you will brake slowly and expect to increase your pressure as you approach the corner, making necessary adjustments along the way. If, however, you are more risk-averse and at some point realize that you might be going too fast and worry that there is a possibility that you lose control and go off the edge, then you immediately brake hard and expect to ease off as you feel that you have regained full control.

Conclusion

Climate change is a risk management issue. If we knew for sure that the worst outcomes from climate change could be addressed successfully in the future, then the appropriate price for emissions would actually be less than the average damages discounted by the risk-free interest rate because climate change damages would be a hedge. If one believes that scientifically plausible scenarios exist in which the worst outcomes from climate change are catastrophic for future consumption, then the appropriate price for emissions would be higher now than the estimate of average damages discounted by the risk-free interest rate.

The fundamental problem, of course, with the insights provided by the economics of risk management is that the answer depends at its core on something unknowable. How significant is the risk of an unimaginable and unmanageable catastrophe? I believe that given that uncertainty, a cautious approach that weighs the cost of catastrophic outcomes above the potential benefits of hedging future economic growth is justified. It would be best to get started immediately by pricing carbon emissions no lower, and perhaps well above, a reasonable estimate of the present value of expected future damages, and allow the price to respond appropriately to new information as it becomes known. R

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Pricing Carbon When We Don't Know the Right Price

Despite the unknowns, we should begin to tax carbon.

BY ROBERT S. PINDYCK

There is almost no disagreement among economists that the true cost to society of burning a ton of carbon is greater than its private cost. Burning carbon produces carbon dioxide and other greenhouse gases (GHGs) that accumulate in the atmosphere. Over time, an increasing concentration of atmospheric GHGs will result in unwanted climate change: higher global temperatures, greater climate variability, and possible increases in sea levels. Burning carbon thereby imposes an externality on society, the cost of which is not incurred by the consumer or firm that is doing the burning. This external cost is referred to as the social cost of carbon (SCC) and is the basis for the idea of imposing a tax on carbon emissions or adopting a similar policy such as a cap-and-trade system.

However, agreeing that the SCC is greater than zero isn't really agreeing on very much. Some would argue that any increases in global temperatures will be moderate, will occur in the far distant future, and will have only a small impact on the economies of most countries. If that's all true, it would imply that the SCC is small, perhaps only around $10 per ton of CO_2, which would justify a very small (almost negligible) tax on carbon emissions, e.g., something like 10 cents per gallon of gasoline. Others would argue that without an immediate and stringent GHG abatement policy, there is a reasonable possibility that substantial temperature increases will occur and might have a catastrophic effect. That would suggest the SCC is large, perhaps $100 or $200 per ton of CO_2, which would imply a substantial tax on carbon, e.g., as much as $2 per gallon of gas.

So who is right, and why is there such wide disagreement? Should we aim for a relatively small tax on carbon, at least initially? Or should we push for a substantial tax that would lead to a large reduction in emissions on the grounds that we need an "insurance policy" against a possible catastrophic outcome?

I begin by briefly reviewing the fundamental uncertainties surrounding climate change and thus the SCC, and I explain why it is so difficult to arrive at a number for the SCC. I then turn to the likelihood and possible effect of a climate catastrophe: an increase in global mean temperature in the next 50 to 100 years that is much

