which depletion of carbon-based fuel is reflected over time in its real price, and
- the elasticity of substitution between carbon-based and noncarbon-based fuel.

High, middle, and low values for each had been determined so that they could be assigned subjective likelihood weights of 0.25, 0.50 and 0.25, respectively.[4] Each was combined with the median values of five other uncertain model parameters so that an exhaustive sampling of the resulting $3^4 = 81$ combinations reflected adequately the range of emissions variation generated by a simulation of more than 1000 randomly selected scenarios drawn from the larger set of 3^9 possible combinations.[5]

[4] In a procedure first employed in Nordhaus and Yohe (1983), underlying distributions of estimates for these (and other) parameters were constructed from published estimates. High, middle, and low values were then chosen for each so that assigning weights of 0.25, 0.50 and 0.25 would preserve both the means and variances of these underlying distributions.

[5] The other parameters included the rate of general productivity growth, bias in the rate of technological change toward the supply of noncarbon-based energy, the elasticity of substitution between energy and other factors of production, the composition of carbon-based energy, and the extraction cost of carbon-based energy. The original simulation included two times the number of runs required to sustain stability in the summary statistics of the distributions of all of the important outputs (global output, emissions, etc...).

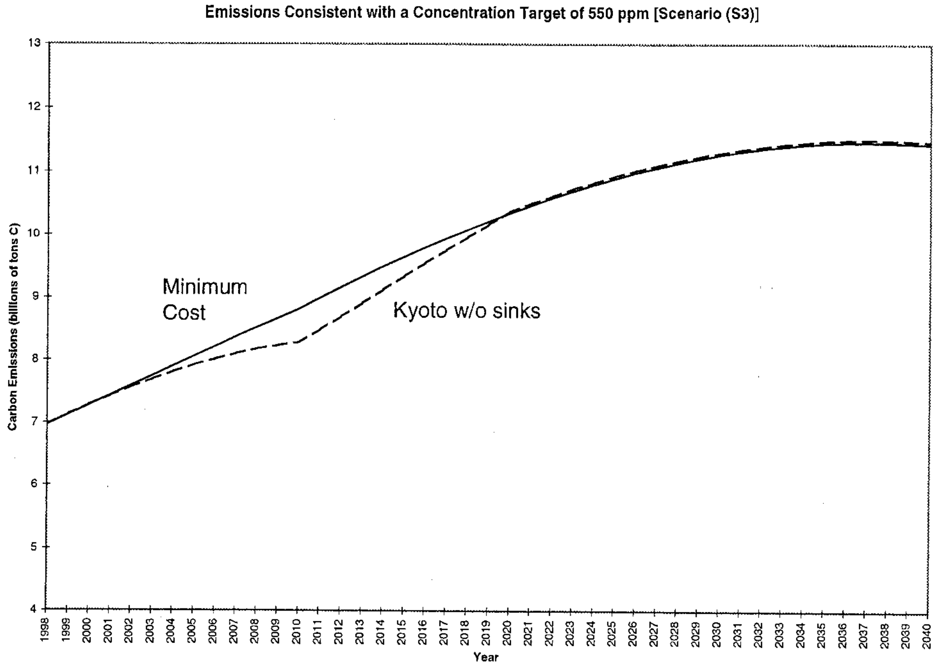

Figure 2 – Panel A. Emissions consistent with achieving a 550 ppmv. concentration target with and without passing through the Kyoto emissions target in 2010 along the (S3) scenario. Emissions are over-regulated by the Kyoto benchmark.

The 81 scenarios were then ranked in order of carbon emissions in the year 2100 and partitioned into seven groups. Following a methodology for selecting ‘interesting scenarios’ described in Yohe (1991), representative scenarios for each group were selected in a way that minimized the sum of the squared errors involved in describing the entire distribution of emissions in the year 2100 by a collection of only seven alternative trajectories.[6] The resulting representative scenarios are, henceforth, identified in ascending order as (S1) through (S7). Panel A of Figure 1

[6] The procedure started by noting that a relative likelihood could be assigned to each of the emission scenarios; it was the multiplicative product of the likelihoods of the values assigned to the four underlying uncertain parameters. Representative scenarios that minimized the probabilistically weighted sum of the squared errors across an arbitrary partitioning of all possible trajectories were then chosen for each partition. In the next step, the highest member of the lowest partition was moved to the next highest category, and a new set of error-minimizing representatives were selected. If the probabilistically weighted sum of squared errors across the entire distribution fell as a result, then the process was repeated by ‘promoting’ another member of the lowest partition. If the probabilistically weighted sum of squared errors rose, on the other hand, then the prospective new member of the higher partition was returned to its position in the lower category. This trial and error method was applied to all of the partition boundaries, in turn, until no further error-reducing transfers remained. Each representative scenario from this final set was then assigned a relative likelihood equal to the sum of the likelihoods of all of the scenarios included in its partition.

