# The Role of Non-CO2 Greenhouse Gases and Carbon Sinks in Meeting Climate Objectives

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## 1. Introduction

In designing a strategy for greenhouse gas (GHG) abatement, perhaps the most important single component is energy-related CO2. This is where most of the analytic effort has been centered. Non-CO2 greenhouse gases and carbon sinks have received less attention, but are important enough to warrant consideration.[1] This topic was the focus of the Energy Modeling Forum study 21 in which we participated.[2] This paper describes our efforts to incorporate multiple GHGs and sinks into the MERGE model, and discusses some of the implications for mitigation cost assessments.

The focus of efforts to reduce the threat of global climate change has shifted over time. Initially, the goal was to stabilize or reduce CO2 emissions. With the UN Framework Convention on Climate Change, the focus shifted to stabilizing atmospheric greenhouse gas concentrations.[3] Although this represents a step forward, it may not go far enough. There are many uncertainties in the causal chain connecting human activities to impacts. These relate to emissions, the carbon cycle, radiative forcing, climate change, and market and non-market impacts. In Energy Modeling Forum study 21 (ref. 2), the target was extended beyond atmospheric concentrations to radiative forcing.

When conducting a multi-gas analysis, there are distinct advantages in moving from concentrations to radiative forcing. With the former, it is customary to use Global Warming Potentials (GWPs) for making tradeoffs among greenhouse gases. A number of studies have shown the arbitrariness of this approach and have argued that tradeoffs should be based on the contribution of each gas to achieving a particular target.[4] Focusing on radiative forcing bypasses the need to rely on GWPs and provides for tradeoffs among gases based on their relative value.

We begin with a description of how the MERGE model has been modified to include multiple greenhouse gases and sinks. We then examine the implications of constraints on radiative forcing under a “CO2 only” control scenario and a “multi-gas and sinks” control scenario. Finally, we add a decadal constraint on temperature change. We find that mitigation costs are substantially higher when the focus is on the rate of change rather than on absolute change. The timing of costs is also significantly changed.

Two caveats are in order. First, we assume complete “when” and “where” flexibility. That is, emission reductions are made both when and where it is most economical to do so. To the extent that these two principles of economic efficiency are violated, mitigation costs may be substantially higher. Second, in this paper, we provide only one component of the cost/benefit calculus. Our focus is exclusively on mitigation costs. No attempt is made to calculate the value of the damage reductions achieved with the adoption of a particular policy initiative. Clearly, such information is essential for informed policy making. However, the necessary analysis is well beyond the scope of the present effort.

## 2. The model

MERGE is a <u>m</u>odel for <u>e</u>valuating <u>r</u>egional and <u>g</u>lobal <u>e</u>ffects of greenhouse gas emission reductions. For technical details, see our website: www.stanford.edu/group/MERGE. A computer listing is available at that website. MERGE contains reduced-form sub-models describing: the domestic and international economy, CO2 emissions, the carbon cycle, global climate change, and market and non-market impacts. Although initially the model accounted for the emissions and decay of methane (CH4) and nitrous oxide (N2O), these gases were not included in abatement strategies. Moreover, due to a paucity of data, the earlier treatment of carbon sinks can be characterized as rudimentary, at best. In more recent versions, the model has been modified to include a more sophisticated treatment of the roles of non-CO2 GHGs and terrestrial carbon sinks.

Each region's domestic economy is viewed as though it were a Ramsey-Solow model of long-term economic growth.[5] The time paths of investment and consumption are strongly influenced by the choice of a "utility" discount rate. In the following calculations, we have based this rate upon a market-oriented "descriptive" viewpoint.[6]

Energy-related emissions in MERGE are projected through a bottom-up perspective. Fuel demands are estimated through "process analysis" and a top-down production function of the inputs of capital, labor, and electric and non-electric energy. Conservation is both price-induced and non-price-induced. Specific allowances are made for technical progress and for learn-by-doing.

Each period's emissions are translated into global concentrations and, in turn, to the impacts on mean global indicators such as radiative forcing and temperature change. The MERGE model may be operated in a "benefit-cost" mode – choosing a time path of emissions that maximizes the discounted utility of consumption, after making allowance for the disutility associated with climate change. It may also be operated in a "cost-effective" mode – supposing that international negotiations lead to a time path of emissions that satisfies a constraint on concentrations, on radiative forcing, or on temperature change.

Individual geopolitical regions are distinguished in the MERGE model. Abatement choices are distinguished by "where" (in which region?), "when" (in which time period?), and for some cases "what" (what greenhouse gas to abate?). As a result, all of our estimates must be viewed as lower bounds on the actual future costs. Since no quota rights are specified for each region, we do not report the regional costs of emissions control. We only provide the global control costs – expressed in terms of consumption losses. These losses are independent of the burden sharing arrangement.

## 3. Population and regional GDP projections

Greenhouse emissions are *not* proportional to population and GDP, but they can be quite sensitive to these projections. For this purpose, we have used what we believe to be a middle-of-road projection of the global population – assuming that it will rise from 6 billion people in 2000 to 10 billion in 2100, and that it will stabilize thereafter. Virtually all of this growth will take place in the developing countries.

Separate projections are provided for each of nine regions. There are four high-income regions. These constituted the OECD in 1990: 1) USA, 2) Western Europe, 3) Japan, and 4) Canada and Australia-New Zealand. There are also five low-income regions: 1) Eastern Europe and former

Soviet Union, 2) China, 3) India, 4) Mexico and OPEC nations, and 5) ROW (rest of world). The model employs ten-year time steps extending from 2000 through 2150.

