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International Institute for Applied Systems Analysis • Schlossplatz 1 • A-2361 Laxenburg • Austria
Tel: (+43 2236) 807 • Fax: (+43 2236) 71313 • E-mail: publications@iiasa.ac.at • Web: www.iiasa.ac.at

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Managing the GLOBAL *Environment*

To enable future generations to drastically–and affordably–reduce carbon emissions if required, we must deal now with science and technology uncertainties.

ARNULF GRÜBLER

Global environmental problems pose entirely new challenges for science, technology, and policy making. Persistent scientific uncertainties, extremely long time horizons (decades to centuries), the potential need for radical and *systemic* technological change, and huge distances in both time and space between those that are supposed to act and those that will benefit are in stark contrast to historical experiences of dealing with environmental issues.

Historically, environmental policy making has relied on scientific advice derived from comparatively well-understood and quantified cause–effect relationships, availability of existing technology "fixes" that could be applied to single (groups of) pollutants, and a national decision-making context in which costs and benefits largely accrue within the same country, the pan-European efforts to regulate acid rain precursors and the Montreal Protocol on Substances That Deplete the Ozone Layer being notable recent exceptions.

In contrast to this type of environmental policy making, consider the issue of climate change. Article 2 of the Framework Convention on Climate Change requires "stabilization of greenhouse gas concentrations in the atmosphere at a level that would prevent dangerous anthropogenic interference with the climate system." But science is currently unable to suggest even rough quantitative guidelines of what would constitute dangerous levels of anthropogenic interference. Therefore, a range of possible climate stabilization targets is usually analyzed (*1*), without, however, being able to narrow down uncertainty ranges or to suggest particular threshold levels.

Even if such targets could be identified, they are necessarily very long-term and refer to future states of the climate system, typically beyond the second half of the 21st century, or sometimes even beyond 2100. Thus, "inverse calculations" are needed to translate such long-term goals into short-term targets for regulating emissions of greenhouse gases (*2*). Unfortunately, these calculations are plagued by enormous scientific uncertainties, precluding their direct use in policy making.

Complicating matters further, a multitude of gases from diverse sources and human activities, including energy production and use, agriculture, forestry, waste management, and so forth need to be considered. Potential emission reductions and their associated costs remain highly uncertain, especially for nonindustrial sources and gases other than CO_2 (*3*).

It should also be noted that, for pragmatic as well as equity-based reasons, regulating emissions is first of all a task for the affluent, industrialized countries. These countries currently emit most of the greenhouse gases (contributing overproportionately to possible climate change) and also have the largest scientific and technological capabilities to research and to implement solutions. Conversely, it is generally agreed that *vulnerability* to possible climate change, at least in the domains that can be quantified (so-called "market damages"), is much greater in poor societies than in affluent ones (*4*). In other words, we have both an intergenerational and an international decision-making problem (*5*). Present generations of Europeans and North Americans are supposed to implement as yet unknown emission reductions that would benefit (in terms of avoided climate change damages) future generations of Africans, Chinese, and Indians. At the same time, we do not seem to care much to improve the damages from a "climate of poverty" of much of the *current* generation of Africans, Chinese, or Indians either.

Models and scenarios

Let us now look at a simplified quantification of the underlying uncertainties. A commonly cited goal is to stabilize atmospheric concentrations of carbon dioxide (the largest anthropogenic cause of global warming) at 550 ppmv, roughly double preindustrial levels. A carbon cycle model is needed for the inverse calculation of emissions levels that would be consistent with that concentration goal. Such models have many uncertainties, notably in their assumptions about the flux (F) in terrestrial carbon. Typically, these models are initialized so that they reproduce the well-known historical record of atmospheric CO_2 through the 1980s. Emissions of carbon dioxide due to the combustion of fossil fuels are relatively well known, yet both the net carbon fluxes due to land use changes (e.g., deforestation) and the carbon uptake due to CO_2 fertilization of plants are known only poorly. The Intergovernmental Panel on Climate Change's (IPCC's) review (*1*) suggests that the best guess for the land use carbon flux in the 1980s is 1.1 GtC yr^{-1}, but the value ranges from 0.6 GtC yr^{-1} to 2.6 GtC yr^{-1}. The level of assumed fertilization depends on the value selected for land use flux—in order to balance the model, high land use flux requires high fertilization.

