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Fixing global carbon emissions: choosing the best target year[1]

Gary Yohe
Wesleyan University, Middletown, CT, USA

Tricia Malinowski
Trinity College, Hartford, CT, USA

Marielle Yohe
Wellesley College, Wellesley, MA, USA

Confronted with issues fraught with the enormous complexity, policy makers have shown a proclivity towards considering and enacting simple and apparently equitable structures that can be easily explained to and understood by their constituents. In the global change arena, this tendency seems to lead to consideration of global emissions targets defined by levels achieved in some specific year along a previously unregulated trajectory. The question raised then is one of determining which year's emissions would, if set as a global limit, maximize the discounted net benefit of the policy? In addition, how sensitive is that year to changes in the damages associated with a doubling of atmospheric concentrations of greenhouse gases and/or the pace of near-term, unregulated emissions of those gases? Results produced here support two qualitative results that speak to the answers to these questions. Support for limiting emission below levels that would be achieved along almost any reasonable unregulated trajectory prior to the year 2020 requires, first of all, accepting the notion that doubling damages will be at least 5% of world GDP. Secondly, discovering that the globe is moving along an emissions trajectory that is higher than otherwise expected need not imply that the target year for fixing emissions should be moved forward; indeed, higher emissions sometimes mean that the discounted net benefit of fixing emissions climbs as the target year is pushed further into the future.

It is an understatement of historic proportion to assert that confident answers to the myriad of policy questions posed by the prospect of global climate change are extraordinarily elusive. Uncertainty dominates any discussion of how to respond, to be sure, but uncertainty is by no means the only source of difficulty. Time horizons are nearly an order of magnitude longer than those confronted in more traditional planning problems, and the international distributions of costs and benefits are diverse and complicated. Still, decision-makers are being asked to propose policy in support of the Framework Convention on Climate Change (FCCC), at least for the near term, even as researchers struggle to reduce uncertainty, philosophers try to deal with intergenerational discounting, and politicians look for ways of handling distributional inequities.

Which of the policies that have or will be proposed have a chance of being enacted? Notwithstanding the Third Conference of the Parties of the FCCC scheduled for four months hence in late 1997 in Kyoto, it will likely be a long time before this question can be answered. If they are to contribute anything to the debate, however, policy analysts must take the risk of describing some notion of how the globe will respond. Some researchers like Nordhaus (1994a) and Manne

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et al. (1995), for example, have looked at the issue as one of dynamic optimization; and so they assume implicitly that global decisions will be made on the basis of economic efficiency as they produce complicated tax trajectories over hundreds of years. Others like Manne and Richels (1995) and Yohe (1996 and 1997) look at the uncertainty and contemplate hedging against "high consequence-low probability" events; they produce similar long-term policy trajectories, but their estimates of near-term behavior are based upon arbitrary assumptions about how and when knowledge of about the future will become clearer. Still others like Kolstad (1993) and Lempert *et al.* (1996) look for near-term policies that are "robust" in the sense of being adequate across a wide range of possible futures. Finally, a growing cohort of analysts like Wigley *et al.* (1996) and Toth *et al.* (1997) try to evaluate alternative policy suggestions outside of the conventional cost-benefit framework.

The work described here takes a tact that is very similar to the one that has to be adopted by this last group. It observes that decision makers frequently enact the simplest and most transparent policies when they are confronted with enormous complexity. Simple policies are the easiest to explain; and if they appear to be fair, at least on the surface, then all the better. In the global change arena, this observation suggests that global decisions will likely set policy targets tied directly to something that is (1) easily measured and (2) obviously labelled as the source of the problem. Emissions of greenhouse gases (GHGs) fit both criteria, so perhaps it is not surprising that most of the negotiation on global mitigation has focused on fixing emissions at some fraction of 1990 levels (for the so-called Annex I countries, at least) by sometime in the early part of the next century. Members of the European Community are currently negotiating among themselves to see how they might reduce their total GHG emissions to 80% or 85% of 1990 levels by the year 2010. It is, however, unlikely that any agreement on such a target will require all members to effect the same reduction. Indeed, countries like Spain may actually be allowed to increase their emissions while others like Germany will agree to reduce theirs by 20 or 25 percent. The United States has meanwhile pledged itself to emissions "restraint", but it has been reluctant to back that pledge with specific numbers; and Japan has assumed a similar stance.

Even before specific targets and timetables for emissions reduction have been solidified, however, it is certainly reasonable to take the prevailing focus on emissions as a signal of policy-maker preference; and from there, of course, it is not a large step to see that there is nothing special about 1990 emissions-except perhaps that they provide some historical context. Why not fix emissions at levels that will be achieved in the year 2000? Indeed, the relevant second best policy question becomes "What year's unregulated emissions should define the emissions limit?" Should emissions be allowed to climb unhindered through the year 2000 and then be fixed? or should the limit be delayed until the year 2010? or 2020?

This paper explores this set of questions over a range of unregulated emissions trajectories that spans current opinion of possibility. Section I describes the global emissions model that supports the analysis. A selection procedure leads to seven representative emissions trajectories along which the relative efficacy of fixing emissions at various levels can be explored. Section II offers some theory that (1) describes simply the sensitivity of the best target year to changes in emissions trajectory *and* (2) changes in the level of damage associated with a doubling of atmospheric concentrations of greenhouse gases. Results are presented in Section III before conclusions are offered. Summarized succinctly, they support two observations. First of all, support for limiting emission below levels that would be achieved along unregulated trajectories prior to the year 2020 requires some support for the notion that doubling damages be at least 5% of world GDP. Secondly, discovering that the globe is moving along an emissions trajectory that is higher than expected need not imply that the target year for fixing emissions should be moved forward. Indeed, higher emissions sometimes mean that the discounted net benefit of fixing emissions climbs as the target year is pushed further into the future. The precise numbers are not to be believed, of course. The qualitative notion that there is time to explore the problem further before enacting fixed emissions policies does, however, seem to be quite robust, at least across the range of possibilities captured by the model. It must be emphasized, though, that the model does incorporate explicitly assume that technological change in the energy supply sector can proceed smoothly and persistently over time, an assumption that researchers like Grubb (1997) and perhaps Dowlatabadi (1997) would find untenable in the short-run.

The model

The results reported here are drawn from an iterative global emissions model designed to accommodate monte carlo simulation over multiple sources of uncertainty. Readers familiar with the lineage of integrated assessment models will recognize that the model as the marriage of the original Nordhaus and Yohe (1983) probabilistic global emissions model with the more recent Nordhaus (1994a) DICE model. A detailed description of its structure drawn in part from Yohe and Wallace (1996) is recorded in an Appendix. In addition, the nine uncertain parameters that defined the scale of an initial monte carlo simulation across the full model (assuming the median DICE parameterization of the concentration to temperature change connection) are displayed in Table 1. In each case, high, middle and low values were assigned subjective probabilities of 0.25, 0.50 and 0.25, respectively, with reference to a variety of sources. Subsequent modelling focused on the four parameters that contributed most significantly to the range of emissions estimates through the year 2100: the rate of growth of population, technological change in the supply of energy (as reflected by the trend in the real price of energy), the degree to which depletion of carbon-based fuel is reflected over time in its price, and the elasticity of substitution between carbon and non-carbon

Table 1 Characterization of the Representative Scenarios[a]