Population projections may be debatable, but there are even more controversies with respect to productivity and per capita GDP growth. Through 2020, we have taken over these projections from the "reference case" defined by the Energy Information Administration.[7] Thereafter, we have extrapolated by using logistic functions. The initial point is the EIA projection for 2020. Each of our logistic functions converges to the identical asymptote. The "limit to growth" is $200 thousand per capita, but this limit is not reached for several centuries. This value is astronomical in comparison with today's GDP in India, China, and other low-income nations. It was chosen so that there would not be an immediate decline in the growth rate of the high-income regions.

For each of the nine regions, the third point along the logistic curve is an arbitrary individual estimate of the per capita GDP in the year 2100. These values were chosen so as to allow for a smooth transition post-2020 – and a *partial* convergence of the low-income countries to those with high incomes by 2100. For example, the U.S. grows from $36 thousand in 2000 to $115 thousand by 2100. India grows rapidly (from $0.5 to $25 thousand), but is still far behind the U.S. by the end of the century.

All dollar values here are expressed in dollars of 2000 purchasing power, and are shown at market exchange rates. If, instead, we had employed "purchasing power parity", there would have been much higher initial GDP values for the low-income nations, but lower growth rates of GDP and of emissions. With PPP, we have found only minor changes for the high-income nations.

## 4. Emissions and abatement of non-carbon greenhouse gases

Our near-term estimates for the baseline trajectories and the abatement costs of the non-carbon greenhouse gases are based on the guidelines for the EMF 21 study (ref. 2). A distinction is made between short-lived and long-lived F-gases. The dynamics of the problem are governed by the abundance of these gases in the atmosphere, the rate of future emissions, differences in their lifetimes, and their contribution to radiative forcing. We deal with these directly, rather than through the comparison of their GWPs. See Table 1 for a description of some of the key characteristics of these gases.

Table 1. Selected Characteristic of Non-CO2 Greenhouse Gases[8]

| Non-CO2 GHG | Abundance ppt (1998) | Decay rates (fraction per year) | Lifetimes (years) |
|---|---|---|---|
| Methane | 1,745.0 | 0.083000 | 12.0 |
| Nitrous oxide | 314.0 | 0.008300 | 114.0 |
| Short-lived F-gases | 20.2 | 0.069000 | 13.8 |
| Long-lived F-gases | 24.9 | 0.000313 | 3,200.0 |

MERGE is based on a simple decay model for each of the non-CO2 gases, From these decay rates, one can see that methane abatement could play a strategic role if there is a need for an immediate reduction in radiative forcing. The short-lived F-gases could play a similar role but their volume is quite small. With nitrous oxide and the long-lived F-gases, there is no possibility of a quick turnabout. Even with extensive near-term abatement, their concentrations would decay slowly.

With the exception of N2O, we took the 2000-2010 baseline emission trajectories from EMF 21 (ref. 2) and extrapolated them *linearly* from 2010 through 2100. Thereafter, it was assumed that there would be no change. With N2O, we assumed that emissions remained constant at their 2000 level.

For each gas, we expressed estimates of abatement costs as a percentage of the baseline for that year. We then supposed that there would be technical progress in abatement over time. Specifically, we assumed that within each cost category, there would be 1.5 times the 2010 percentage of abatement in 2050 and twice the 2010 percentage in 2100, etc.

## 5. Carbon sinks

Our estimates of carbon sinks are based on the global results from two of the forestry models participating in EMF 21 (ref. 2): GCOMAP and GTM. For details on these models, see, respectively, refs. 9 and 10. Each of these is a dynamic partial equilibrium model of the timber industry. That is, both of these models take the efficiency price of carbon as an input datum. Each allows for the carbon uptake in the timber growth cycle, and each gives an estimate of supplies, demands and timber prices in individual markets.

GCOMAP and GTM were each run under six standardized scenarios with respect to the global efficiency price of carbon. For each of these scenarios, the models then reported the year-by-year net absorption of carbon through afforestation sinks. In turn, the two models were each coupled to MERGE by taking a convex combination of the six time-phased scenarios – and also allowing for the possibility of a delay in initiating them.