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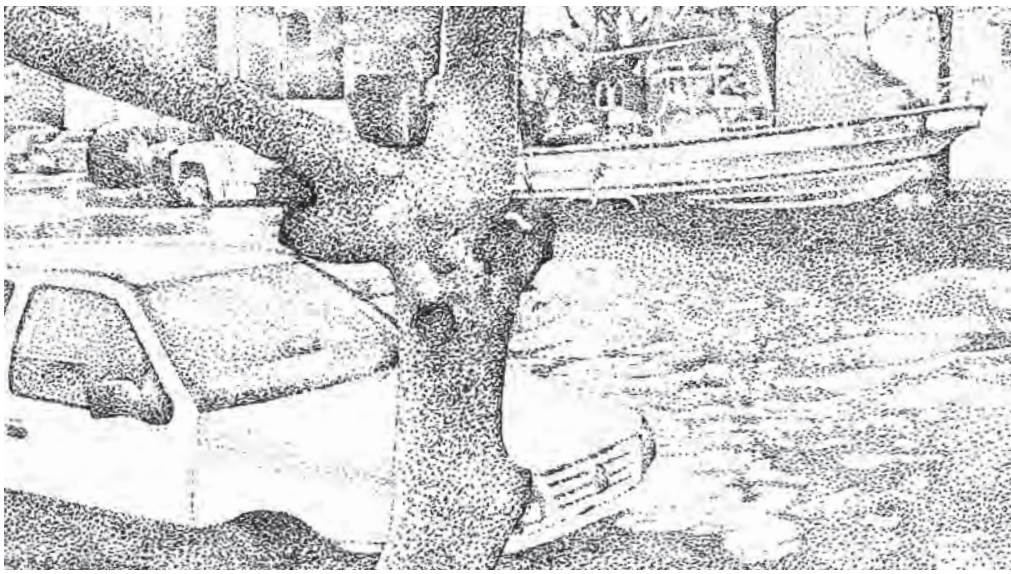
larger than the "average" numbers currently estimated by climate scientists, with a resulting substantial and irreversible reduction in the growth of world gross domestic product. Can that possibility be "priced," and if so, how? I conclude with a simple but concrete policy recommendation: At this point, we need to establish that there is indeed a social cost of carbon that, while uncertain, is positive (yes, almost all economists agree on this, but not all politicians), so that a carbon tax is clearly justified. In addition to implementing at least *some* carbon tax as soon as possible, research on climate change and its effect should be refocused, with an emphasis on getting a better understanding of the possibility of a climate catastrophe.

Why Don't We Know the Right Price?

The uncertainties surrounding climate change and its possible effect are vast, making the economic argument for stringent GHG abatement far from clear. There is disagreement among both climate scientists and economists over the likelihood of alternative climate outcomes, as well as the nature and extent of the uncertainty over those outcomes. There is even greater disagreement over the possible impacts of those alternative climate outcomes, which is what matters in the end. In fact, we know very little about the effects of climate change, in part because of the possibility of adaptation (climate change will occur slowly, over decades) and in part because we know little about technological change that might reduce GHG emissions and/or facilitate adaptation. Finally, there is disagreement about the framework that should be used to evaluate the benefits from GHG abatement, including the social welfare function and discount rate to be used to value benefits that will occur in the distant future.



Given all of this disagreement and uncertainty, how did a U.S. government study manage to arrive at a $20 per ton estimate of the SCC? That study obtained its estimate by running simulations of three integrated assessment models (IAMs): the Dynamic Integrated Climate and Economy model developed by Yale University's William Nordhaus, the Policy Analysis of the Greenhouse Effect model developed by Cambridge University's Chris Hope, and the Climate Framework for Uncertainty, Negotiation, and Distribution model developed by the University of Sussex's Richard Tol and the University of Michigan's David Anthoff. The IAMs "integrate" a description of GHG emissions and their effect on temperature (a climate science model) with projections of abatement costs and a description of how changes in climate affect output, consumption, and other economic variables (an economic model). All of the simulations were based on "most likely" scenarios (i.e., climate and impact outcomes that were within the 90 percent confidence range of the models). Depending on the discount rate used, the average estimate of the SCC from these models ranged from $5 to $40 per ton today, rising to $16 to $65 per ton in 2050. Using a "consensus" discount rate of 3 percent resulted in an average SCC estimate of roughly $20 per ton.

Can we therefore conclude that the SCC is $20 per ton? No. Unfortunately, the study had two fatal flaws. First, even if we assume that the climate science part of the three IAMs was accurate (a dubious assumption), the treatment of economic impact in those (and most) IAMs is completely ad hoc and of almost no predictive value. The typical IAM has a loss function that relates temperature increases to reductions in GDP. But there is no economic theory behind the loss function; it is simply made up. Nor are there data on which to base the parameters of the function; instead the parameters are simply chosen to yield moderate losses that seem "reasonable" (e.g., 1 or 2 percent of GDP) from moderate temperature increases (e.g., 2° or 3°C). Furthermore, once we consider larger increases in temperatures (e.g., 5°C or higher), determining the economic loss becomes pure guesswork. One can plug high temperatures into IAM loss functions, but the results are just extrapolations with no empirical or theoretical grounding.