Scenario	Subjective Likelihood	(3) Population Growth	(4) Secular Trend in the Real Price of Energy	(5) Degree to Which Depletion Appears in Carbon-fuel Price	(6) Interfuel Substitutional Elasticity
(A)	0.27	high (H)	positive (H)	high (H)	large (H)
(B)	0.13	high (H)	none (M)	middle (M)	large (H)
(C)	0.23	high (H)	negative (L)	little (L)	large (H)
(D)	0.19	middle (M)	none (M)	little (L)	median (M)
(E)	0.09	middle (M)	negative (L)	high (H)	little (L)
(F)	0.05	high (H)	negative (L)	middle (M)	little (L)
(G)	0.04	high (H)	negative (L)	little (L)	little (L)

Note:
[a]The entries are meant to be suggestive; the notation in the (-) correspond to the specifics in Table A.1. So, "high", "middle" and "low" designations for population growth in Column (3) correspond to rapid, expected, and slow rates, respectively. Notation of "positive", "none" and "negative" in Column (4) indicates that, *ceteris paribus*, the real price of energy climbs, stays constant, or falls over time indicating that technological change in the supply of energy might be relatively slow, typical, or relatively fast, respectively. Notation of "high", "middle" and "little" in Column (5) indicates that the price of carbon-based fuel reflects depletion of fossil-fuel resources vigorously, as might be expected, or slightly, respectively. Notation in Column (6) of "large", "median" and "little" signifies ample, normal, of little potential of substitution out of carbon-based fuel in favor of non-carbon fuels, respectively.

based fuel. They combined with the baseline DICE parameterization of the carbon cycle to solidify the foundation for an exhaustive, probabilistically weighted sampling that adequately reflected the initial monte carlo outcomes of 500 randomly selected scenarios drawn from the larger set of 3^9 possible combinations.

The resulting 81 scenarios were ranked in order of emissions (in 2100) and partitioned into seven groups. Following a methodology for selecting "interesting" scenarios described in Yohe (1991), these partitions were defined and representative scenarios [denoted henceforth as Scenarios (A) through (G)] were selected in a way that minimized the probabilistically weighted sum of the squared errors in emissions (again, in 2100) involved in describing the entire distribution by a collection of only seven trajectories.[2] Table 2 characterizes each heuristically in terms of the values assumed by the remaining underlying four random variables; again, the particulars are noted in Table 1. Figures 1 and 2 display unregulated trajectories for carbon emissions and atmospheric concentrations along the lowest [(Scenario (A)], the median [Scenario (C)] and highest [Scenario (G)] alternatives. The first section of Table 3 finally portrays all seven trajectories in terms of emissions and concentrations in the year 2100. The likelihood values assigned to each are recorded in brackets along the left hand side of the table; they represent the sum of the subjective weights of all of the scenarios located in each specific partition of the full distribution of outcomes.

[2]The procedure that lead to the selection of seven representative trajectories also creates a specific partition of all possible trajectories-partitions that were also defined by the minimizing procedure. The procedure starts with an arbitrary partitioning for which error minimizing representatives were chosen. In the next step, the highest member of the lowest partition was moved to the next highest partition and the calculations redone. If the sum of squared errors fell, then another member was moved up; if not, then it was returned to the lowest partition. This trial and error method was applied to all of the partition boundaries until no more error reducing moves were available. There are theorems that describe when this procedure converges to a unique outcome. Their conditions appear to have been met by the collection of 81 emissions values, but confidence can be placed on the fact that starting from different initial partitions and working from both the bottom up and the top down produced the same results.

Table 2 Selected Results-Comparisons with Established Results[a]

	Emissions in 2100	Concentrations in 2100
(A) Representative Scenarios		
Median inputs {n/a}	20.2	679
Scenario (A) {0.27}	7.8	502
Scenario (B) {0.13}	15.6	615
Scenario (C) {0.23}	20.2	679
Scenario (D) {0.19}	28.7	785
Scenario (E) {0.09}	43.4	972
Scenario (F) {0.05}	48.9	1044
Scenario (G) {0.04}	59.9	1165
(B) IPCC Scenarios		
Scenario IS92c	4.6	n/a
Scenario IS92d	9.9	n/a
Scenario IS92b	18.6	n/a
Scenario IS92a	19.8	n/a
Scenario IS92f	25.9	n/a
Scenario IS92e	34.9	n/a
(C) DICE[b]		
Tenth percentile	6.4	465
Median trajectory	24.1	671
Ninetieth percentile	82.5	1203
(D) Energy Modeling Forum–14[c]		
Modeler's choice (low)	8.5	605
Modeler's choice (high)	32.0	1150
Standardized Reference (low)	12.0	605
Standardized Reference (high)	48.5	1550

Notes for Table 2.1:
[a]Emissions are given in billions of metric tons of carbon; concentration is parts per million volume.
[b]Values reported for 2095, actually, in Table 7.3 of Nordhaus (1994a).
[c]Values estimated from graphical presentations of First Round EMF-14 results.

Even a casual review of Table 2 can offer insight into the sources of the wide ranges of emissions and concentrations that are evident in Table 3. Notice, for example, that all but two of the scenarios assume relatively rapid growth in population; differences in the rate of growth of population cannot, therefore, be used to explain much of the wide range. Movement from the lowest emissions paths to the highest emissions paths can, however, be explained to a large degree by looking at change in the assumed interfuel elasticity of substitution, the parametric reflection of the ability of the modeled aggregate economy to respond any increase in the relative

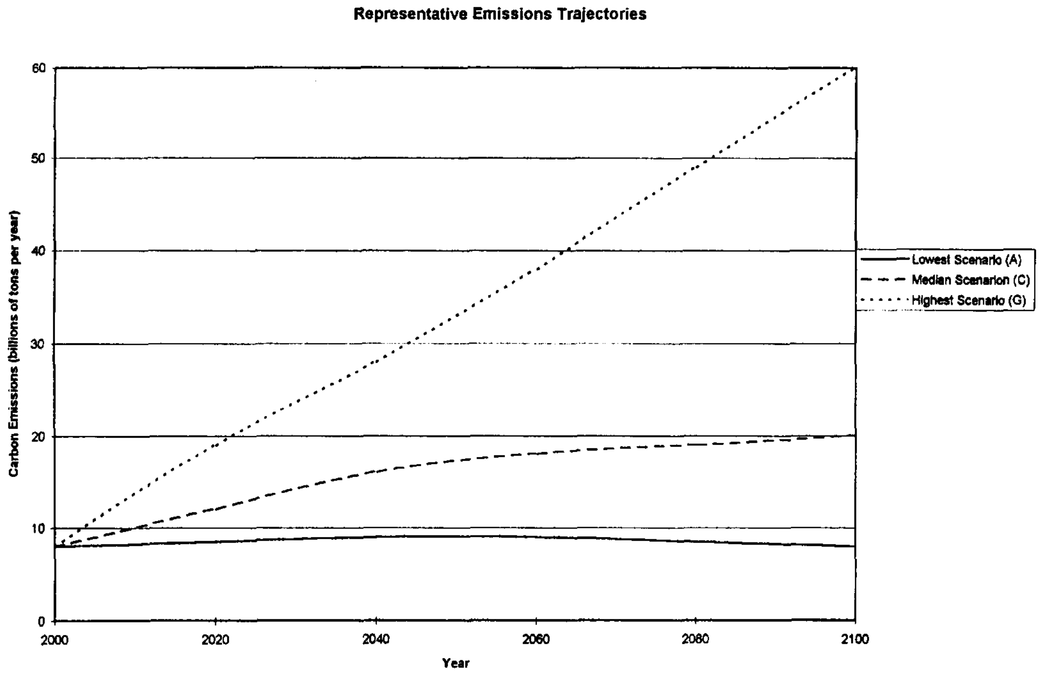

Figure 1 Carbon emission trajectories for representative scenarios-the highest, lowest, and median cases.