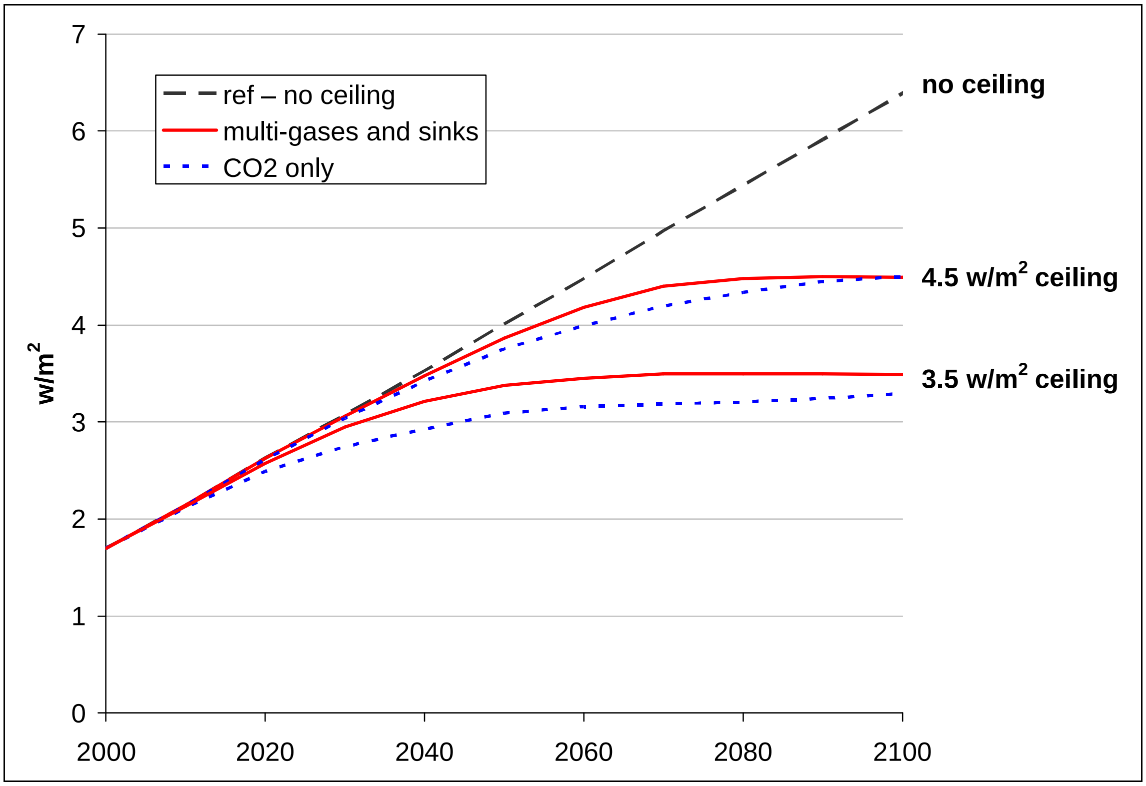
At this point, our calculations lead us to believe that afforestation sinks will not have a major impact upon the optimal price and quantity of carbon abatement. There are differences between the results from GCOMAP and GTM, but the optimal afforestation sinks are small in relation to the total quantity of carbon that would need to be abated in order to meet a radiative forcing target.

## 6. Stabilizing radiative forcing

In this section, we examine how radiative forcing might evolve under “business as usual”, and compare this with a 4.5 or a 3.5 w/m$^2$ (watts per square meter) ceiling on radiative forcing. For the control scenarios, we explore two alternatives for complying with a cap on radiative forcing. In one, we rely exclusively on reductions in fossil fuel emissions (a “CO2 only” scenario). In the other, we rely on the full range of trace gases, described earlier, and afforestation (a “multi-gas and sinks” scenario).

Figure 1 shows radiative forcing with the proposed caps and compares these trajectories with those for the reference case, i.e., the “no policy” scenario. With a cap, radiative forcing initially rises faster under the “multi-gas and sinks” scenario. This is because here we are able to take advantage of the short-lived nature of CH4. This allows us to slow the rate of increase of radiative forcing more quickly as we approach the ceiling.[*]

Figure 1. Radiative Forcing from 1750



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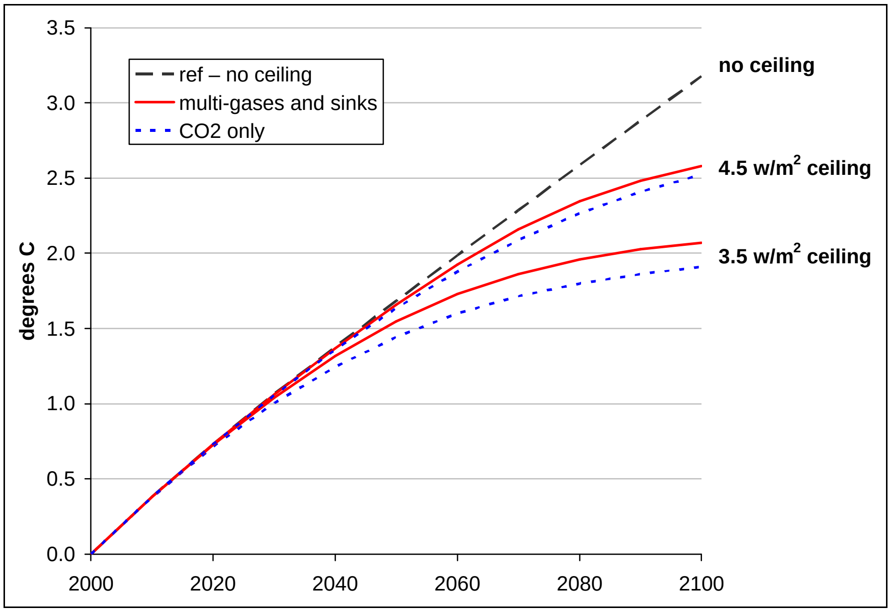
[*] We note that 2150 is the time horizon for the EMF 21 study (ref. 2). In some cases the EMF cap does not become binding until post-2100.

Figure 2 focuses on temperature change, a metric that is perhaps more understandable to non-physical scientists. For these calculations, we assume a climate sensitivity of 2.6 degrees C and a thermal ocean lag of 25 years. In the absence of climate policy, the temperature increase over the 21st century would exceed 3 degrees C. With a cap on radiative forcing of 4.5 and 3.5 w/m$^2$, the temperature increase over this period is approximately 2.5 and 2.0 degrees C, respectively.

Figure 2. Comparison of Temperature Change



Although we have argued that concentrations are an inappropriate end-point for a multi-gas analysis, nevertheless it is useful to examine the implications of stabilizing radiative forcing on concentrations. Figure 3 shows CO2 concentrations for our various scenarios. A multi-gas approach increases the allowable level of CO2 concentrations in the atmosphere by approximately 50 ppmv in 2100.

