Symposium:
The Economics of Climate Change: The *Stern Review* and Its Critics

An Even Sterner Review: Introducing Relative Prices into the Discounting Debate

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Introduction

The *Stern Review* (2006) has come to symbolize something of a dividing line in the evolution of the common appreciation of the climate problem. It is fair to say that during the last decade, there has been a gradual but uneven increase in the perceived gravity of anthropogenic climate change, among scientists and, with some time lag, the general public. However, save the United Nations' Intergovernmental Panel on Climate Change (IPCC) assessments (see for example, IPCC, 2001, 2007a, b), the *Stern Review* is the first major, official economic report to give climate change a really prominent place among global problems. The political backing of the *Stern Review* in the UK—at its first presentation, Sir Nicholas Stern was flanked by both Prime Minister Tony Blair and Chancellor Gordon Brown—has been impressive and one of the factors commanding attention.

Still, the *Stern Review* has been criticized on a number of accounts. The criticism has regarded both the manner in which the results are presented and the methodology underlying them, especially when it comes to the *discount rate* used when analyzing the future economic benefits and costs of climate change.

The reason for the preoccupation with the discount rate, a seemingly trivial parameter, is simple: since the impacts of climate change will mostly be felt in the future (because emissions of greenhouse gases are rising and because of the inertia of the climate system), the rate at which we discount the future will have a huge impact on the level of emissions reduction that

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is economically warranted today. A simple example illustrates this point. If we use a discount rate of 1 percent, the discounted value of $1 million 300 years hence is around $50,000 today. But if we use a discount rate of 5 percent, the discounted value is less than 50 cents! Note how this difference is strongly nonlinear—in this example, the discounted value is changed by a factor of 100,000 when the discount rate is changed by a factor of five.

Although a relatively simple concept in economics, the discount rate debate cuts to the core of many fundamental questions regarding global environmental change: how much weight should we put on the welfare of future versus current generations? Will growth continue so that future generations are all richer than we are today? How important is the distribution of impacts (i.e., how should we value costs that disproportionately fall upon the poor or the rich)? Consequently, when it comes to analyzing climate change policy, we are far from a consensus in the economics literature on which value to choose for the discount rate.

The main argument of this article is that results similar to the *Stern Review* can be obtained, even without making the assumptions concerning the discount rate that have been so strongly criticized, by taking into account the neglected but important fact that *relative price changes* are an inherent aspect of economic growth. More specifically, we show that rising relative prices can have important implications for the efficient level of climate change mitigation. Briefly, because the rate of growth is uneven across sectors of the economy, the composition of economic output will inevitably change over time. If output of some material goods (e.g., mobile phones) increases, but access to environmental goods and services (e.g., access to clean water, rain-fed agricultural production, or biodiversity) declines, then the relative price of these environmental amenities should rise over time. The result will be augmented economic damages from climate change, which means that higher levels of climate change mitigation would be warranted today. We conclude by arguing that *even more restrictive stabilization scenarios* than those discussed in the *Stern Review* can be justified on economic grounds.

The article is structured as follows. In the second section, we discuss the metric used by the *Stern Review* to present future costs. In the third section, we make some observations concerning the rate of discounting and its determinants, both in the *Stern Review* and in the broader literature. Further, we introduce our main contributions: the effect of higher nonmarket damages and unbalanced growth on relative prices and the importance of these factors for the value of future climate damage. Using a well-established climate model, the Dynamic Integrated Model of Climate and the Economy, or DICE (Nordhaus 1994), in the subsequent section, we illustrate the effect of making different assumptions regarding discount rates and incorporating relative price changes on efficient levels of emission abatement. In the sixth section, we discuss the estimates of the economic impacts of climate change on precisely those nonmarket goods and services whose prices we expect to rise over time. Finally, in the last section, we discusse our findings and conclude.

The *Stern Review*'s Presentation of Damage Estimates

One of the features of the *Stern Review* that has stirred controversy concerns the way it presents the estimated damages from climate change. While earlier studies (e.g., Nordhaus 1994) have estimated costs of climate change impacts on the order of 1 percent of future GDP, the *Stern Review* boldly asserts that business-as-usual (BAU) emissions of greenhouse gases will lead to a minimum damage of 5 percent of GDP, and could be as high as 20 percent of GDP, *now and forever* (pp. 162–163).