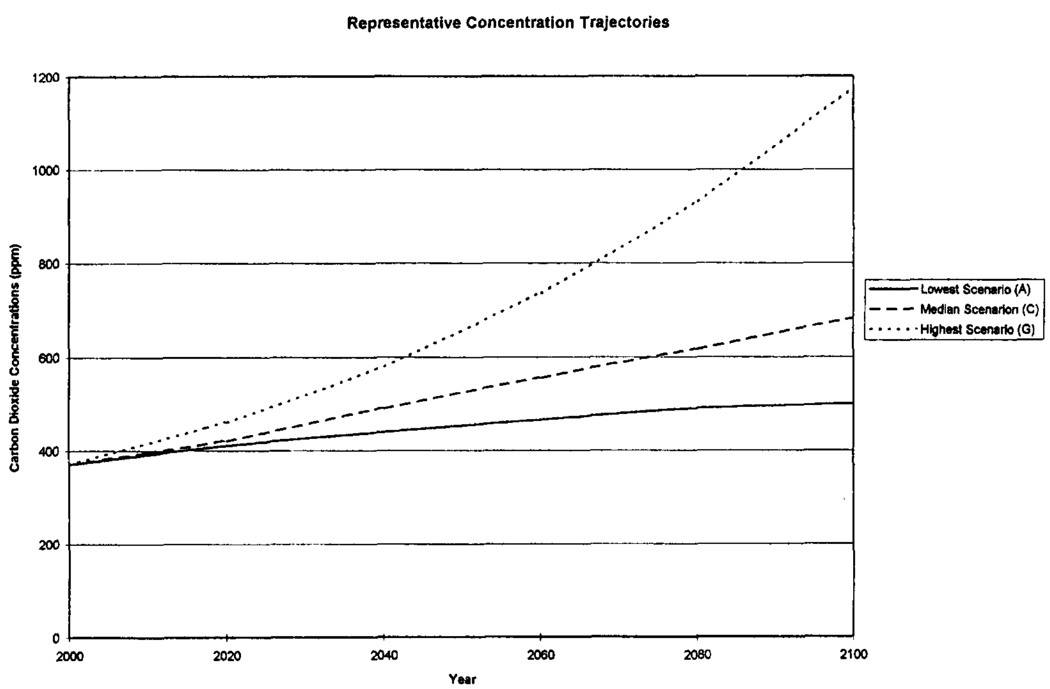

Figure 2 Carbon dioxide trajectories for representative scenarios-the highest, lowest, and median cases.

price of carbon-based fuel that may appear over time. A high elasticity indicates an ability to respond vigorously to changes in the relative prices energy by substituting, say, non-carbon based fuel for carbon-based fuel. As a result, any increase in the real price of carbon-based fuel caused, for example, by depletion of carbon-based resources can be expected to cause a noticeable decline in its consumption. It is not surprising, therefore, that low emissions paths emerge from high elasticity scenarios. Conversely, low elasticities indicate a limited potential for substitution. As a result, higher carbon consumption and emission trajectories can be supported even along scenarios where the relative price of carbon-based fuel happens to climb.

The rate of change of that price is, meanwhile, determined in large part by the degree to which the depletion of global carbon-based fuel resources is reflected in its price; more rapid depletion and/or more rapid translation of depletion into price pushes for interfuel substitution to diminish carbon

Table 3 Net Benefit of Optimal Intervention along the Median Trajectory

Damage[a]	Net Benefit[b]
2%	$0.33
3%	$0.59
5%	$1.31
7%	$2.11
9%	$2.98

Notes:
[a]Damage associated with a doubling of atmospheric concentrations expressed in% of world GDP.
[b]Benefits net of cost discounted through 2200 at 3% expressed in trillions of 1990 dollars.

emissions in any elasticity regime. For any collection of scenarios with the same underlying elasticity, then, more exaggerated reflections of resource depletion produce lower emissions over time; and *visa versa*. The pace of technological change in the supply of energy can, finally, work either to amplify or to diminish this "substitution" effect by superimposing a fuel-neutral "income" effect on the secular trend. More rapid progress translates into lower real energy prices than might otherwise be expected over time and, *ceteris paribus*, higher consumption of both types of fuel.

Since the scenarios described in Tables 2 and 3 and displayed in Figures 1 and 2 emerged from a process that artificially collapsed a potential of 3^9 runs from one specific model into a manageable set of scenarios deemed representative and "interesting," it is reasonable to question the degree to which they reflect anything more than the idiosyncrasies of the model, the selection process, or both. It is comforting to note that the seven representative scenarios chosen here do reasonably well in reflecting the diversity of expert opinion. The middle portion of Table 3 shows that they span completely the emissions recorded by the IPCC (1992) in its six specified scenarios; indeed, approximately 20% of the likelihood range reported here exceeds the highest IPCC emission trajectory (IS92e). The last section of Table 3 finally shows that the seven selected scenarios also lie between the 10th and 90th percentile Nordhaus (1994a) DICE results in both emissions and concentrations and that they show much more potential on the "high side" than the sample of trajectories reported by nearly twenty researchers to the Energy Modelling Forum. Comparison with even a full set of alternative scenarios would not constitute validation of these scenarios, to be sure. There is, nonetheless, some convincing evidence that the seven scenarios described in Tables 2 and 3 do, indeed, adequately span the range of current opinion about what the future might hold and that their underlying structure does not produce anomalous cost or concentration statistics.

Turning preliminarily to a few results, Figure 3 displays "optimal" carbon-tax trajectories starting in 1995 for the median emissions scenario estimates of the damage associated with a doubling of greenhouse gas concentrations ranging from 2% of world GDP up to 9% of world GDP. Notice the trajectories behave as one might expect. Tax rates always climb over time, and higher damages are associated with higher taxes from the start. Figure 4 highlights the discounted net benefits associated with applying the "optimal" tax trajectories; and they, too, climb with damages.

Figure 4 turns to the focus on the specific work reported here. Looking again at the median scenario, each locus in Figure 4 tracks the discounted net benefit of fixing emissions at some future date for each of the damage estimates noted above. Net benefits peak in each case, but at levels that fall

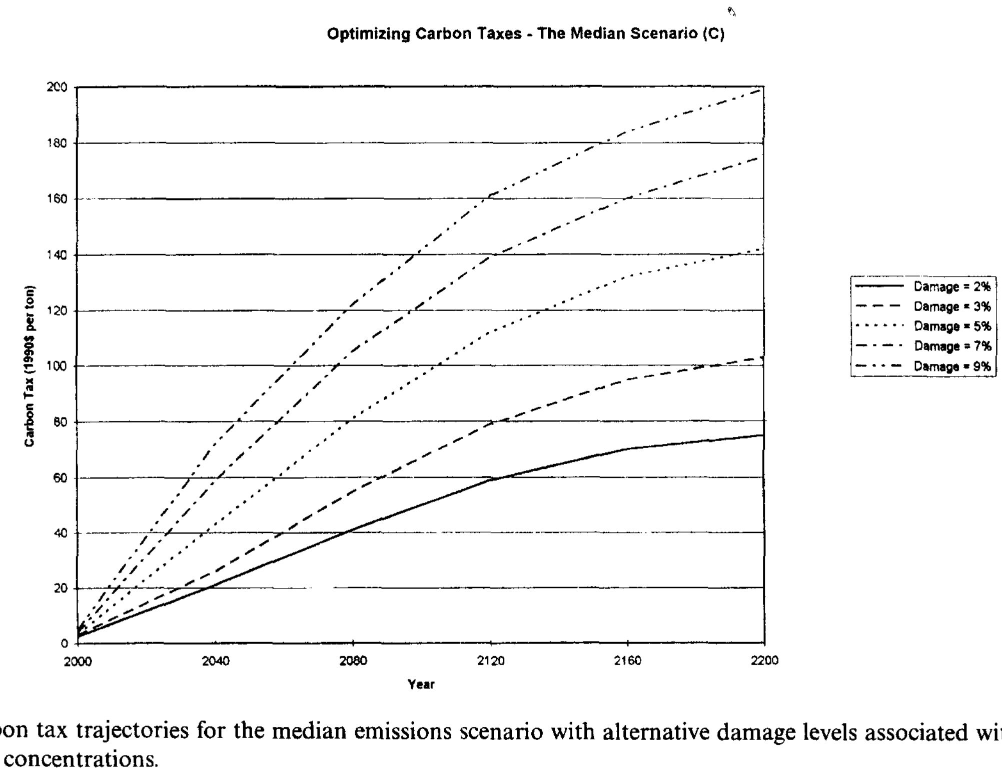

Figure 3 Carbon tax trajectories for the median emissions scenario with alternative damage levels associated with a doubling of greenhouse gas concentrations.