Figure 3. Comparison of CO2 Concentrations

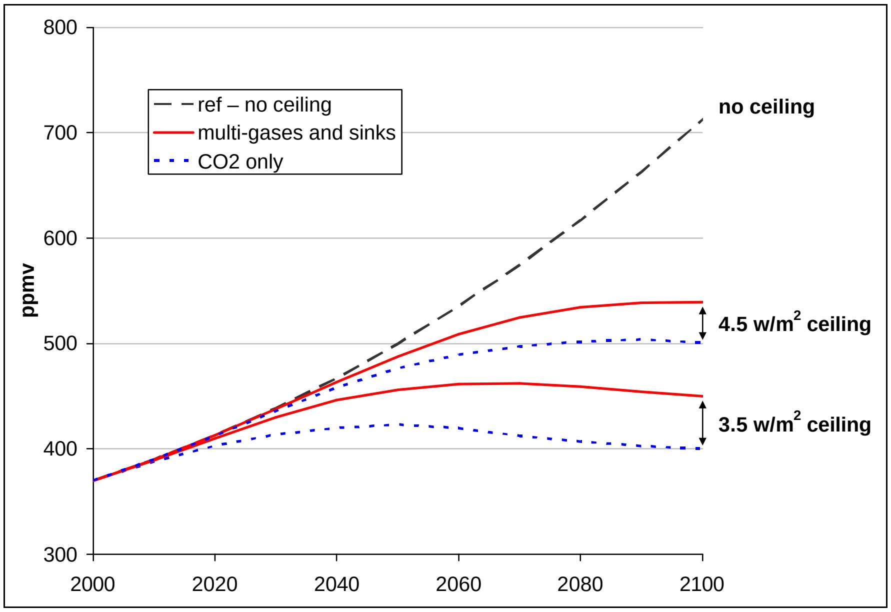


Figure 4 shows the implications for energy-related CO2 emissions. In the case of the tighter cap, it is particularly important to have multiple gas and afforestation options. Otherwise there would be a need for an immediate and rapid departure from the baseline. This is reflected in the carbon tax that would be required under such a scenario (see Figure 5). In the remaining scenarios, the taxes start at much lower levels but nonetheless rise substantially over time.

Figure 4. Comparison of CO2 Emissions

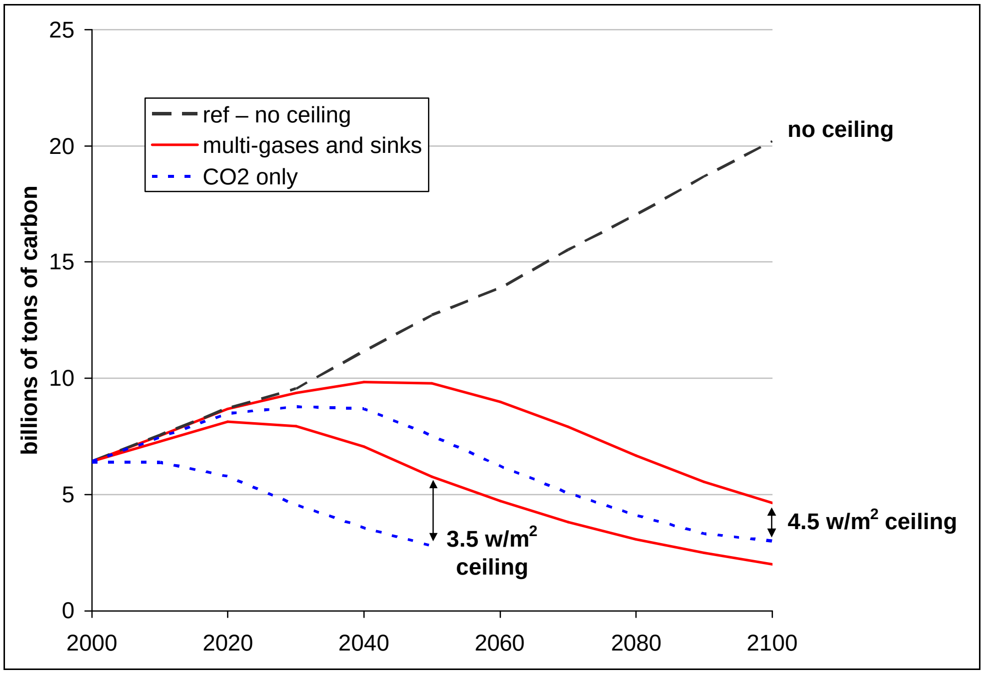
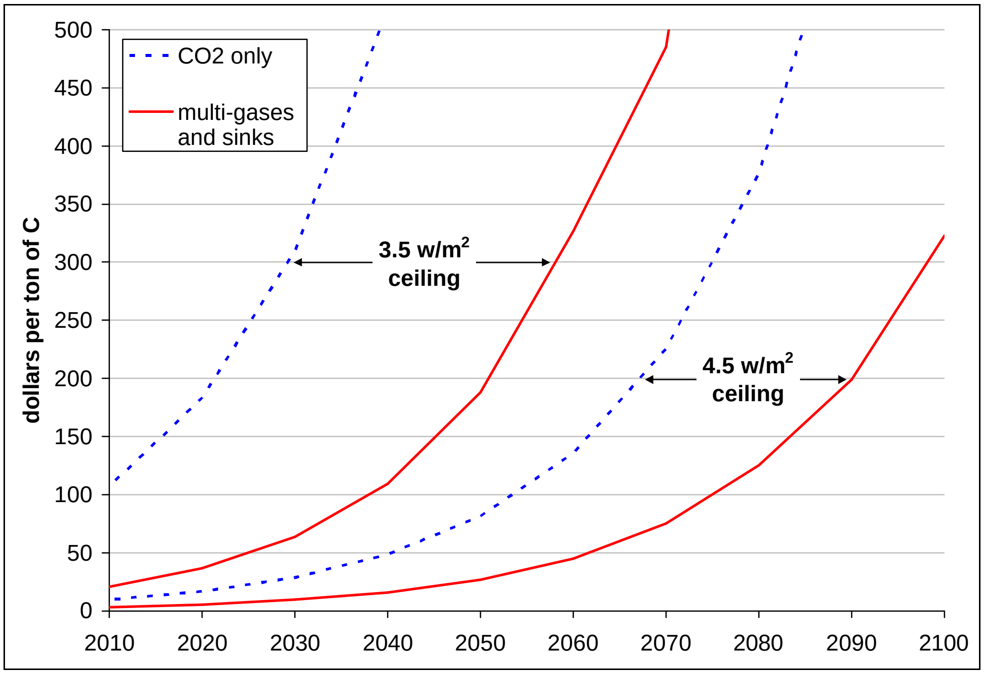