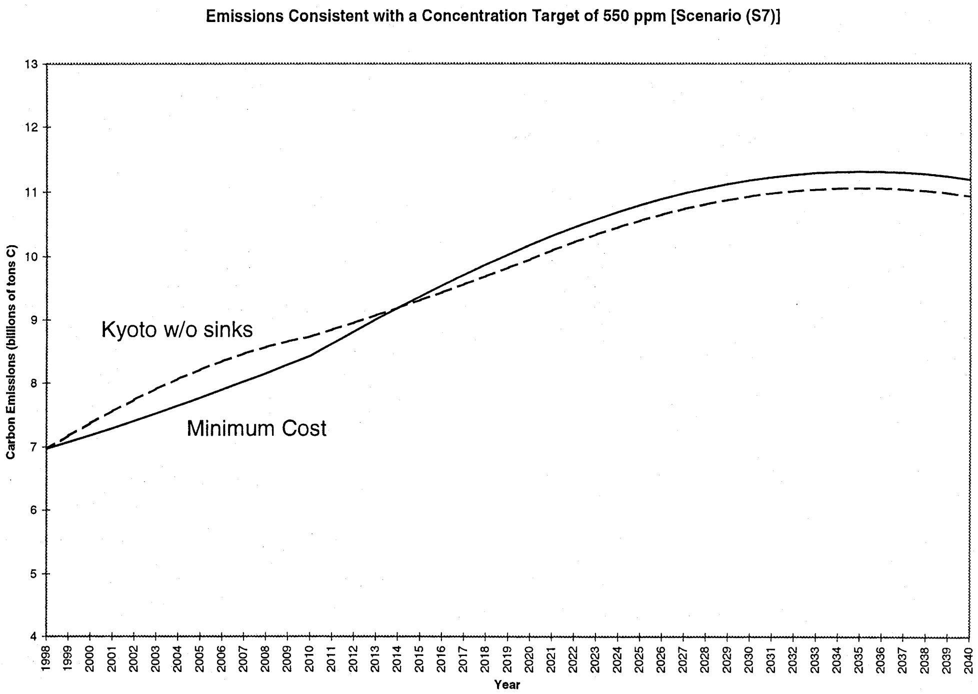
Emissions Consistent with a Concentration Target of 550 ppm [Scenario (S7)]

Figure 2 – Panel B. Emissions consistent with achieving a 550 ppmv. concentration target with and without passing through the Kyoto emissions target in 2010 along the (S7) scenario. Emissions are under-regulated by the Kyoto benchmark.

displays the seven emissions trajectories that emerge from the selection procedure for the next century; as reported in Schlesinger and Yohe (1998), they have all been calibrated to track actual emissions through 1997, and so they deviate only slightly from one another in the year 2000. Panel A of Table 1 highlights why they differ in the more distant future and indicates their respective subjective likelihoods.[7] Panel B records projected emissions for the year 2100 along each scenario; and it indicates the range of emissions captured in each partition. Panel B of Figure 1 finally depicts a cumulative distribution of emissions projected for the year 2100; the likelihoods reported in Table 1 are plotted there, and a smoothed trend line is superimposed.

All of the results depend critically on the model, and so their quality rests on these scenarios' spanning a reasonable range of future emissions – not too small, but not too large, either. It is, in confronting this issue of credibility, instructive to compare the range reported in Table 1 with ranges of published emissions trajectories that were derived from other models. How do (S1) through (S7) compare, for

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[7] It should be clear that the likelihoods assigned to the representative scenarios are very dependent upon both the model and the selection process. Within this particular modeling environment, though, they are quite consistent when alternative numbers of partitions are chosen.

instance, with the IS92 trajectories? Scenario (S3) is the representative 'median' trajectory. It corresponds for the year 2100 most closely (although not exactly) with the IS92a 'business as usual' scenario authored by the Intergovernmental Panel on Climate Change (Leggett et al., 1992); indeed, IS92a ends the century with emissions equal to 19.8 Gt. [2.5% lower than (S3)]. The IPCC offered scenarios on either side of IS92a, of course. The lowest (IS92c) landed at 4.6Gt. in 2100 – slightly below Scenario (S1); and the highest (IS92e) finished at 34.9 Gt. – below even Scenario (S5). How do (S1) through (S7) compare with other published projections? A spaghetti graph published for the IPCC as Figure 2 by Morita, et al. (1994) displayed a range for emissions in the year 2100 that ran between 1 Gt. and 60Gt., but its inner-90th percentile range was much smaller. Ninety percent of the recent scenarios reported there finished the year 2100 with emissions running from 5 Gt. on the low side to roughly 35 Gt. on the high side. Meanwhile, three of the four proposed emissions scenarios and story-lines that the IPCC released electronically for public review late in the summer of 1998 climb modestly between the years 2000 and 2100. In fact, only one shows total world emissions in excess of even the 20.3Gt. reflected by (S3) for the year 2100. Finally, the modelers' reference runs for the EMF First Round Modeling Exercise have now been reported. Weyant (1998b) shows that six of the eleven modeling groups that participated offered global emissions estimates for 2100 that ran roughly from 17 Gt. to 31 Gt.[8]

In light of these comparisons, it should be clear that the range reported in Panel B of Table 1 is not too small; but is it too large? The scenarios recorded there put much more subjective weight on emissions trajectories that run higher than most published 'baselines', but that is to be expected. Baselines are hardly ever chosen to reflect much more than a 'best guess' of one sort or another. It has been the experience of the Energy Modeling Forum that the dispersion in emissions across models is larger for a standard set of assumptions about driving variables than it is when the modelers get to 'fiddle' with those assumptions themselves.[9] Disagreement among modelers' published results may, therefore, underestimate the range of uncertainty that should be examined. Moreover, high-consequence and low-probability events, be they related to impacts or to the consequences of policy, are much more likely to appear along high scenarios; and so these scenarios cannot be ignored simply because they run above the published range. The threshold question of the applicability of an emissions scenario for a study of possibilities like this

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[8] Carbon concentrations for the year 2100 from the seven scenarios ran from 547 ppmv. to 1307 ppmv. This range is large, and the median scenario achieved a level of 773 ppmv. by 2100 – a value that places it exactly in the middle of sixteen modelers' reference scenarios reported to EMF-14 in 1996 (Weyant, 1996).

[9] This observation was first made in EMF-12, but it was a consistent theme until the organizers stopped specifying underlying scenarios of driving variables for fear of peoples' interpreting scenarios designed for model-difference diagnostics as 'best guesses' with the EMF 'stamp of approval.'

should, instead, be one of asking a question with a purposeful double-negative – is it *not implausible*?