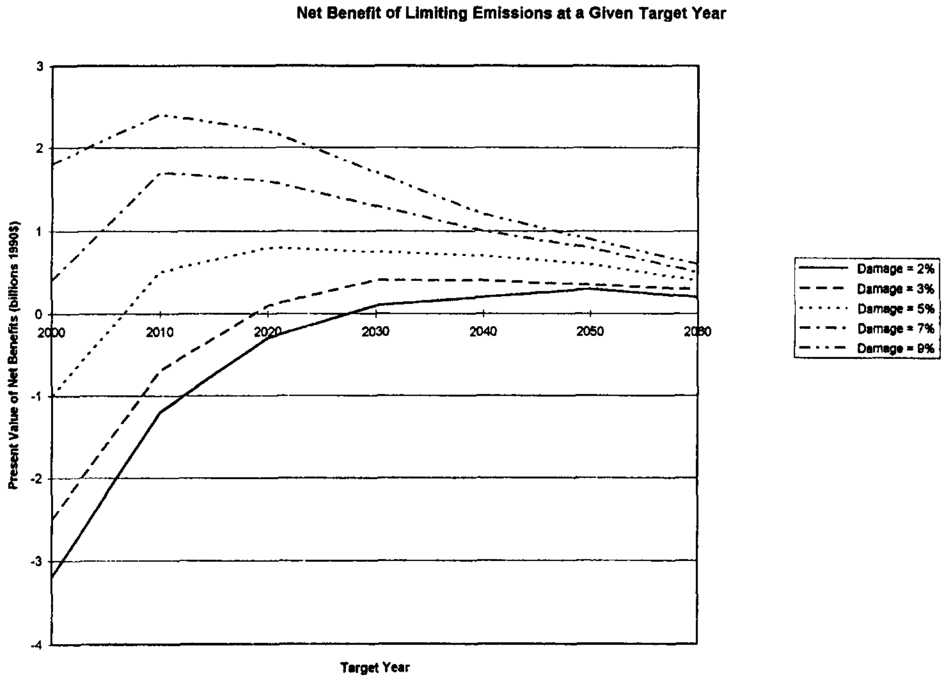

Figure 4 The net benefit of fixing emissions at the level achieved at specific years along the median emissions trajectory with alternative damage specifications.

short of the values associated with adopting an "optimal" policy now. Differences in net benefits between the peak and the optimum fall with damages; and the date where fixing emissions pays off the most also falls with damages. It is interesting to note, however, that fixing emissions below levels achieved along the unregulated scenario before the year 2020 can only be justified by believing that doubling would reduce world GDP by upwards of five percent. How likely is it that damages would be that high? Only 3 of the 24 respondents in a survey conducted by Nordhaus (1994b) offered estimates of 5% or higher for a 3°C warming in 2090; 12 respondents did, however, include 5% damages within their subjective 80% confidence intervals.

Some underlying theory

Figure 5 depicts the generalizable geometry of the timing decision captured in Figure 4. Costs (discounted to the present) are displayed, there, as a declining function of the year whose unregulated emissions define the emissions target. It is simply more expensive to meet earlier targets because they commit policy makers to implementing more restrictive abatement policies earlier and for longer periods of time. Benefits (also discounted) similarly decline with the target year because distant benefits are smaller and are discounted more heavily. If any fixed emissions policy were deemed to be desirable, however, discounted benefits would have to exceed discounted costs, at some point, they would have to peak sometime later, and they would have to decline toward zero, at least eventually. This portrait is offered in Figure 5 by the net benefit curve, a portrait that is consistent with the net benefit schedules drawn in Figure 4 for the median emissions scenario.

Figure 6 offers a consistent glimpse at the geometry of second best optimization to be considered here. Schedule MB1 depicts the marginal benefit of bringing the fixed emissions target one year closer from the year reflected on the horizontal axis. It is declining in time because moving the emissions limit marginally closer from a distant time is worth less than a comparable move from a closer date. Near term emissions may be associated at the time of their release with lower marginal damages, but early reductions are binding throughout the future and thus accumulate the value of a longer stream of benefits. Schedule MC1 similarly depicts the marginal cost of meeting a fixed emissions target that is one year closer and thus slightly more restrictive. It, too, is downward sloping, but for a different reason. Costs are not incurred until the limit is imposed, and so the costs of distant restrictions are discounted more heavily after intervening years of unregulated emission.

Point E1 represents a point where the marginal benefit of bringing the target closer matches the marginal cost; and so Y1 can be offered as the optimal target time. The relative slopes of MC1 and MB1 satisfy the second order conditions for a maximum for the interpretations offered above. A more usual view taken directly from Figure 5 would contemplate the marginal costs and benefits of moving the limiting year into the more distant future. In that case, however, both marginal schedules would be negative and climb toward zero; and as shown in Figure 5, marginal cost would be steeper than marginal benefit. Figure 6 simply inverts this more direct reflection of Figure 5 to bring the geometry into the more familiar first quadrant.

Figure 7 now offers some insight into what to expect if the doubling damages associated with global change were

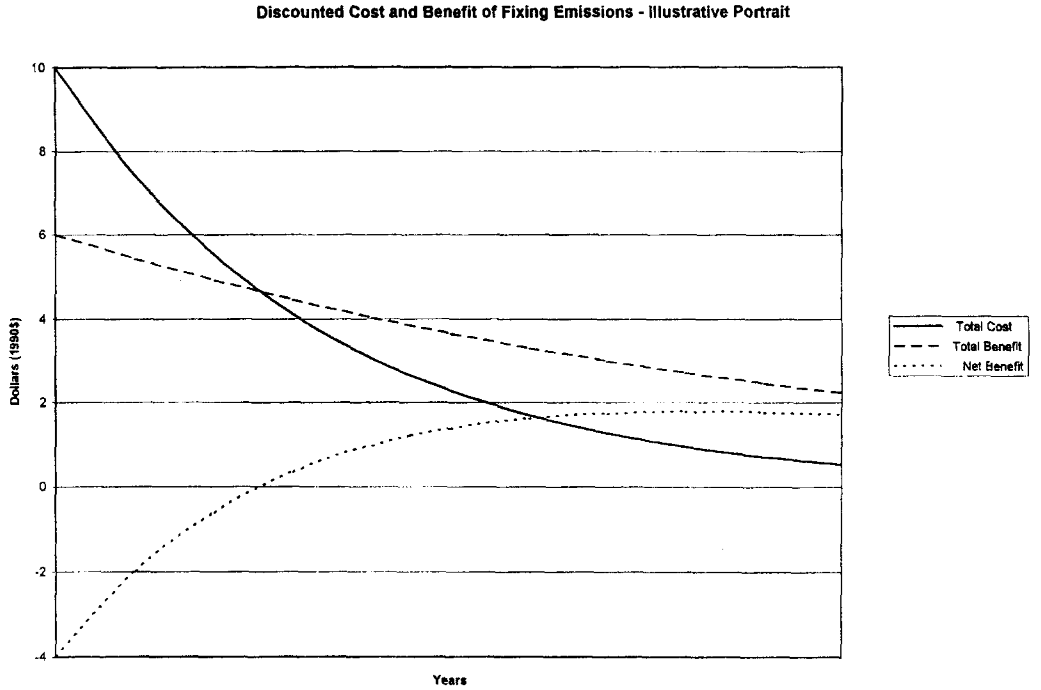

Figure 5 An illustrative portrait of the costs, the benefits and the benfits net of costs associated with fixing emissions at the level achieved at a specific year.