Figure 5. Comparison of Carbon Taxes



## 7. A decadal constraint on temperature change

There is concern not only about the absolute temperature level but also the rate of temperature change. For example, some ecosystems may be able to adapt if climate change is gradual. But abrupt change may be problematic. The issue of what constitutes "abrupt" remains unclear and is likely to vary from one species to another. In this section, we examine the implications of imposing an additional constraint on climate change, i.e., decadal temperature change is limited to 0.2 degrees C. As in previous sections, our focus is exclusively on mitigation costs. We make no attempt to examine the implications for the value of damages avoided. Again, such analysis is critical but well beyond the scope of the present effort.

Figure 6 shows decadal temperature change for the reference case and the control policy cases. For the latter, we assume that multiple greenhouse gases and afforestation are among the options for meeting a constraint. Because of the lags in the climate system, we find it virtually impossible to impose a 0.2 degrees C decadal constraint prior to 2030. Figure 7 suggests that in the absence of climate policy, the rate of decadal change would exceed 0.3 degrees C for the entire 21st century. For the control cases, the least-cost pathway is governed by the decadal constraint until 2060. After that, the constraint on radiative forcing causes the pathways to diverge.

Figure 6. Constraint on Decadal Temperature Change

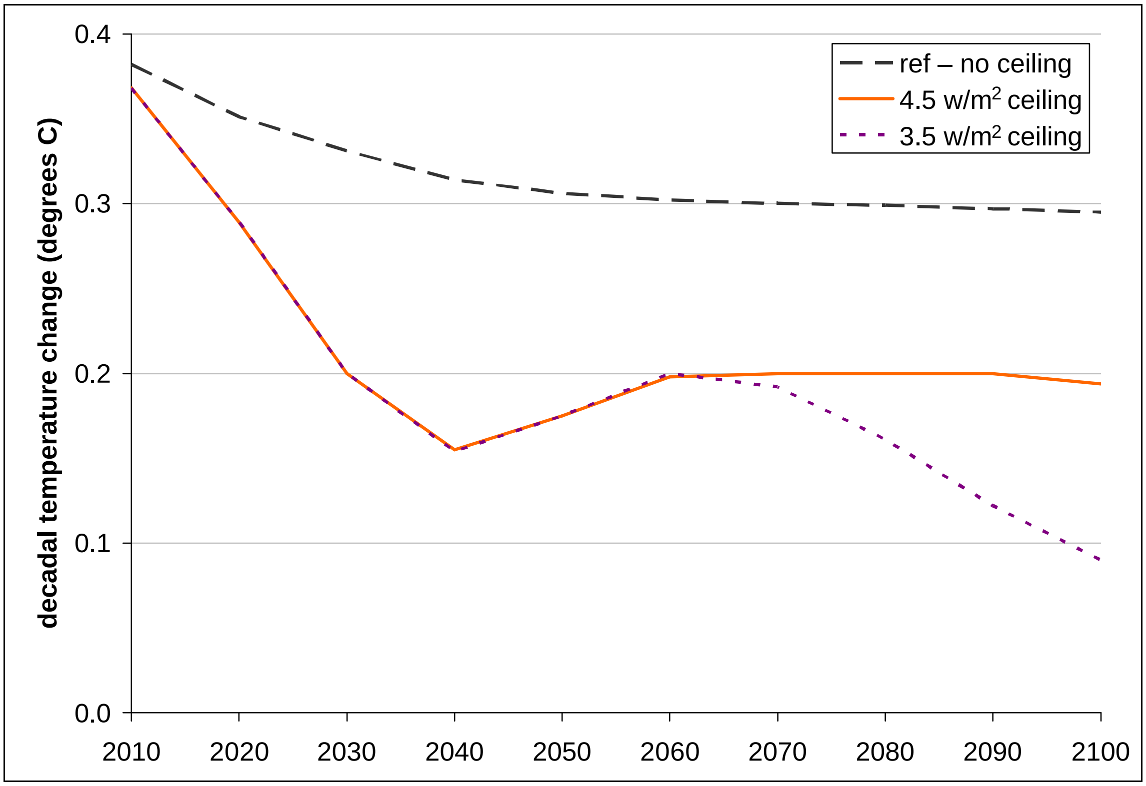
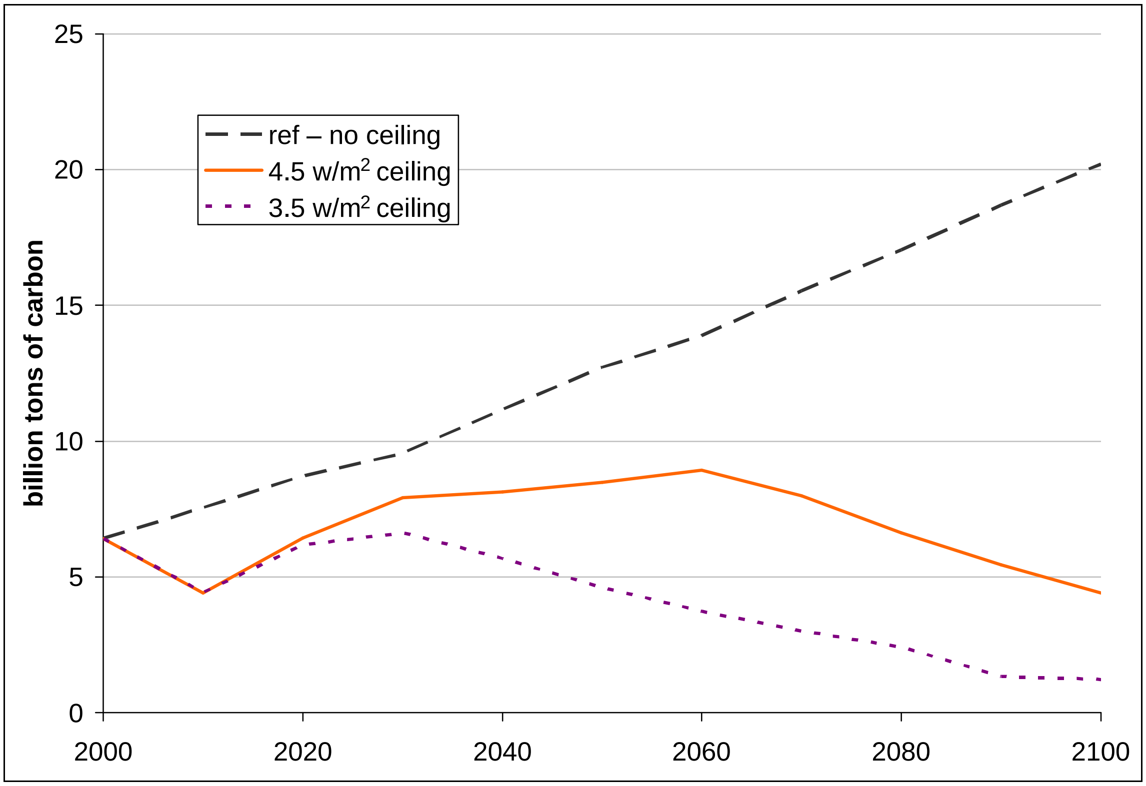


Figure 7 compares CO2 emissions for our reference and for two control scenarios. Notice that both control cases require a rapid departure from the reference case. The “look ahead” feature of the model is the reason for the substantial reductions prior to the imposition of the decadal constraint. That is, anticipating a sharp constraint on decadal temperature change in the future, the economic system begins reconfiguring itself immediately to adapt to such a constraint.

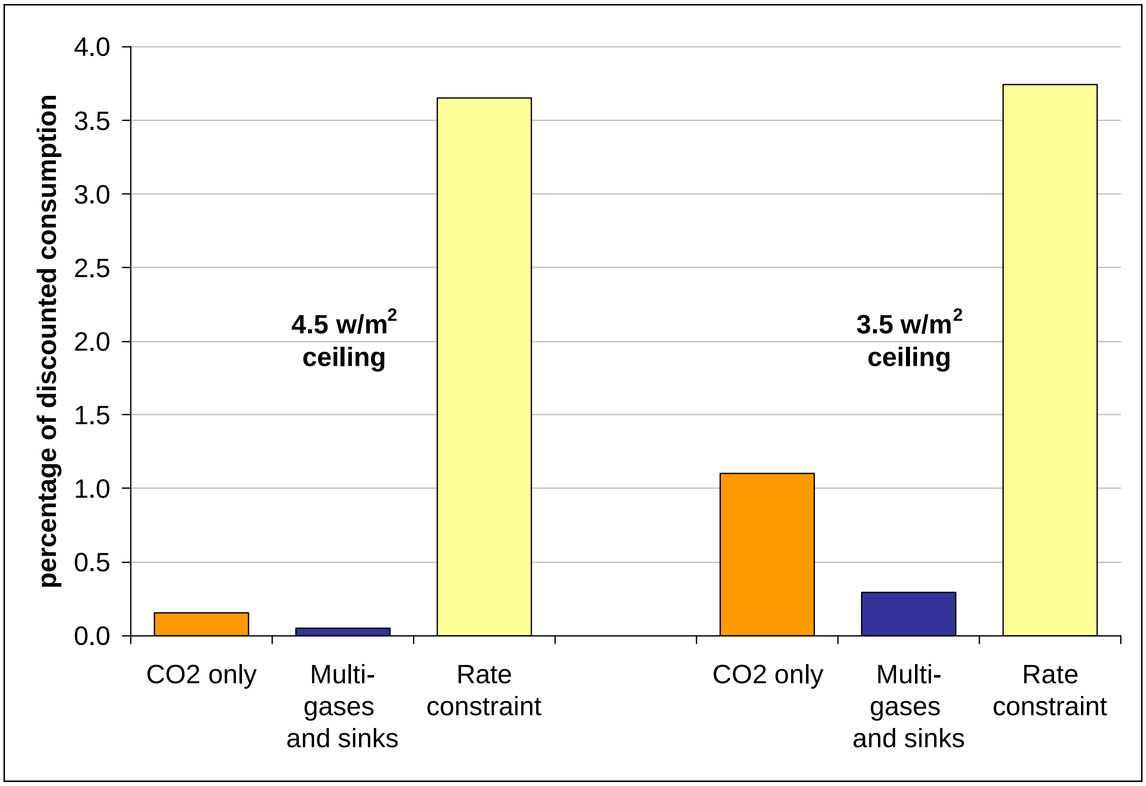
Figure 7. Implications of 0.2 degrees C Decadal Constraint on CO2 Emissions