This way of presenting future damages builds upon an expected utility framework developed by Mirrlees and Stern himself (1972). Although a relatively simple framework, it has apparently been quite confusing to many readers. Consider a hypothetical future with eternal growth in consumption at some fixed rate. The *Stern Review* assumes that climate change will introduce costs that lower this growth, leading to a lower consumption trajectory. The damage from climate change is the difference between these two trajectories. The question then becomes how do we illustrate, in a simple and transparent way, this difference in future consumption?

The difficulty in comparing the various welfare paths lies in the fact that the percentage difference between the two paths varies over time. For example, the difference can be described as a discounted sum, which would be a huge number (of a magnitude that would be hard to grasp), or as the number of additional years it will take to attain a given level of consumption. However, neither approach is fully satisfactory. Stern addresses this issue by calculating a consumption path that has the same total discounted utility as the climate damage path, but that has the same growth rate as the BAU path. Thus, this path must start at a lower level than today's per capita consumption, e.g., X percent lower, but the path will then always be exactly X percent lower.

This gives the policy-maker a single figure (X) to use as a cost equivalent. This figure (between five and twenty) is described in the *Stern Review* as a "Now and Forever" reduction. Of course, the *Stern Review* does not suggest that consumption or utility will actually fall *instantaneously*. Rather, it is merely an attempt to find a single figure that is equivalent to something that actually varies over time. However, the risk that it may be interpreted in this way has led some (e.g., Tol 2006) to call this way of presenting the results "preposterous."

Still, there may be something more than a misunderstanding here. Most economists, including Stern, appear to believe we will have much higher incomes in the future, despite climate change. But the risk of perhaps being only eleven—instead of thirteen—times as rich in the year 2200 is unlikely to get many people upset about climate change. It may seem that by presenting the damage estimates in the way that he does, Stern has fallen for the temptation of overstating his case. This also shifts the focus from what we believe to be the true issue: the presumably small (but unknown) risk that climate change will actually make us *significantly* worse off in some respect. We believe Weitzman (2007a, b) is right to focus on what he calls the fat tails of the probability distribution: the potentially catastrophic scenarios as a motivation for abatement. One of the main points of our article is that we also need to consider *in what ways* we will be richer in the future. If we experience growth in manufactured gadgets but deterioration in environmental quality, the relative importance of the latter will have to be reassessed when evaluating the utility loss from climate change. This is why we need to take changing prices into account in the analysis.

Discussion of the Discount Rate

There are many uncertainties when it comes to the climate. There are uncertainties related to cloud formation, feedback from methane in melting permafrost, and ecosystem responses to rapid change, to mention just a few. Hence, it may come as a surprise to some noneconomists that the main source of uncertainty in estimates of the economic consequences of climate change is something else: *the discount rate*. In fact, much of the criticism of the *Stern Review* has focused not on the climate science embodied in the report or its assessment of the costs and benefits of climate change mitigation, but on the low discount rate used in the analysis and how this drives the central results of the Review (see, for example, Dasgupta 2006; Yohe 2006; Nordhaus 2007; Weitzman 2007a).

Despite the controversy, most participants in the debate about what constitutes an appropriate discount rate for estimating climate change damages acknowledge that a good starting point is the so-called Ramsey rule. The Ramsey rule holds that the discount rate should equal the sum of two factors, the pure rate of time preference, δ, and the product of the growth rate of income, g, and the elasticity of the marginal utility for money, η. The first component, δ, implies discounting of future utility *per se*, while the second implies discounting the value of future consumption goods based on the notion that we will be richer in the future and that the rich gain less welfare than the poor from a given quantity of money.

In this section, we will discuss the discount rate used in the *Stern Review* and focus on aspects of the discount rate that we believe have been overlooked in the ensuing debate. In particular, we will attempt to clarify how the choice of parameter values affects policy advice when it comes to short-term emissions abatement. For a more thorough account of the arguments and counter arguments in the discounting debate, we refer the interested reader to Lind, Arrow, and Corey (1982); Arrow, Cline, and Mäler (1996); and Portney and Weyant (1999).

The Discount Rate Used in the Stern Review

The *Stern Review* contains a very careful and nuanced discussion of the discount issue in chapter 2, and eventually settles for a pure rate of time preference, δ, of 0.1 percent and an elasticity of marginal utility, η, of one. When combined with an assumed per capita growth rate of 1.3 percent, Stern arrives at an unusually low discount rate of 1.4 percent. As shown by Dasgupta (2006), Tol (2006), Nordhaus (2007), Yohe (2006), and others, and as illustrated numerically in the fifth section, this is indeed one of the most important reasons for the *Stern Review*'s high damage figures. Rightly the discount rate has been at the center of the debate.