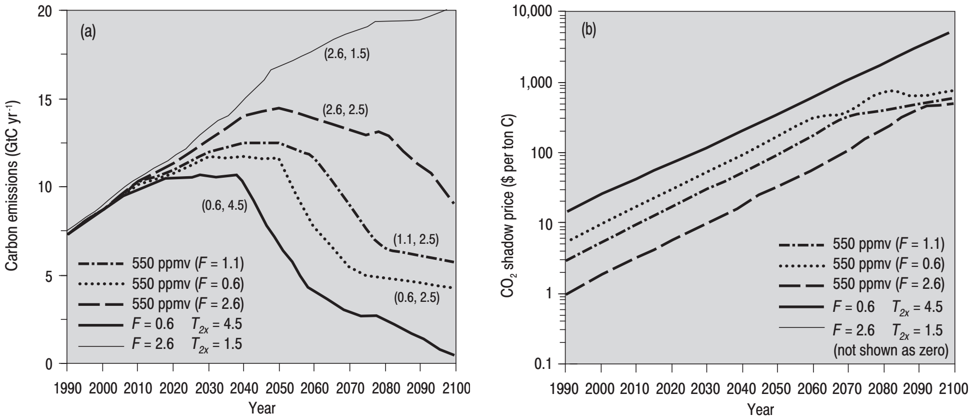
A simple carbon cycle and climate model (*6, 7*) was linked with an energy systems model at the International Institute for Applied Systems Analysis (IIASA) (*8, 9*) to illustrate the implications of this wide uncertainty. If fertilization is high, then compliance with a 550-ppmv CO_2 concentration can be achieved with much higher levels of fossil fuel CO_2 emissions than if assumed fertilization is plausibly much lower (see Figure 1a).The cumulative allowable emissions of carbon dioxide from 1990 to 2100 vary from 937 to 1306 GtC. Relative to a baseline similar to the IPCC IS92a (*10*) scenario, the "shadow price" of carbon that would be needed to comply with the 550-ppmv CO_2 concentration target (see Figure 1b), was computed with the IIASA energy model. In these calculations, we used a 5% discount rate and assumed full spatial and temporal flexibility; that is, the model is free to choose emission reductions *when* and *where* they are cheapest to do. The shadow price, which is akin

FIGURE 1

The effect of uncertainties on climate change analysis

(a) Maximum carbon emissions (GtC yr^{-1}) that comply with long-term climate targets are shown as emission trajectories based on model calculations. The lines show emission trajectories predicted when initializing a simple carbon cycle model with 1980s land-use carbon fluxes of *F* = 0.6 (.........), 1.1 (–·–·–), and 2.6 (— —) GtC yr^{-1} (IPCC's range of uncertainty), ΔT_{2x} = 2.5 K, and a long-term (2150) atmospheric CO_2 concentration constrained below 550 ppmv. The top and bottom trajectories show the additional effect of varying the climate sensitivity parameter ΔT_{2x} within the IPCC uncertainty range of 1.5 (——) to 4.5 (**——**) K per doubling of CO_2. Meeting the long-term climate target eventually requires a reduction in the maximum allowable emissions level, but for the trajectory with the highest fertilization (*F* = 2.6) and lowest climate sensitivity (ΔT_{2x} = 1.5), the period of decline occurs after the 2100 end point of these figures.

(b) "Shadow prices" for carbon have been calculated for each of the three uptake and the two climate sensitivity parameter values of the scenarios shown in Figure 1a. The shadow price is the marginal cost (relative to a baseline similar to IPCC's IS92a (*9*) scenario) of meeting the long-term climatic goal. For these calculations the energy model is allowed full spatial and temporal flexibility, that is, emissions are reduced *when* and *where* it is cheapest to do so. Costs increase over time as a function of the discount rate (5%) and because of the assumption of static future technologies.



Carbon emission constraints are plotted, consistent with stabilization of 550 ppmv and a 2.5 K temperature change by 2150. The range of carbon emissions illustrates the impact of uncertainties in the carbon cycle and of climate sensitivity.

The range of shadow prices (for carbon emission constraints consistent with stabilization of 550 ppmv and 2.5 K temperature change per Figure 1(a)) illustrates the impact of uncertainties in the carbon cycle and of climate sensitivity. The shadow price of the *F* = 2.6 and ΔT_{2x} = 1.5 parameter combination remains zero in all time points as no emission reductions are required compared with the IS92a baseline scenario. Note the semilogarithmic scale of shadow prices that increases roughly by 5% per year, the discount rate used in the calculations. Costs also rise continuously because of the assumption of exogenous (largely static) technology, the "state of the art" of comparable model calculations.