## 8. Annual consumption losses

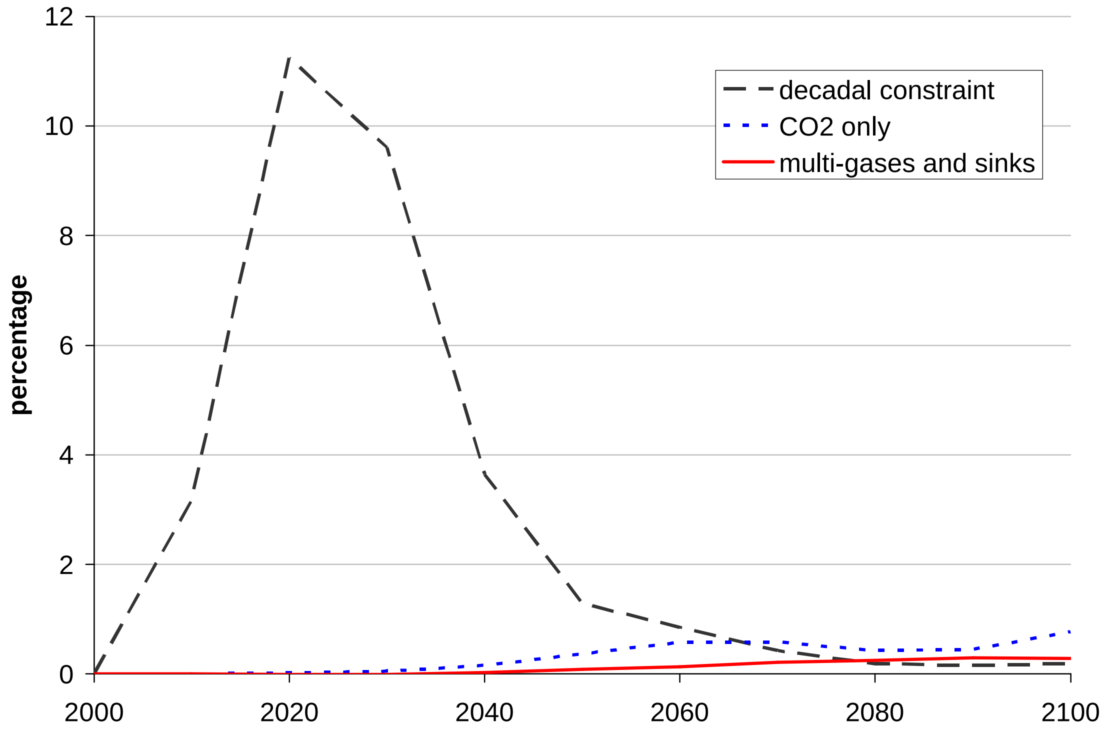
One measure of the welfare impact of a particular policy on consumers is the impact on aggregate consumption. This can be expressed in a number of ways. One is to compare the present value of consumption with and without the climate policy. We can then calculate the aggregate loss in consumption. See Figure 8. Not surprisingly, the rate of change constraint entails much higher losses than those for a constraint on absolute change. For the latter, as we would expect, total losses are higher with the tighter constraint on radiative forcing and when the burden for meeting the constraint is placed entirely on CO2.