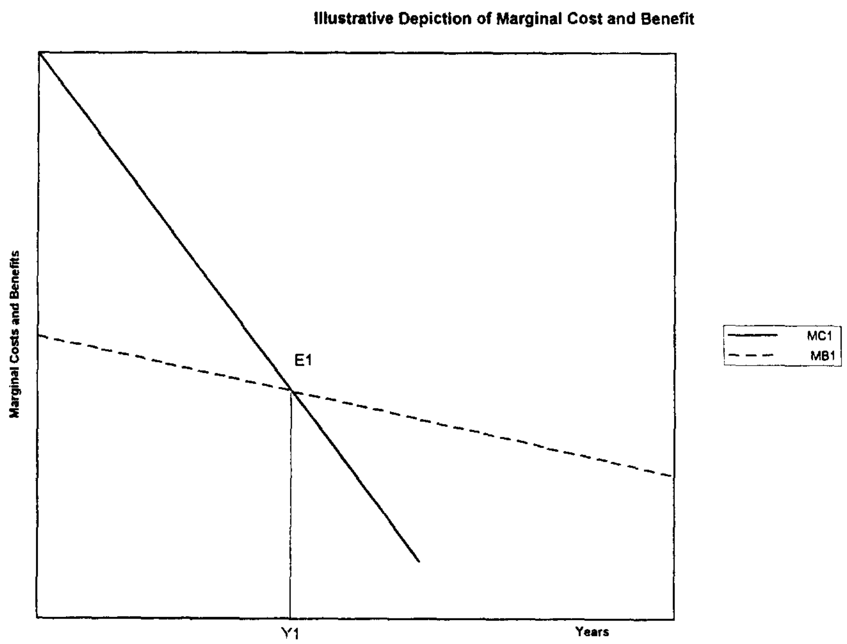

Figure 6 Illustrative marginal costs and benefits associated with fixing emissions at the level achieved at a specific year; Y1 depicts the efficient choice.

higher than the estimate that supported schedule MB1. Quite simply, the marginal benefit of fixing emissions at any target year would climb; and a higher schedule like MB2 would obtain. The second best optimum would be achieved at point E2; and the best target year would fall from Y1 to Y2.

Figure 8(a) and 8(b) reflect similar comparative statics across two different emissions trajectories. In Figure 8(a), for example, MB2 and MC2 represent the higher marginal benefits and marginal costs that would be associated with a higher emissions trajectory. Higher emissions would mean higher damages. The marginal social benefit to bringing the target year closer would thus be higher, and so the marginal benefit curve must shift up. Higher emissions would also mean that meeting closer target years would be more expensive, though; as a result, the marginal cost curve must shift upward, as well. In Figure 8(a), then, the

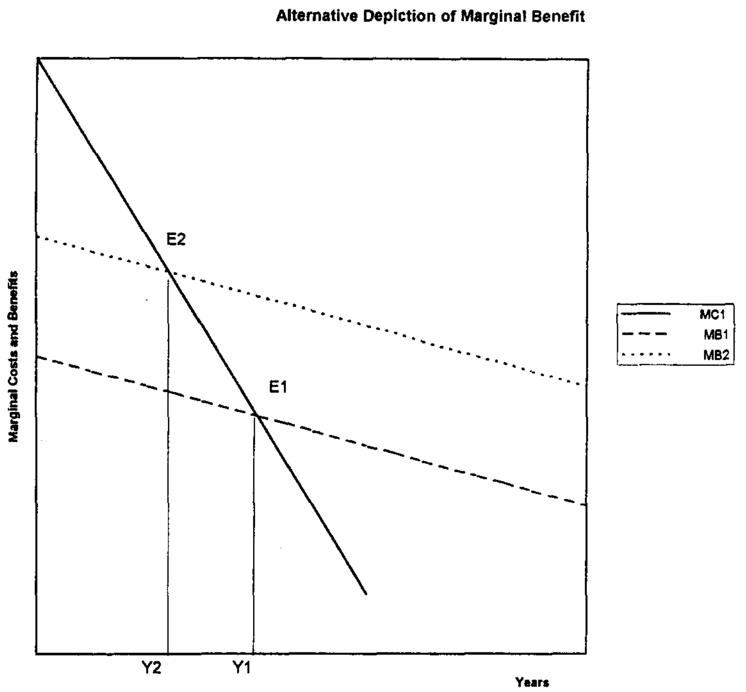

Figure 7 Illustrative marginal costs and benefits associated with fixing emissions at the level achieved at a specific year. Schedule MB2 depicts a shift in marginal benefit associated with a higher damage specification for doubled greenhouse gas concentrations; the efficient choice moves closer to the present.

second best optimum reappears at point E2, and the target years moves closer to the present.

Figure 8(b) shows a different result, however. If the marginal cost of meeting targets shifts enough (and/or rotates to display a steeper slope) to a schedule like MC2', in particular, Figure 8(b) shows the possibility that the target year may actually rise. Some attention should therefore be paid to the circumstances that influence the relative applicabilities of these two alternatives. Since the marginal cost schedules depicted here are really reflections of the derived demand for carbon-based fuel, however, it is not difficult to describe those circumstances qualitatively. Changes in the drivers that define higher emissions trajectories supported by a derived demand structure that is more inelastic (e.g., a lower elasticity of substitution between carbon and non-carbon based fuel and/or market conditions that force taxes to be applied to relatively higher unregulated carbon-based fuel prices) would surely do the trick. Changes in the drivers that exaggerate demand but do not diminish its sensitivity to changes in relative prices (e.g., higher population growth) would likely not.

Results

Figure 4 charted the effect of changes in the level of damage associated with a doubling of the atmospheric concentrations of greenhouse gases for the median scenario. Recall that the discounted values of the net benefit derived from fixing emissions at the unregulated levels achieved along the median trajectory were plotted there. As predicted in Figure 7 above, the best target year fell consistently from 2050 down to 2010 as damages rose from 2% to 9% of world GDP.

Figure 9 explores the relevance of the Figure 8(a) and 8(b). Target years for four representative scenarios are specified along the horizontal axis, and the three columns drawn for each reflect the best target year for specific emissions trajectories with doubling damages set equal to 2%, 5% and 9%, respectively. Notice that Figure 8(a) applies uniformly as emissions climb through the upper portion of the range for 2% damages. The target year falls with emissions, in other words, but it is important to recognize that the smallest reduction is produced by moving from emissions supported by scenario (D) up to emissions supported by scenario (E). That the move from scenario (D) to (E) might be special is supported by the 5% and 9% damage loci, as well. Indeed, the target year climbs in both cases, making it clear that the content of Figure 8(b) is more than an academic curiosity. The target year actually climbs along the 9% locus for two moves, the first from scenario (C) to (D) and the second from (D) to (E).