The work here accepts the premise that scenario (S1) and scenarios (S5) through (S7) should be included in a consideration of *not implausible* futures because they are the products of inserting plausible futures for population, technological change, depletion-driven price effects and substitution potential into a standard emissions model. It is a model that, in defining scenarios (S2) through (S4), produced more standard trajectories for other combinations of the same driving variables. The model did not need much of a 'push' to reach 45 or 50 Gt. in emissions by 2100; nor did it need much in the way of braking to keep emissions below 10 Gt. over the same period. Slow population growth with each substitution out of fossil fuel worked to lower emissions below the median in the latter case; and high population growth with limited substitution accomplished the former.

3. Control Cost Comparisons for the 550 ppmv. Target Across Seven Emissions Trajectories

Table 2 records the present values of the control cost involved in limiting concentrations to 550 ppmv. along all seven emissions trajectories with and without passing through the Kyoto benchmark for two feasible policy alternatives:

- Annex B nations' meeting their Kyoto target by 2010 followed by a policy that limits atmospheric concentrations to 550 ppmv. at least cost; and
- the global community's adopting a policy in 1998 that limits concentrations to 550 ppmv. at least cost without regard to the Kyoto emissions 'checkpoint'.

Panel (A) covers the three alternative assumptions about carbon sinks for each scenario (no sinks; one-sixth of the estimated maximum potential, and two-thirds of that potential). Panel (B), meanwhile, reports results for the three alternative assumptions about the specification of the Kyoto benchmark for carbon emissions in 2010 (90%, 100% and 110% of the specified target). The control costs reported there were estimated, as usual, in terms of the dead-weight losses associated with restricting emissions by imposing a tax on the carbon content of fossil fuel equal to the reported shadow price. In the rarefied context of the model, the shadow price is equivalent to the price of carbon permits that would emerge from a market designed to effect the requisite emissions reduction; it is thus the minimum economic cost of removing the last ton of emissions from the global total. Since the model worked with a tax, though, it is important to note that the revenue was assumed to be recycled back into the system in a lump sum fashion. The cost estimates reported therefore assume full trading of emissions permits, and so each reflects maximal 'where' efficiency (subject to passing through the Kyoto target in case (1)). It is equally important to note that the reported costs reflect 'when' efficiency

TABLE II

Control costs with concentrations limited to 550 ppmv.[a]

A. Minimum costs vs Kyoto with alternative sink specifications

	Minimum cost[b]			Cost with Kyoto[c]			Difference[d]		
Scenario	Base	1/6	2/3	Base	1/6	2/3	Base	1/6	2/3
(S1)	0.000	0.000	0.000	0.009	0.009	0.009	0.009	0.009	0.009
(S2)	0.659	0.486	0.163	0.667	0.496	0.180	0.008	0.010	0.017
(S3)	2.118	1.756	0.979	2.125	1.766	1.002	0.007	0.010	0.023
(S4)	3.300	2.763	1.605	3.304	2.770	1.627	0.004	0.007	0.022
(S5)	8.128	7.139	4.892	8.143	7.148	4.904	0.015	0.009	0.012
(S6)	11.490	10.224	7.325	11.523	10.242	7.333	0.033	0.018	0.008
(S7)	16.124	14.502	10.755	16.197	14.545	10.765	0.073	0.043	0.010

B. Minimum costs vs Kyoto with alternative emissions targets for 2010

	Minimum cost[e]			Cost with Kyoto[f]			Difference[g]		
Scenario	–10%	Base	+10%	–10%	Base	+10%	–10%	Base	+10%
(S1)	0.000	0.000	0.000	0.025	0.009	0.002	0.025	0.009	0.002
(S2)	0.659	0.659	0.659	0.681	0.667	0.661	0.022	0.008	0.002
(S3)	2.118	2.118	2.118	2.136	2.125	2.120	0.018	0.007	0.002
(S4)	3.300	3.300	3.300	3.313	3.304	3.303	0.013	0.004	0.003
(S5)	8.128	8.128	8.128	8.139	8.143	8.156	0.011	0.015	0.028
(S6)	11.490	11.490	11.490	11.507	11.523	11.545	0.017	0.033	0.055
(S7)	16.124	16.124	16.124	16.167	16.197	16.235	0.043	0.073	0.111

[a] Annual costs, calculated in terms of dead-weight loss, are discounted through the year 2100 according to the Ramsey rule noted in the text. All losses are in trillions of 1990 dollars.

[b] Minimum discounted costs of limiting concentrations to 550 ppmv. with the indicated allowances for sinks.

[c] Discounted costs of passing through the Kyoto emissions benchmark and subsequently limiting concentrations to 550 ppmv with the indicated allowances for sinks.

[d] Computed simply as the arithmetic difference between the discounted costs with the Kyoto benchmark and the minimum cost with the indicated allowances for sinks.

[e] Minimum discounted costs of limiting concentrations to 550 ppmv. with no adjustment in 2010 emissions targets.

[f] Discounted costs of passing through the Kyoto emissions benchmark and subsequently limiting concentrations to 550 ppmv. with the indicated adjustment in 2010 emissions targets.

[g] Computed simply as the arithmetic difference between the discounted costs with the alternative Kyoto emissions benchmarks for 2010 and the minimum cost.

for ‘investment’ in climate policy because they are solutions to an intertemporal cost-minimizing problem using the Ramsey discount rule.[10]

The model described above is, of course, a global model whose very construction ignored the geographical distribution of emissions. The distinction between emissions from Annex B and non-Annex B countries was therefore artificially imposed. To be precise, the scenarios that observed the Kyoto checkpoint assumed that the contribution of non-Annex B countries would, with no intervention, climb from 41.0% of the world’s total in 1990 to 48.2% of the world’s total by 2010.[11] As a result, adhering to the Kyoto emissions targets meant that the remaining 51.8% of what would be unregulated emissions in the year 2010 denoted $E^{u}{}_{2010}$ that were allocated to Annex B had to fall to 94.8% of the Annex B share of 1990 global emissions denoted E_{1990}. That is, they had to fall to

$$(.948) \times (1 - .41) \times [E_{1990}] = 3.7\text{Gt}.$$

Global emissions tracked by the model along each scenario were therefore forced to fall to

$$(.482)[E^{u}_{2010}] + .948(1 - .41)[E_{1990}]\text{Gt}. = \{(.482)[E^{u}_{2010}] + 3.7\}\text{Gt}.$$

by the year 2010 to meet the Kyoto objectives.