The second major flaw is that the IAM simulations ignore the possibility of a *catastrophic* climate outcome. The kind of outcome I am referring to is not simply a very large increase in temperature (or large changes in other climate indicia), but rather a very large *economic* effect, in terms of a decline in human welfare, from whatever climate change occurs. That such outcomes were ignored is not surprising; the IAMs have nothing to tell us about them. The problem (as Bob Litterman explains in his article, p. 38) is that the possibility of a catastrophic outcome is an essential driver of the SCC. Thus we are left in the dark; the IAMs that completely ignore catastrophic outcomes cannot provide meaningful estimates of the SCC.

Even if we ignore the possibility of a catastrophic outcome and take the treatment of economic effect in the IAMs at face value, we are still left with considerable uncertainty over the SCC. First, the $20 per ton estimate depends on the chosen discount rate of

3 percent, and there is nothing magic about that discount rate. A higher discount rate (that might better reflect market returns) will yield a smaller value for the SCC. A lower rate (that gives greater weight to the welfare of future generations) will yield a larger SCC. As I have shown in a recent *Journal of Environmental Economics and Management* paper, the value to society of GHG abatement depends critically on the discount rate, and also on the extent of society's aversion to risk. Given that there is wide disagreement among economists over the "correct" values for the discount rate and the degree of risk aversion, it shouldn't come as a surprise that there is so much disagreement—and uncertainty—over the SCC.

Possibility of a Catastrophe

Given that the IAMs can tell us nothing about the probability or likely effect of a catastrophic outcome, how can we incorporate this possibility in an assessment of the SCC? If we somehow could determine the probability and likely impact, what discount rate should we apply to the benefits from avoiding such an outcome? And given how little we know about the probability and likely impact, how can we even begin to evaluate the benefits that would accrue from an abatement policy that reduced or eliminated the probability and/or effect of a catastrophic climate outcome?

As Litterman explains, "no one can credibly promise to provide insurance to future generations against a catastrophic climate disaster. Thus, catastrophic climate risk is a nondiversifiable risk. And ... [the discount rate] commands a risk premium determined by societal risk aversion." However, as I mentioned above, there is wide disagreement regarding the degree of societal risk aversion. If one views a climate disaster as a reduction in the effective capital stock (thereby reducing output and consumption), one might apply a discount rate that reflects the overall return on capital—something around 4 percent or more. That, however, would imply a very small present value for benefits (even if they are very large) that will accrue at least 50 to 100 years from now.

In fact, the proper discount rate might be quite small. First, given that a disaster implies a large drop in consumption, it also implies a high marginal utility of consumption. Second, one can think of a GHG abatement policy as a form of insurance: society is paying for a guarantee that the low-probability climate disaster (or its economic impact) will not occur. Buying such a guarantee is analogous to buying an out-of-the-money put option. The effective discount rate on such a guarantee, like the effective discount rate on a put option, will often be small (less than the risk-free rate) or even negative. Depending on the cost of the insurance (i.e., the cost to society of the required GHG abatement), it may indeed be economical to buy the insurance and invest in abatement, even though any climate disaster would occur only in the distant future. This is another way of saying that the SCC might be large.

Putting the discount rate aside, determining the SCC still requires us to come up with some estimate of the probability and likely effect of a climate catastrophe. How might this be done? Given how little we know at this point, it is unlikely that a detailed and complex IAM-style modeling exercise will be helpful. Perhaps the best we can do is come up with rough, plausible estimates of the probability of a climate change sufficiently large to have a catastrophic impact, and then some distribution for the size of that impact (in terms, say, of a reduction in GDP, or a reduction in the effective capital stock).

This approach has been used in recent studies of "consumption disasters," defined as events that caused consumption to decline by some substantial amount (say, more than 10 percent). In Robert Barro's 2009 *American Economic Review* paper, my forthcoming paper with Neng Wang in the *American Economic Journal: Economic Policy*, and related work, disasters are modeled as random arrivals, the impact of which are random percentage reductions in the capital stock (and thus in ongoing consumption), with the loss fraction given by a simple probability distribution. Barro estimates the mean arrival rate of disasters and the parameter of the impact distribution from consumption data for a sample of countries over the past century; Pindyck and Wang infer these numbers from the behavior of macroeconomic and financial aggregates. For climate change, however, a catastrophic outcome has not yet occurred, so estimating impact parameters from panel data or from macroeconomic aggregates is not feasible.