The key to understanding why is found in the specifications of the representative scenarios. The dramatic difference in unregulated cumulative emissions between scenario (D) and scenario (E) is driven by changes in two critical parameters. On the one hand, the elasticity of substitution between carbon and non-carbon based fuel falls by 45%. Emissions reductions are therefore much more difficult to achieve in the scenario (E) environment, and so the marginal cost schedule depicted in Figure 8 must become much more inelastic. This (in)elasticity effect is, on the other

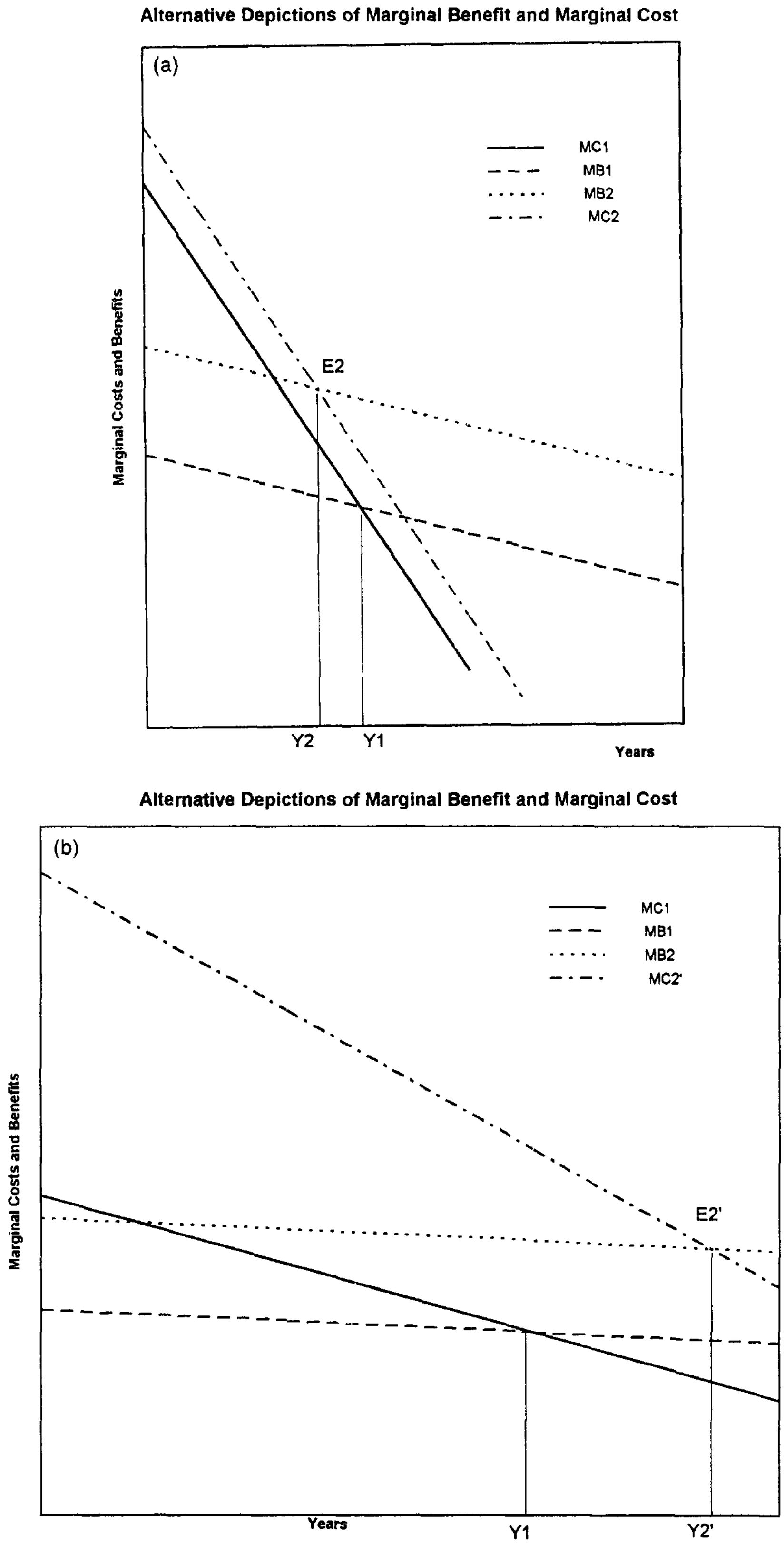

Figure 8 (A) Illustrative marginal costs and benefits associated with fixing emissions at the level achieved at a specific year. Schedules MB2 and MC2 depict shifts in marginal benefits and costs associated with a higher damage specification for doubled greenhouse gas concentrations and higher emissions trajectories, respectively; the efficient choice moves closer to the present.(B) Illustrative marginal costs and benefits associated with fixing emissions at the level achieved at a specific year. Schedules MB2 and MC2' depict shifts in marginal benefits and costs associated with a higher damage specification for doubled greenhouse gas concentrations and higher emissions trajectories, respectively; the efficient choice moves further into the future in this case.

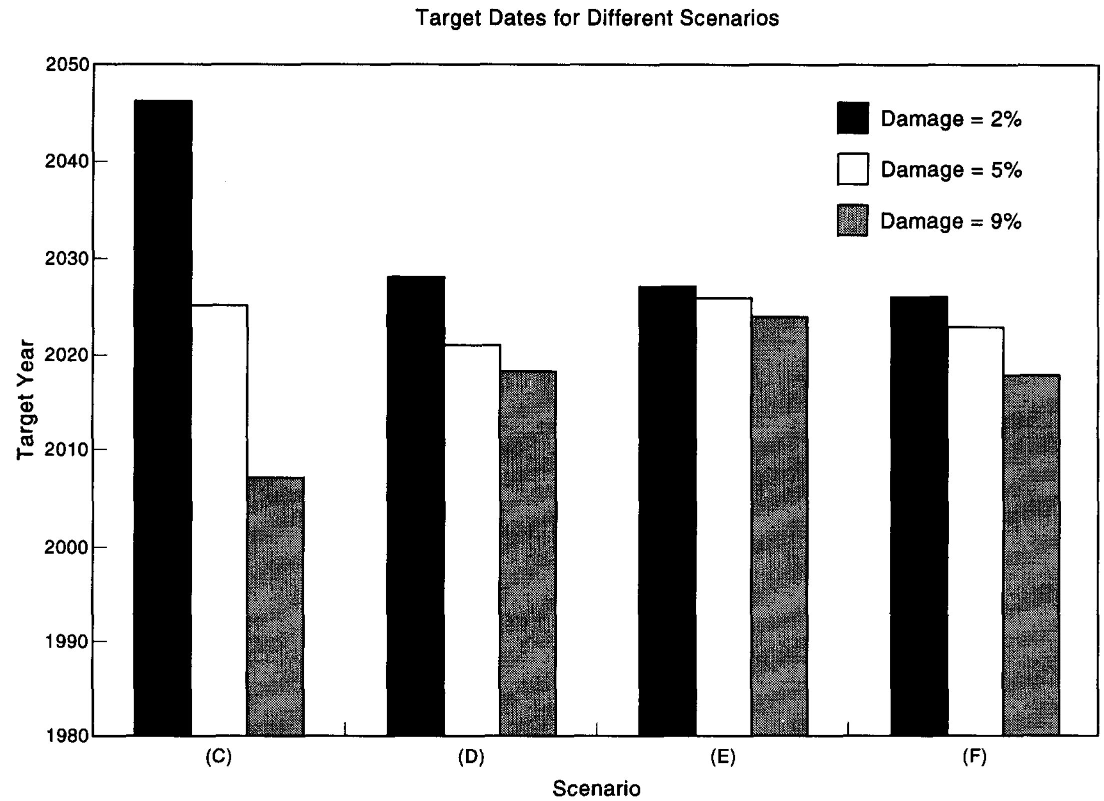

Figure 9 Efficient target dates for four alternative emissions trajectories for three different damage specifications. Higher damages always imply earlier efficient target years for a given emissions trajectory, but higher emissions do not necessarily imply earlier targets.

hand, exaggerated by a supply curve for carbon-based fuel that is, itself, more responsive to the effects of depleting fossil fuel reserves in scenario (E) than it is in scenario (D). Any carbon tax must therefore work harder against prices that are already inflated by scenario (D) standards to achieve any percentage increase in carbon-based fuel prices.