Some graphical representations of selected emissions trajectories can make reading Table 2 a bit easier. Figure 2 displays emissions trajectories for two scenarios [(S3) and (S7)] for both of the policy alternatives. Notice that making emissions

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[10] The Ramsey discounting rule is derived from optimal growth theory. Koopmans (1967) is a primary source for a thorough derivation, but the intuition behind its definition is not too difficult. It begins by noting that individuals usually demonstrate what is termed a ‘pure rate of time preference’ – the rate at which they are willing to trade present consumption for future consumption when confronted with constant income over time. The work here presumes that this is 3%, meaning that individuals who have $X available for consumption in each of two successive years would willingly trade exactly $1.00 in consumption in the first year for an extra $1.03 in consumption during the second. The Ramsey rule then adds a ‘growth discounting factor’ equal to the rate of growth of per capita consumption multiplied times the elasticity of the marginal utility of consumption. The idea here is that each marginal increase in consumption has utility (i.e., ‘marginal utility’ is positive), but that that this marginal utility declines as consumption increases. For example, then, an extra dollar of consumption would be worth less in utility terms if consumption were initially $10,000 per year than it would be if consumption were $5,000 per year. The work here presumes that utility is logarithmic in per capital consumption so that the critical elasticity of marginal utility is unity. The Ramsey rule therefore simply adds the rate of growth of per capita consumption computed by the model to the assumed 3% pure rate of time preference.

[11] These estimates were drawn from Wigley (1998). He prepared them for IS92a; proportionality in the relative contribution of Annex B and non-Annex B was assumed for all other emissions scenarios. In every case, Annex B was held to 3.7 Gt. of emissions in 2010 (94.8% of the 1990 total of 3.9 Gt.), but non-Annex B emissions grew through 2010 as they would have without any Kyoto accord. The post-Kyoto environment then imposed a cost-minimizing trajectory on global emissions from the resulting world sum in 2010 – a sum that was different for each scenario.

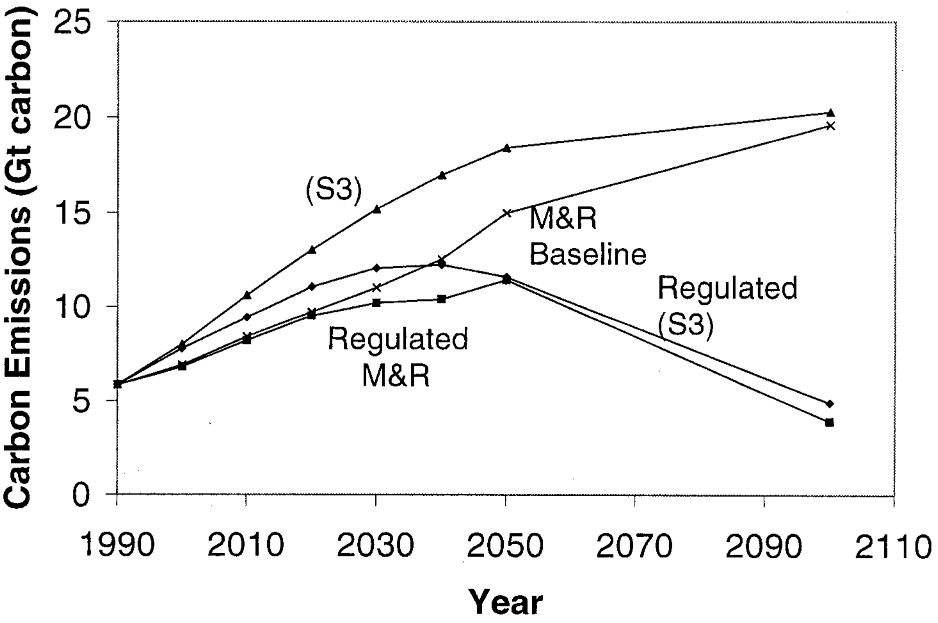

Figure 3. Unregulated emissions for scenario (S3) track above the Manne and Richels (1997) representation of the IPCC IS92a scenario designed M&R Baseline. Emissions restricting concentrations to 550 ppmv. run correspondingly higher for (S3) than along the analogous Manne and Richels trajectory designated Regulated M&R; they are nonetheless the result of more aggressive emissions reduction.

pass through the Kyoto checkpoint is not necessarily consistent with minimizing the cost of limiting concentrations at 550 ppmv. That should not be a surprise, though; passing through the Kyoto target for 2010 could hardly be expected to be right for every emissions path. Perhaps more surprisingly, passing through the Kyoto checkpoint can be either ‘too restrictive’ or ‘too permissive’ relative to the cost minimizing policy along lower or higher emissions trajectories, respectively. A quick comparison of the two panels makes this point. Emissions run below the least cost trajectory on their way through the Kyoto target for Scenario (S3) but *above* the least cost trajectory for Scenario (S7). As a result, associated graphs that would display the trajectories of the shadow prices of carbon would show the shadow price of carbon falling short of the least cost path for the Kyoto-constrained (S7) trajectory, but running *higher* for (S3). Figure 3 meanwhile reveals, for reference, that the minimum cost trajectory for the median (S3) tracks above the Manne and Richels (1997) least cost path derived from IS92a. Notice, though, that the unregulated (S3) scenario runs significantly higher than IS92a for much of the next century (even though it comes close in the year 2100); as a result, the least cost path from (S3) involves significantly larger reductions in near-term emissions and thus significantly higher cost.