Figure 8. Consumption Losses over 21st Century – discounted to 2000

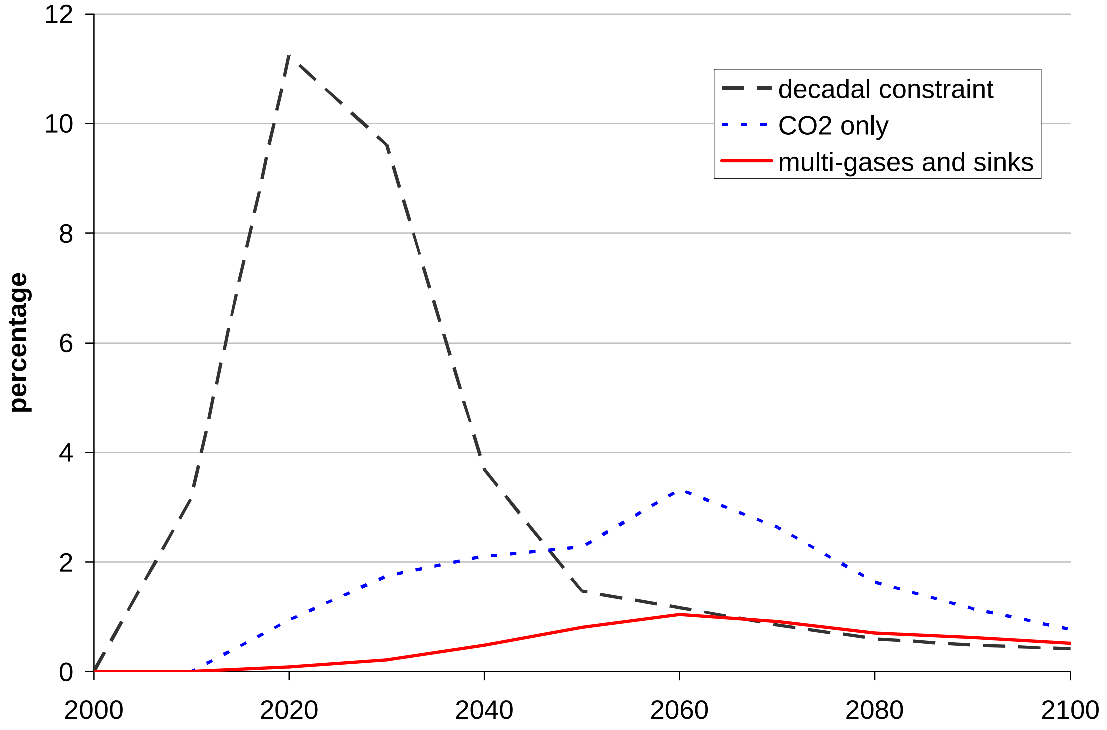


Although Figure 8 is informative, it is perhaps more instructive to examine the annual loss in consumption under alternative policies. See Figure 9. Given the momentum in the climate system, keeping decadal change beneath 0.2 degrees C will require a major change in several economic sectors, most notably energy. The majority of the losses are incurred during the first half of the century. A substantial investment would be required to stay within the constraint. With an absolute constraint on radiative forcing, both the magnitude and timing of the losses differ from those for the rate of change constraint. For example, post-2050 losses are substantially higher with an absolute constraint, which must be met solely through reductions in CO2 emissions. The timing of losses is obscured when the focus is on aggregate century-scale results.

Figure 9. Loss in Annual Consumption



a) 4.5 w/m$^2$ Ceiling Constraint on Radiative Forcing



b) 3.5 w/m$^2$ Ceiling Constraint on Radiative Forcing

## 9. Some closing comments

For its long-term stabilization target, the EMF 21 study (ref. 2) chose radiative forcing rather than atmospheric concentrations for a ceiling. Using the latter is problematic since it requires an *arbitrary* way to make trade-offs among gases. By choosing a ceiling to which each gas contributes (i.e., radiative forcing), the trade-offs among gases can be based on the relative prices of each gas as determined by its contribution to the ceiling. This approach, which includes both physical and economic considerations, avoids the methodological problems associated with the use of GWPs.

The results of the present study show that total abatement costs can be reduced (in some cases substantially) when multiple greenhouse gases and sinks are included in the abatement strategy. Although the focus is on limiting radiative forcing, we also calculate the concentration levels associated with each gas in order to meet a particular target. Hence, if policy-makers still choose to continue to focus on atmospheric concentrations, we can provide more defensible cost estimates for complying with a prescribed ceiling.

Recently, there has been some effort to extend the analysis further along the causal chain connecting human activities and impacts.[11] The goal is to incorporate such uncertainties as climate sensitivity and ocean heat uptake into the analysis. Given the current uncertainties in our understanding of the climate system, it is impossible to project with any degree of confidence the effect of a given concentration ceiling on the things we care about. Extending the analysis to temperature change will help policy-makers gain a more realistic understanding of the consequences of their actions.

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[1] Reilly, J., R. Prinn, J. Harnisch, J. Fitzmaurice, H. Jacoby, D. Kicklighter, J. Melillo, P. Stone, A. Sokolov and C. Wang (1999). "Multigas Assessment of the Kyoto Protocol", *Nature*, **401**, 549-555.

[2] Stanford EMF (Energy Modeling Forum) (2004).

[3] Intergovernmental Negotiating Committee for a Framework Convention on Climate Change (1992). Fifth Session, Second Part, New York, NY, 30 April-9 May.

[4] Manne, A. S. and R. G. Richels (2001). "An Alternative Approach to Establishing Trade-offs Among Greenhouse Gases", *Nature*, **410**, 675-677.

[5] Solow, R. M. (1970). *Growth Theory: An Exposition*, Oxford University Press, New York, NY.

[6] Portney, P. R. and J. P. Weyant (Eds.) (1999). *Discounting and Intergenerational Equity*, Resources for the Future, Washington, D.C.

[7] Energy Information Administration (2003). "International Energy Outlook 2003", U.S. Department of Energy, Washington, D.C.

[8] IPCC (Intergovernmental Panel on Climate Change) (2001). *Climate Change 2001. The Science of Climate Change*, Cambridge University Press, UK.

[9] Sathaye, J., P. Chan, L. Dale, W. Makundi and K. Andrasko (2003). "A Summary Note: Estimating Global Forestry GHG Mitigation Potential and Costs: A Dynamic Partial Equilibrium Approach", working draft, August.

[10] Sohngen, B. and R. Mendelsohn (2003). "An Optimal Control Model of Forest Carbon Sequestration", *American Journal of Agricultural Economics*, **85**(2), 448-457.

[11] Richels, R. G., A. S. Manne and T. M. L. Wigley (2004). "Moving Beyond Concentrations: The Challenge of Limiting Temperature Change", AEI-Brookings Joint Center for Regulatory Studies, *Working Paper 04-11*, April.