Movement between scenarios (E) and (F), by way of contrast, is driven by expanded population growth and a reduction in the sensitivity of the unregulated price of carbon-based fuel to depletion. A modest shift to a more elastic derived demand is therefore supported, and Figure 8(a) should apply. It should be no surprise, therefore, that the "best" target year falls in all cases.

Conclusions and context

Focusing on the qualitative conclusions that can be drawn from this analysis is most appropriate. After all, aggregate global models can do little more than identify issues that more detailed models might productively explore. Still, the qualitative results produced here are remarkably robust. On the one hand, restricting emissions to levels achieved in years prior to 2020 seldom maximized the discounted net benefits of this second best policy across the full range of representative emissions scenarios and assumed doubling damages as high as 9% of global GDP. Indeed, only very high damages and very high emissions produced an "optimal" emissions target date as low as the year 2010. If policy will fix emissions at some future level, therefore, it would appear from these results that there is time to explore the problem more fully before choosing the target date precisely.

On the other hand, and perhaps more importantly methodologically, it would appear that the global emission system can be expected to behave differently in a state of high entropy than it does in a state of lower or normal activity. More precisely, it did not always follow that moving along a higher emissions trajectory would necessarily imply that the globe should burden itself with a more restrictive emissions target. High emissions trajectories can be supported by a number of factors — high population growth, larger quantities of carbon-based fuel reserves, small potentials for substituting out of carbon-based fuel, etc., — but not all of them translate into more restrictive emissions targets if the objective is to maximize the net benefit of the policy. Perhaps researchers who exercise detailed and disaggregated integrated assessment models should focus some increased attention on high emissions scenarios to see if higher entropy causes other things to change.

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Appendix

The Specific Structure of the Model

World economic output in any year t [the standard GDP denoted here by X(t)] is taken to be functionally related to the capital stock [K(t)], the size of population [L(t)], and the consumption of carbon-based and non-carbon based fuel [$E_c(t)$ and $E_n(t)$, respectively] according to

$$x(t)=W(t)A(t)K(t)^{g}\{L(t)^{d(t)}[bE_c(t)^{a}+(1-b)E_n(t)^{a}]^{(1-d(t))/a}\}^{1-g} \quad (1)$$

so that the elasticity of substitution between energy types [s_{cn}] is given by [1/(a–1)]. The share of output devoted to paying labor will change over time so that Equation 1 can be adjusted each year to approximate a more general constant elasticity of substitution production structure with a series of evolving Cobb-Douglas schedules. More specifically [see Yohe (1983)], letting the share of output devoted to labor vary over time according to:

$$d(t)=[(k_2P(t)^{[q/(q-1)]}+1]^{-1}$$

with

$$k_2=[(1-m)/m]^{[1/(q-1)]}$$

supports a general CES structure of the form

$$x=AK^{g}[mL^{q}+(1-m)E^{q}]^{(1-g)/q}$$

Of course, the initial share of labor is,

$$d(0)=[(k_2(P(0)^{[q/(q-1)]}+1]^{-1}$$

As a result, the effective elasticity of substitution over time between labor [L(t)] and energy [$E(t)^{\circ}E_c(t)+E_n(t)$], denoted s_{EL} is given by [1/(q–1)] even though the production structure for any one year has s_{EL}=–1. Note, in passing, that

$$P(t)=\{[P_c(t)E_c(t)+(P_n(t)E_n(t)]/[E_c(t)+E_n(t)]\}$$

is the (weighted) average price of energy given the prices of carbon and non-carbon based fuels [$P_c(t)$ and $P_n(t)$, respectively].

Trajectories for population [L(t)] and neutral technological change [A(t)] are given exogenously by:

$$L(t)=L_0e^{l(t)t}\ with \quad (2a)$$

$$l(t)=(1-d_L)l(t-1)and \quad (2b)$$

$$A(t)=A_0e^{a(t))}\ with \quad (3a)$$

$$a(t)=(1-D_A)a(t-1) \quad (3b)$$

The capital stock at any point in time [K(t)] and the consumption of fossil and non-fossil fuels [$E_c(t)$ and $E_n(t)$] will be determined endogenously. The cost of warming is given by W(t). According to the Nordhaus structure (1994a),

$$W(t)=[1+D(t)]^{-1},\ where \quad (4)$$

$$D(t)=a[T(t)/3]^{q} \quad (5)$$

is a function of temperature at time t[T(t)]. It is W(t) that is anchored to aggregate damages associated with the 2.5°C increase in global mean temperature that is usually attributed to a doubling of concentrations.

The price of non-fossil fuel is given by

$$P_n(t)=P_{no}+P_0e^{[h(t)+z(t)]t} \quad (6)$$

with h(t) representing the rate of technological change in the supply of energy and z(t) reflecting the bias of technological change toward (or away from) non-carbon based fuel. The price of carbon-based fuel is similarly given over time by

$$P_c(t)=P_{co}+[g_0+\{[g_1R(t)]/[R-R(t)]\}e^{h(t)t}+t(t) \quad (7)$$

with

$$R(t)=\sum_{i=1}^{t-1}E_i(i) \quad (8)$$

representing cumulative carbon-based fuel consumption through year (t–1). In addition,

$$t(t)=t_o z(t)e^{rt}+t_d(t)z(t) \quad (9)$$

summarizes a range of the carbon tax policy options denominated in dollars per ton of carbon emissions. In writing Equation 9, z(t) is taken as the carbon content of carbon-based fuel burned in year t. It is applied first to a tax anchor [t_o] to produce an emissions reduction shadow price that grows over time at a rate equal to an appropriate rate of discount [r]. This first term uses the standard Hotelling result to reflect, from a demand side perspective, an efficient allocation over time whenever cumulative emissions are to be constrained beyond the power of the second $t_d(t)$ term. The carbon content factor is also applied in this second term, a term designed to modify the Hotelling trajectory to accommodate how the marginal damage associated with emissions might change over time. Taken together, the two parts of Equation 9 are constructed to weigh dynamic economic efficiency in the "demand" for constrained carbon emissions over time with a dynamic portrait of their marginal damage and the shadow price of meeting any additional constraint.

To see that Equation 9 handles a wide range of possibilities, note that it could be used to model efficient allocation over time if $t_d(t)$ were framed to reflect how (people thought that) the marginal damage of carbon emissions might change over time along a specific, regulated scenario of how the future might unfold. A constant $t_d(t)$ would be appropriate, for example, if the marginal damage of carbon emissions were thought not to change over time; but $t_d(t)$ would not be constant if the marginal damage of emissions were seen by most to climb over time as emissions feed into higher and higher atmospheric concentrations of greenhouse gases. Meanwhile, note that t_o=0 unless the targeted constraint on cumulative emissions continued to be binding even along a trajectory regulated by $t_d(t)>0$; i.e., t_o=0 unless cumulative emissions are to be reduced beyond the level justified by the efficient reaction over time to $t_d(t)$. Such is nearly always the case when emissions are to be limited below specified thresholds.