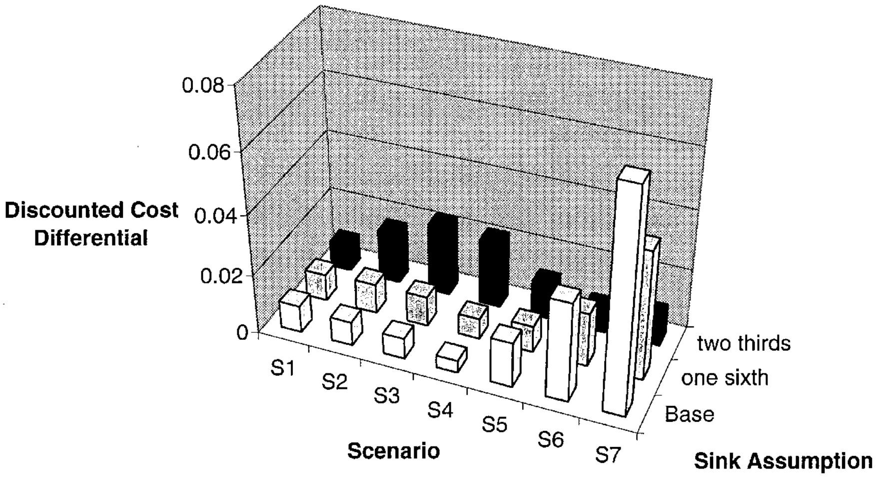

Figure 4 – Panel A. Differentials between the minimum control cost of limiting concentrations to 550 ppmv. along alternative emissions scenarios passing through sink-determined variants of the Kyoto benchmark for the year 2010.

Turning now to the details portrayed across the entirety of Panels A and B of Table 2, notice that both report that the minimum discounted cost of limiting concentrations to 550 ppmv. is $2.118 trillion (1990$) and $16.124 trillion (1990$) along scenarios (S3) and (S7), respectively. When constrained to pass through the nominal Kyoto target, however, the comparable costs are $2.125 trillion (1990$) and $16.197 trillion (1990$). The extra discounted cost involved in passing through the Kyoto target is not enormous, but it is nonetheless denominated in tens of billions of aggressively discounted present value dollars. The careful reader will have nonetheless noted that the minimum discounted cost statistic for (S3) is significantly higher than the $0.6 trillion (1990$) estimate reported in Manne and Richels (1997). Recall from Figure 3, though, that Manne and Richels worked from the IS92a scenario with its emissions trajectory that runs significantly below (S3) well into the next century. Indeed, Scenario (S2) tracks IS92a more closely through 2060 or so; and Table 2 reports a minimum discounted cost for limiting concentrations to 550 ppmv. along (S2) of $0.659 trillion (1990$) – a value that is quite comparable to the Manne and Richels estimate.

The two panels of Figure 4 display the cost-differential content of Table 2 graphically. Differences in discounted costs reported in Table 2 between the minimum cost trajectory and the various Kyoto benchmarks are portrayed there for the seven emissions trajectories in combination with the alternative sink [Panel (A), again] and Kyoto-target [Panel (B)] assumptions defined in the column headings. Notice that there is a ‘trough’ running through both that indicates combinations for which passing through the Kyoto checkpoint is least expensive. Panel A shows, more specifically, that the smallest extra cost imposed by moving through the Kyoto

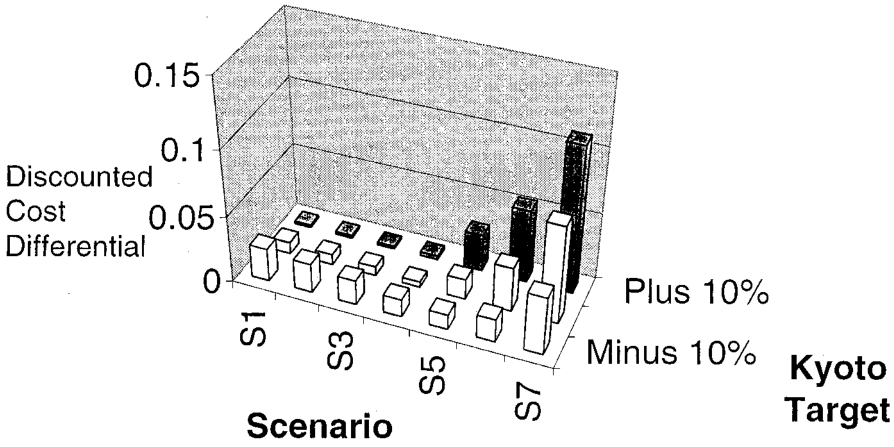

Figure 4 – Panel B. Differentials between the minimum control cost of limiting concentrations to 550 ppmv. along alternative emissions scenarios passing through target-determined variants of the Kyoto benchmark for the year 2010.

benchmark on the way to restricting concentrations to 550 ppmv. runs from $4 billion (1990$) to $8 billion (1990$) depending on the sink assumption. The trough for alternative sinks runs ‘southwest’ from the (S6); ‘Two-third’ Sinks combination to the (S4); ‘Base’ combination. Move from the bottom of the trough toward higher emissions for any sink assumption and the added discounted cost of passing through the Kyoto checkpoint climbs to more than $70 billion (1990$) for the base-case (no) sink assumption because it becomes increasingly permissive relative to the least cost trajectory. Move, conversely, toward lower emissions and the discounted cost of passing the checkpoint climbs to as much as $9 billion for the baseline because it is too restrictive.[12]