Source: (*9, 19*).

to the optimal level for a carbon tax, rises over time with the discount rate, not the least because the calculations assume exogenous (and largely static) technology, following “state-of-the-art” methodology (*2, 3, 10*).

Uncertainties compound if goals are set in terms of climatic variables such as temperature change. In addition to carbon cycle uncertainties, sensitivity of climate to increased radiative forcing from greenhouse gases is highly uncertain. IPCC’s review suggests a typical value (2.5 K) for the increase in global average temperature due to a doubling of atmospheric CO_2 concentrations, but that the value of the co-called climate sensitivity parameter ΔT_{2x} ranges plausibly from 1.5 to 4.5 K (*1*). A wide range of maximum carbon emissions that comply with long-term climate targets (from near 0 to 20 GtC yr^{-1} in 2100) occurs (see Figure 1a) if a limit of $\Delta T_{2x} = 2.5$ K is adopted and the inverse calculation includes uncertainties in both the carbon cycle *and* the climate sensitivity. Cumulative carbon emissions from 1990 to 2100 range from 751 to 1605 GtC, for which corresponding carbon shadow prices are again shown in Figure 1b. (Note that prices are zero throughout the simulation period for the scenario combining low climate sensitivity ($\Delta T_{2x} = 1.5$) and high carbon fertilization ($F = 2.6$), as emissions (the highest emission trajectory in Figure 1a) are similar to those of the widely used IS92a (*10*) baseline scenario and hence require no emission reductions).

Policy implications

Several implications for policy follow directly from this analysis. A wide range of emissions targets results from the inverse calculations, even considering only the few carbon and climate model uncertainties in the analysis. Although inverse calculations have been used to provide important insights (*1, 2*), their rigorous use for policy purposes seems highly premature.

Despite the uncertainties, there is remarkable convergence to a current value of less than $10 per ton carbon as the near-term price of carbon. This value, based on an arbitrary long-term limit of 550 ppmv, is consistent with the optimal carbon tax computed by Nordhaus (*11*), using an entirely different method. Over the long term, however, the price of carbon in the simple model calculations reported here rises persistently and to very high levels (a few hundred to thousands of dollars per ton of carbon) that are prohibitive from today’s perspective, making corresponding drastic emission reductions rather unlikely. Overall, rising future carbon costs depend on three fundamental variables (*12*): the (uncertain) amount of emission reduction that generally rises over time; how technological change is factored into the analyses (static or dynamic); and the discount rate (5% used here, for a sensitivity analysis (*12*)).

The values presented here follow “state-of-the-art” methodology (for example, (*2, 3, 10*)) by assuming that rates of technological change are determined exogenously and are also largely static. It can be shown with improved methodologies (*13, 14*) that over the long term, one can *induce* technological change in the direction of further *decarbonization* (*15, 16*), where costs of drastic emission reductions could be very small, even nil. Such a benign state of future affairs, however, does not emerge autonomously. Rather, it requires continued and dedicated efforts in R&D and niche market developments to nurture the new technologies (and to identify and to accept also some failures) that can take decades to develop fully (*13, 14*). Only improved technology can enable future generations to drastically reduce carbon emissions at moderate or zero costs, whatever the quantitative emission target might be.

R&D and accumulation of experience in niche markets require up-front expenditures of money and effort. But increasingly, these are viewed as having too high a price in liberalized markets (*17*), in which maximization of shareholder value takes precedence over long-term development and environmental protection goals. New initiatives for the public sector are also called for (*18*). Because of the convergence of short-term prices of carbon from very different analytical perspectives, it may be more productive and accurate for policy to focus on coordinating “prices” of carbon. In contrast, current policy debates such as the Kyoto Protocol have focused on controlling greenhouse gas quantities (emissions targets).

Imposing a moderate carbon tax and earmarking resulting tax revenues to improve the science and technology that best prepare us for an uncertain carbon-constrained world might indeed be the best hedging strategy, in view of pervasive uncertainties.

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Arnulf Grübler is research scholar at the International Institute for Applied Systems Analysis (IIASA) in Laxenburg, Austria. He can be reached by e-mail at gruebler@iiasa.ac.at.

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