The problem of assessing catastrophic climate outcomes is analogous to assessing the world's greatest catastrophic risk during the cold war: the possibility of a thermonuclear exchange between the United States and the Soviet Union. How likely was such an event? There were no data or reliable models that could yield good estimates. Instead, analyses had to be based on the *plausible*, i.e., on events that could reasonably be expected to play out, even if with

ILLUSTRATION BY MORGAN BALLARD

low probability. The same approach had to be taken with respect to the range of potential effects of a thermonuclear exchange. Such analyses were useful because they helped evaluate the potential benefits (and risks) of arms control agreements.

We might use the same approach to assess climate change catastrophes. Begin by considering a plausible range of catastrophic outcomes (assuming no GHG abatement) as measured by a percentage decline in the stock of productive capital (thereby reducing future GDP over time). That range could be discrete (e.g., three or more potential outcomes) or continuous. Next, what are plausible probabilities? Here, "plausible" would mean acceptable to a range of economists and climate scientists. Given those plausible outcomes and probabilities, we can calculate the benefits from an abatement policy that would avert those outcomes or reduce the probabilities of their occurrence. Expressing the cost of that abatement in terms of a carbon tax yields the SCC. (Note that as with estimates obtained from "most likely" IAM simulations, the SCC will likely increase over time.) The estimated SCC will once again depend on the discount rate and degree of risk aversion. But finding that the estimate is large and robust to reasonable ranges for those parameters would be extremely informative.

This approach to estimating the SCC does not carry the perceived precision that is part of an IAM-based analysis. But that perceived precision is likely to be illusory. To the extent that we are dealing with unknowable quantities, it may be that the best we can do is rely on the "plausible."

What to Do?

I have argued that we simply don't know the SCC and won't be able to determine it from the set of IAMs currently available. If we focus on "most likely" scenarios for which temperature increases are moderate and effects are small, the SCC is probably in the $10 to $40 range, justifying only a small tax on carbon emissions. But the "most likely" scenarios are not the ones that should be of major concern. We should focus more on the unlikely but devastating scenarios, i.e., the possibility of a climate catastrophe. Depending on the probability, potential effect, and timing, that might lead to an SCC as high as $200 per ton (although I have not tried to actually estimate the number).

That leaves us with two policy priorities: First, we should take the $20 Interagency Working Group estimate as a rough and politically acceptable lower bound and impose a carbon tax (or equivalent policy) of that amount. Of course, climate change is a global problem and we should pressure other countries to adopt a similar abatement policy. There will always be "free riders" (China, for example), but that is not a reason to delay action.

Why is it so important to impose a carbon tax now, even though we know so little about the correct size of the tax? Because it is essential to establish that there *is* a social cost of carbon, and that social cost must be internalized in the prices that consumers and firms actually see and pay. Later, as we learn more about the true size of the SCC, the carbon tax can be increased or decreased accordingly.

The second policy priority relates to climate change research, the volume of which has ballooned in the past two decades. Much of that research deals with the physical science of climate change: the dynamic effects of increasing GHG concentrations on temperature, rainfall, and climate variability in different parts of the world. The models developed to date provide a reasonable picture of the "most likely" outcomes given different scenarios for changing GHG concentrations, but they tell us very little about the likelihood and characteristics of more extreme outcomes. The problem is that extreme outcomes depend on feedback parameters that remain poorly understood and that cannot be estimated in any reliable way. When it comes to modeling the economic effect of climate change, the situation is even worse. As I explained earlier, given our lack of theory and data, our ability to predict the economic effects of higher temperatures is virtually nil. And that harsh assessment applies even to moderate ("most likely") temperature change scenarios, never mind extreme outcomes. This means that IAM-based analyses of climate change are unlikely to take us very far and are of very limited (if any) use as a policy tool.

We already know that "most likely" scenarios can justify a small tax on carbon emissions, but that's not very interesting. What matters is the possibility of a catastrophic outcome, which does not simply mean a very high increase in temperature and rising sea levels, but rather an *economic* effect of those physical changes that is catastrophic. We need to develop plausible estimates of probabilities of extreme climate outcomes and plausible estimates of the impacts of those outcomes.

So how should carbon emissions be priced? I have tried to explain why the question is so inherently difficult, why an answer won't come from the kinds of modeling exercises that have permeated the literature, and why the case for a substantial carbon tax—if that case is to be made at all—must be based on an analysis of potential catastrophic outcomes. That should be the focus of future climate policy research. R

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