Panel B of Figure 4 shows the results of contemplating alternative carbon benchmarks for the year 2010. It shows that the smallest extra cost imposed by moving through alternative Kyoto benchmarks as concentrations are limited to 550 ppmv. runs from $2 billion (1990$) to $11 billion (1990$) depending on the target. The trough for alternative targets now runs ‘northwest’ – this time from the {(S5); ‘Minus 10%’ target} combination to the {(S3); + 10%’ target} combination. Move from the bottom of the trough toward higher emissions for any sink assumption and the added discounted cost of passing through the Kyoto checkpoint climbs to more than $110 billion (1990$) for the ‘Plus 10%’ target because it becomes increasingly permissive relative to the least cost trajectory. Move, conversely, toward lower emissions and the discounted cost of passing through the Kyoto checkpoint climbs to as much as $25 billion for the ‘Minus 10%’ target because it is too restrictive.

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[12] Note that the estimates of additional costs also fall as unregulated emissions fall for the maximum sink assumption; this is because little cost is incurred to meet the 550 ppmv. limit along the lowest emissions trajectories.

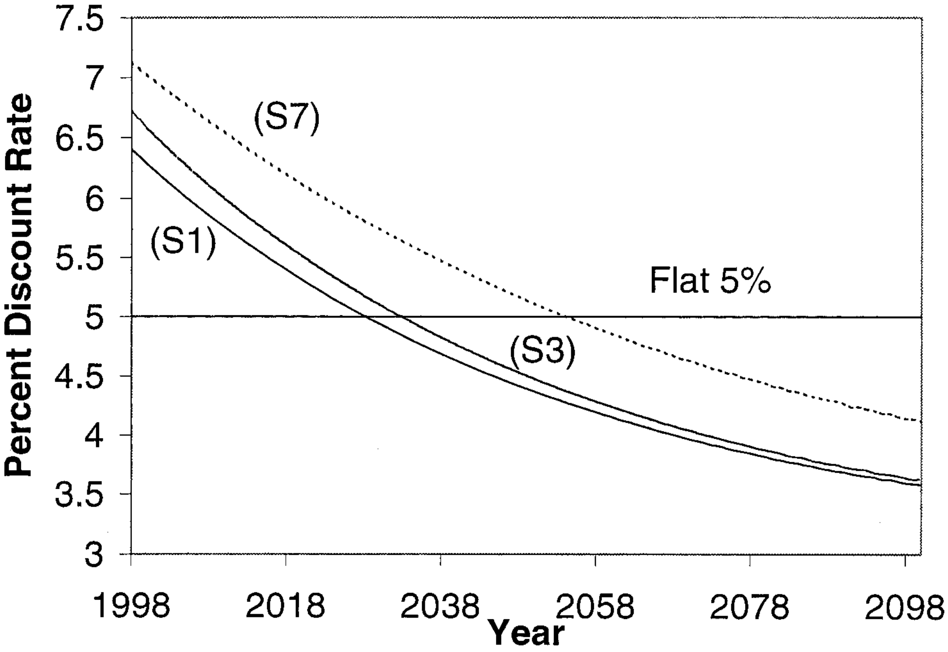

Figure 5. Discount rates derived from the Ramsey rule for scenarios (S1), (S3) and (S7) are drawn along constrained trajectories that limit concentrations to 550 ppmv. Each starts above the 5% level chosen by Manne and Richels (1997); but each falls well below 5% by the middle of the next century.

Two technical details need to be reviewed before the implications of setting alternative concentration targets are explored. Recall from footnote 10, first of all, that the Ramsey discount rule was employed with the pure rate of time preference set at 3% and aggregate welfare presumed to be logarithmic in per capita consumption. Discounting has been a source of controversy in weighing the economics of global change for several years, and the reader is referred to Heal (1997) and Arrow et al. (1995) for some current commentary. For present purposes, though, it is enough to ponder the difference between using the discounting Ramsey rule and using a constant rate of 5%, as in Manne and Richels (1997). Figure 5 compares the Ramsey rule discount rates for Scenarios (S1), (S3) and (S7) along the minimum cost emissions trajectories that limit concentrations to 550 ppmv. and graphically compares them with a fixed 5% fixed rate. The Ramsey rule imposes higher early rates along each scenario, driven by growth rates in per capita consumption in excess of 2% per year; and so they work to keep the cumulative discount factor in any year through 2100 lower than the compounded 5% alternative.

Secondly, the model presumes that there are no pre-existing distortions in the world economy whose inefficiencies could be diminished by imposing an emissions reduction policy. Just as in the case of alternative means for recycling any tax revenue generated by such a policy, Schneider and Goulder (1997) have, among

TABLE III

Control costs with concentrations limited to 450 ppmv.[a]

A. Minimum costs vs Kyoto with alternative sink specifications

	Minimum cost[b]			Cost with Kyoto[c]			Difference[d]		
Scenario	Base	1/6	2/3	Base	1/6	2/3	Base	1/6	2/3
(S1)	1.975	1.349	0.332	2.017	1.367	0.333	0.042	0.018	0.001
(S2)	5.630	4.439	2.189	5.776	4.519	2.197	0.146	0.080	0.008
(S3)	10.135	8.361	4.866	10.473	8.566	4.906	0.338	0.205	0.040
(S4)	14.968	12.337	7.220	15.578	12.713	7.302	0.610	0.376	0.082
(S5)	27.174	23.049	14.816	28.574	23.969	15.079	1.400	0.920	0.263
(S6)	34.428	29.401	19.391	36.227	30.603	19.764	1.799	1.202	0.373
(S7)	44.407	38.224	25.877	47.041	40.026	26.494	2.634	1.802	0.617