Input decisions in any year conform to the neoclassical fundamentals which set the marginal products inputs equal to their real, net input prices. Full employment over the very long term means that Equations 2a and 2b always holds. Applying these fundamentals to capital, then

$$K(t)=\{[gW(t-1)x(t-1)]/[r+d)], \quad (10)$$

where d represents the applicable rate of depreciation. Investment in any year t[I(t)] must now cover not only depreciation, but also any net investment required to bring K(t–1) up to the level K(t) given in Equation 10; i.e.,

$$I(t)=K(t)-K(t-1)+dK(t-1)=K(t) -(1-d)K(t-1) \quad (11)$$

summarizes investment, the portion of GDP devoted each year to maintaining the appropriate capital stock. Applying the same marginal product rules to energy,

$$E_n(t)=\{[(1-g-d(t)-a)W(t-1) x(t-1)]/[P_n(t)]\}, and \quad (12)$$

$$E_c(t)=\{[aP_n(t)]/[1-g-d(t) -a)P_c(t)]E_n(t)=\{[aW(t-1) x(t-1)]/[P_c(t)]\} \quad (13)$$

characterizes the derived demands for energy consistent with the production schedule given in Equation 1.

Following the usual convention of imposing the savings equals investment conditions for macroeconomic equilibrium, per capita consumption [c(t)] is

$$c(t)=[W(t)X(t)-I(t)]/L(t); \quad (14)$$

Per capita consumption is known because Equations 2a, 2b, 10, 12 and 13 combine with Equation 1 to set GDP [X(t)] and Equation 11 sets investment [I(t)]. Assuming that utility displays constant relative risk aversion [denoted by h] in per capita consumption, then

$$U(c(t))=[c(t)^{h+1}]/[h+1],$$

and the de facto optimization envisioned in the construction of the optimal policy seeks to maximize the discounted sum of U(c(t)).

The damage side of the model is driven by emissions. Following the DICE construction,

$$G(t)=z(t)E_c(t), where \quad (15a)$$

$$z(t)=(1+g_z(t))z(t-1) and \quad (15b)$$

$$g_z(t)=(1-d_z)g_z(t-1). \quad (15c)$$

Emissions are converted into atmospheric carbon concentrations [M(t)] by

$$M(t)=bG(t)+(1-d_M)M(t-1). \quad (16)$$

In writing Equation 16, parameter b is the instantaneous airborne fraction for carbon and d_M reflects a seepage factor. The DICE accommodation of the Schneider forcing model completes the portrait. Forcing [F(t)] is, more specifically, represented by

$$F(t)=4.1\{[\log(M(t)/590)]/\log(2)\} +O(t) \quad (17)$$

where O(t) represents other forces; they are taken to be exogenous. The temperature index [T(t)] upon which damages depend in Equation 5 is related finally to forcing through the now standard two equation simplification of complex global climate models:

$$T(t)=T(t-1)+\{F(t)-1T(t-1) -(R_2/t_{12}[T(t-1)-T^*(t-1)]\}/R_1 and \quad (18)$$

$$T^*(t)=T^*(t-1)+\{(t-1)-T^*(t-1)\}/t_{12}, \quad (19)$$

where the T*(t) variable reflects ocean temperature.

Table A.1. highlights the nine uncertain parameters over which preliminary monte carlo simulation was conducted and indicates the sources of their initial distributions. In each case, high, middle and low values were assigned subjective probabilities of 0.25, 0.50 and 0.25, respectively. Subsequent modeling focused on the four parameters that contributed most to the range of estimates of emissions through to 2100; the full set of values for these are recorded first. Median values only are noted for the other five. These medians combined with the baseline parameterizations of equations (15) through (19) from DICE to solidify the foundation for an exhaustive, probabilistically weighted sampling over the other four that adequately reflected the initial monte carlo outcomes of 500 randomly selected scenarios drawn from the larger set of 3^9 possible combinations. As noted in the resulting 81 scenarios were ranked in order of emissions (in 2100) and partitioned into seven groups. Table A.2 quantifies the underlying specifications of all seven alternatives described heuristically in Table 1.1.

Table A.1 Sources of Uncertainty — Parameter Location and Specification

Description	Location	Specification	Likelihood
(1)[a] Population	Eq. (2b)	l(t)=(.873) l (t−1)	.25 H
		l(t)=(.805) l (t−1)	.50 M
		l(t)=(.732) l (t−1)	.25 L
(2)[b] Technological Change in Energy Supply	Eqs. (6) & (7)	h(t)=0.01	.25 H
		h(t)=0.0	.50 M
		h(t)=−0.01	.25 L
(3)[c] Depletion Factor in Fossil Fuel Price	Eq. (7)	g_l=145 & R=21	.25 H
		g_l=687 & R=21	.50 M
		g_l=1230 & R=21]nt].25 L	.25 L
(4)[d] Interfuel Elasticity of Substitution [σ_{cn}]	Eq. (1)	σ=−0.4 & a=−1.50	.25 L
		σ=−0.7 & a=−0.43	.50 M
		σ=−1.2 & a=0.17	.25 H
(5) General Technological Change	Eq. (3b)	a(t)=(0.89) a(t−1)	median
(6) Carbon Content Factor	Eq. (15)	$g_z(t)=(1.039)\ g_z(t-1)$	median
(7)[b]Technological Bias Toward Fossil Fuel	Eq. (6)	z(t)=0.0	median
(g)[g] Energy/Labor Elasticity of Substitution [σ_{el}]	Eq. (1)	σ=−0.7 & q=−0.43	median
(9)[h] Marginal Airborne Fraction	Eq. (16)	b=0.64 & d_M=0.001	median

Notes for Table A.1:

[a]Growth rates per decade beginning in 1990 with 5.16 billion people and based on an initial annual growth rate of 2.03%; source: Nordhaus and Yohe (1983) and Nordhaus (1994a).

[b]Rate of change per year; source: Nordhaus and Yohe (1983).

[c]Reflection of depletion of the high resource estimate in Nordhaus and Yohe (1983) fit to reflect the 1993 IEW poll results.

[d] Measure of the percentage change in fuel mix (fossil to nonfossil) associated with each 1% change in relative energy prices; source: Nordhaus and Yohe (1983).

[e]Rate of change per decade beginning in 1990 with a unitless calibrating value of 483 and based on an initial annual growth rate of 1.85%; source: Nordhaus and Yohe (1983) and Nordhaus (1994a).

[f]Carbon emission per metric ton of coal equivalent with an initial value of 0.688; source: Nordhaus (1994a).

[g]Measure of the percentage change in energy consumption in proportion to labor employment associated with each 1% change in the relative price of energy with respect to the wage paid to labor; source: Nordhaus and Yohe (1983).

[h]*Source*: Nordhaus and Yohe (1983) and Nordhaus (1994a).

Table A.2. Characterization of the Representative Scenarios[a]

Scenario	Subjective Likelihood	Population Growth	Technological Change	Depletion	Substitution Elasticity
(A)	0.27	H	H	H	H
(B)	0.13	H	M	M	H
(C)	0.23	H	L	L	H
(D)	0.19	M	M	L	M
(E)	0.09	M	L	H	L
(F)	0.05	H	L	M	L
(G)	0.04	H	L	L	L

Note: [a]Designations refer to the specific parameterization noted in Table A.1.