B. Minimum costs vs Kyoto with alternative emissions targets for 2010

	Minimum cost[e]			Cost with Kyoto[f]			Difference[g]		
Scenario	–10%	Base	+10%	–10%	Base	+10%	–10%	Base	+10%
(S1)	1.975	1.975	1.975	1.996	2.017	2.045	0.021	0.042	0.070
(S2)	5.630	5.630	5.630	5.731	5.776	5.827	0.101	0.146	0.197
(S3)	10.135	10.135	10.135	10.400	10.473	10.551	0.265	0.338	0.416
(S4)	14.968	14.968	14.968	15.463	15.578	15.696	0.495	0.610	0.728
(S5)	27.174	27.174	27.174	28.389	28.574	28.764	1.215	1.400	1.590
(S6)	34.428	34.428	34.428	36.008	36.227	36.450	1.580	1.799	2.022
(S7)	44.407	44.407	44.407	46.770	47.041	47.318	2.363	2.634	2.911

[a] Annual costs, calculated in terms of dead-weight loss, are discounted through the year 2100 according to the Ramsey rule noted in the text. All losses are in trillions of 1990 dollars.

[b] Minimum discounted costs of limiting concentrations to 450 ppmv. with the indicated allowances for sinks.

[c] Discounted costs of passing through the Kyoto emissions benchmark and subsequently limiting concentrations to 450 ppmv. with the indicated allowances for sinks.

[d] Computed simply as the arithmetic difference between the discounted costs with the Kyoto benchmark and the minimum cost with the indicated allowances for sinks.

[e] Minimum discounted costs of limiting concentrations to 450 ppmv. with no adjustment in 2010 emissions targets.

[f] Discounted costs of passing through the Kyoto emissions benchmark and subsequently limiting concentrations to 450 ppmv. with the indicated adjustment in 2010 emissions targets.

[g] Computed simply as the arithmetic difference between the discounted costs with the alternative Kyoto emissions benchmarks for 2010 and the minimum cost.

others, observed that this can be a big omission. The reported costs can, in this regard, be interpreted as maximum estimates, *under the assumption that all of their other incumbent 'when' and 'where' efficiencies are exploited fully.*

4. Alternative Concentration Targets

Tables 3 and 4 report the results of repeating the analysis for alternative concentration targets. If concentrations were ultimately limited to 450 ppmv., for example, then Table 3 would apply. Careful review of its contents reveals

- that the additional cost associated with passing through the Kyoto benchmark is exaggerated in comparison with the 550 ppmv. case and
- that passing through the benchmark is, in this case, always too permissive.

Panel A reveals further that adding sink capacity to both the post-Kyoto policy environment and the minimum cost context lowers the cost of holding to the Kyoto accord. Adding sink capacity reduces the incumbent permissiveness of the Kyoto target because sinks diminish the emissions restraint required to cap concentrations at 450 ppmv. Adding sinks lowers control costs for both policies, but they fall faster along the Kyoto run. Panel B meanwhile illustrates that relaxing the Kyoto benchmark for carbon works in the opposite direction to increase the additional cost of the Kyoto accord; increasing allowable emissions in 2010 would only serve to aggravate its under-restriction of near-term emissions on the way to a lower concentration limit.

The costs of complying with 650 ppmv. concentration limit are portrayed in Table 4. Careful review of this case reveals, conversely,

- that the additional cost associated with passing through the Kyoto benchmark is diminished relative to the 550 ppmv. case and
- that passing through the benchmark is, for this higher concentration limit, always too restrictive.

Panel A builds on these insights to show that adding sink capacity to both the post-Kyoto policy environment and the minimum cost context increases the cost of holding to the Kyoto accord, now because adding sink capacity exaggerates Kyoto's over-regulation of emissions in the near-term. Adding sinks again lowers control costs for both policies, but now they fall faster along the cost-minimizing trajectory. Panel B finally reveals, as should be expected, that relaxing the Kyoto benchmark actually lowers the additional cost of the Kyoto accord because increasing allowable emissions in 2010 works against over-restriction of near-term emissions on the way to a higher concentration limit.

TABLE IV

Control costs with concentrations limited to 650 ppmv.[a]

A. Minimum costs vs Kyoto with alternative sink specifications

	Minimum cost[b]			Cost with Kyoto[c]			Difference[d]		
Scenario	Base	1/6	2/3	Base	1/6	2/3	Base	1/6	2/3
(S1)	0.000	0.000	0.000	0.009	0.009	0.009	0.009	0.009	0.009
(S2)	0.005	0.000	0.000	0.029	0.025	0.025	0.024	0.025	0.025
(S3)	0.362	0.279	0.110	0.400	0.319	0.157	0.038	0.040	0.047
(S4)	0.662	0.529	0.248	0.705	0.575	0.303	0.043	0.046	0.055
(S5)	2.820	2.485	1.692	2.857	2.529	1.751	0.037	0.044	0.059
(S6)	4.640	4.179	3.062	4.667	4.212	3.111	0.027	0.033	0.049
(S7)	7.247	6.620	5.081	7.265	6.645	5.125	0.018	0.025	0.044

B. Minimum costs vs Kyoto with alternative emissions targets for 2010

	Minimum cost[e]			Cost with Kyoto[f]			Difference[g]		
Scenario	–10%	Base	+10%	–10%	Base	+10%	–10%	Base	+10%
(S1)	0.000	0.000	0.000	0.025	0.009	0.002	0.025	0.009	0.002
(S2)	0.005	0.005	0.005	0.050	0.029	0.015	0.045	0.024	0.010
(S3)	0.362	0.362	0.362	0.425	0.400	0.382	0.063	0.038	0.020
(S4)	0.662	0.662	0.662	0.733	0.705	0.684	0.071	0.043	0.022
(S5)	2.820	2.820	2.820	2.885	2.857	2.838	0.065	0.037	0.018
(S6)	4.640	4.64	4.640	4.690	4.667	4.652	0.050	0.027	0.012
(S7)	7.247	7.247	7.247	7.283	7.265	7.255	0.036	0.018	0.008

[a] Annual costs, calculated in terms of dead-weight loss, are discounted through the year 2100 according to the Ramsey rule noted in the text. All losses are in trillions of 1990 dollars.

[b] Minimum discounted costs of limiting concentrations to 650 ppmv. with the indicated allowances for sinks.

[c] Discounted costs of passing through the Kyoto emissions benchmark and subsequently limiting concentrations to 650 ppmv. with the indicated allowances for sinks.

[d] Computed simply as the arithmetic difference between the discounted costs with the Kyoto benchmark and the minimum cost with the indicated allowances for sinks.

[e] Minimum discounted costs of limiting concentrations to 650 ppmv. with no adjustment in 2010 emissions targets.

[f] Discounted costs of passing through the Kyoto emissions benchmark and subsequently limiting concentrations to 650 ppmv. with the indicated adjustment in 2010 emissions targets.

[g] Computed simply as the arithmetic difference between the discounted costs with the alternative Kyoto emissions benchmarks for 2010 and the minimum cost.

5. Concluding Remarks – Caveats and Research Recommendations

There are, of course, a large number of caveats that must be recorded before the results reported here can be taken in their proper context. Some are obvious; but it should be noted that many of the most obvious sources of concern are also sources of "strength' because the point of the exercise was to prepare a quick review of potentially interesting questions across a wide range of possible futures. The model is very aggregated and presents a painfully oversimplified view of the world; but that simplicity sustains concise and understandable portraits of how and why global emissions might track above or below any single 'best-guess' business as usual scenario. The model treats the division between Annex B and non-Annex B countries artificially; but it nonetheless supports broad and suggestive analysis without making overly sensitive political assumptions. The link from emissions to potential damage is ignored for the most part because this is a cost analysis; but there is a modest and extremely simple feedback link between damage caused by increased concentrations of greenhouse gases and contemporaneous economic activity. In an exercise designed to examine the cost side of policies that are not proposed on the basis of economic optimization, though, this is all that is required. The discounting is more aggressive than in models where a constant positive rate of interest is presumed. Adhering to what Arrow, et al (1995) would call a descriptive approach is, however, perhaps more appropriate in a cost analysis where the ultimate question ponders how to minimize the cost of investing in climate change mitigation policy. Indeed, it is the discounted cost of this investment that will be compared with the costs of other social investments for which the benefit side of the calculus is equally difficult to perform. Finally, the model includes a static biosphere. This is perhaps the most damaging limitation, but it is fairly standard at this point. The list of caveats can be extended, but to what end? The point of the exercise was to uncover some hypotheses about the policy regime that will ultimately evolve from the Kyoto Protocol so that more detailed and 'realistic' models can be deployed most effectively as we try to improve our understanding of that regime.

This preliminary analysis suggests that holding ourselves to the emissions targets that emerged from the Kyoto meeting can increase the discounted cost of ultimately limiting atmospheric concentrations for one of two reasons. The Kyoto targets can be either too restrictive *or* too permissive depending upon *both* the trajectories of carbon emissions over the near- to medium-term *and* the concentration target that frames long-term policy. Table 5, for example, applies the results of Tables 2 through 4 to match combinations of emissions trajectories (from low to high) and ultimate concentration targets (again, from low to high) with sink and 2010 emissions targets that would bring the Kyoto targets closest to the least cost trajectories. Low concentration targets like 450 ppmv. favor allowing large sinks *and* more restrictive near-term emissions benchmarks (even if only Annex B countries were bound). High concentration targets like 650 ppmv. favor allowing no sinks *and* less restrictive emissions benchmarks. Intermediate concentration

TABLE V

Cost minimizing combinations of Kyoto targets for alternative concentration targets and alternative emissions trajectories[a]

Concentration target Scenario	450 ppmv	550 ppmv	650 ppmv
(S1)	2/3 sink –10%	Base sink +10%	Base sink +10%
(S2)	2/3 sink –10%	Base sink +10%	Base sink +10%
(S3)	2/3 sink –10%	Base sink +10%	Base sink +10%
(S4)	2/3 sink –10%	Base sink +10%	Base sink +10%
(S5)	2/3 sink –10%	1/6 sink –10%	Base sink +10%
(S6)	2/3 sink –10%	2/3 sink –10%	Base sink +10%
(S7)	2/3 sink –10%	2/3 sink –10%	Base sink +10%

[a] The entries in this table indicate sink allowances and adjustments in carbon emissions targets for the year 2010 that correspond with the smallest incremental increases in the discounted control cost when emissions are constrained to the Kyoto benchmark on the way to holding concentrations below the indicated limits for the designated scenarios. Scenarios (S1) through (S7) are listed in ascending order of unregulated emissions in the year 2100 as illustrated in Figure 1.

targets like 550 ppmv. look like high concentration targets (favoring no sinks and expanded near-term emissions) along low emissions paths; but they look like low concentration targets (favoring the opposite) along high emissions paths. Emissions trajectories that lie above the median, but not excessively so, are intermediate cases where no adjustments in benchmarks and/or modest allowances for sinks would be most appropriate.

The complication depicted in Table 5 underscores the need for flexible and adaptive mitigation policy of the sort being proposed by Hammit et al. (1992), Lempert et al. (1996) as well as Schellnhuber and Yohe (1997). Both look for policies that can be set for periods of time with a clear understanding of how and when they might be changed in the future as uncertainty is resolved and things like concentration targets become more well defined. Reviewing the content of Table 5 does more than that, though. It suggests, as well, that cost-conscious policy-makers can use modestly flexible emission benchmarks and/or adjustable allowances for sinks as ‘policy handles’ with which they can make the appropriate adjustments.

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