One way to judge discount rates is to compare the assumptions made with observable market variables, e.g., interest rates and savings behavior. This is the track taken by some of the critics of the *Stern Review*. Nordhaus (2006) notes that the resulting discount rate numbers do not match the observed market rate of interest. Similarly, Dasgupta (2006) argues that the values of δ and η assumed by Stern would not be compatible with observed savings rates. However, there are two major problems with this line of critique.

First, real market complexities make it far from obvious which values the discount rate should match. The market rate used should be a risk-free rate, and presumably, we should use an average over a very long time period, since we are going to use the rate over extremely long time periods. As noted by Cline (1999), this could well imply a discount rate that is close to zero, matching that of the historical real rate of return on treasury bills.

Second, this is a critique that, in its purest form, misses the point. In our opinion, using observable real market variables as a benchmark is not appropriate, since we are searching for a number on which to base *ethical* or *normative* judgments: We are not simply observing the market as we do in positive or empirical studies; we are providing arguments for public action that involve the provision of very complex public goods.

The Ramsey framework provides a tool for organizing our thoughts on this topic, and naturally it is of some interest to compare our numbers to the observable market or savings rates. But the latter cannot alone determine whether or not we have chosen appropriate numbers for δ and η—since then there would be no point in taking the trouble to attempt this ethical exercise—and there would be no independence of the normative from the positive. As Hume (1740) concluded long ago, one cannot derive an *ought* from an *is*. Hence, the disagreement over the discount rate is not merely a case of *scientific* uncertainty, that can be logically or empirically resolved, but a question for which value judgments are an inseparable part of the answer.

The Size of δ—How Much Should We Care about Future Generations?

As mentioned above, the pure rate of time preference, δ, measures the extent to which we discount future welfare *per se*. The effect of δ on our estimate of optimal abatement is straightforward: a higher value implies less weight being put on future damages and hence less abatement today. The major difference between the discount rate in the *Stern Review* and most other benefit-cost analyses of climate change is that Stern uses a very low pure rate of time preference. This implies that Stern takes a very egalitarian view of intergenerational distribution. In fact, the only reason Stern gives for a δ that differs from zero is the risk that future generations might not be around at all.[1] We agree with Stern and many other prominent economists and thinkers throughout time (e.g., Ramsey, Pigou, Rawls, and Dasgupta) who have argued that no such justification (against a zero rate of time preference) exists.

The Size of η—How Curved Is the Utility Function?

The marginal elasticity of utility to income, η, measures the curvature of the utility function. The higher the value of η, the less we care for a dollar more of consumption as we become richer. Since we expect that we will be richer in the future, when climate damages will be felt, a higher η also implies that damages will be valued lower. Thus, a higher value of η implies less greenhouse gas abatement today, unless for some reason we will be *poorer* rather than richer in the future. In this case, a higher η would give higher damage values, which would justify more abatement.

The idea that a rich person would have less marginal utility for money than a poor person is deeply rooted in economic theory and has also been well established empirically (although the magnitude of the effect is disputed). However, the practical implications of this are actually quite radical: an η of unity already means utility is logarithmic, which implies that the utility of a million is just 20 percent more than the utility of a hundred thousand. To

[1]The pure rate of time preference of 0.1 percent used in the Stern Review is compatible with about a 10-percent risk of extinction of humanity per century, or 65 percent per millennium. When viewed in this light, 0.1 percent is a fairly high number. The reader should be warned that there is a risk of δ being treated in a way that makes it endogenous: in other words, those who believe in a high value for the pure rate of time preference will in fact suggest policies (of doing nothing much) that make extinction more likely!

illustrate, let us assume that person R is a hundred times richer than person P. Then, taking \$1 from R and giving it to P would increase P's utility a hundred times more than the loss of utility to R. But with an η of two, P's increase in utility would be 10,000 times more than R's loss in utility!

If η is large, and if we assume a utilitarian social welfare function (which is the simple sum of the individual utilities), then aggregate welfare would be much higher in an economy with an even income distribution. This does not automatically imply that redistribution of wealth is desirable, since we must consider the problems of actually implementing the redistribution. Still, a strongly curved utility function is quite radical, with an η of even one having strong implications: it suggests high and progressive taxes as well as large transfers of development assistance to poor countries.

To account for the diminishing marginal utility of income, it was popular in the 1970s–1990s to argue that benefit-cost analysis (BCA) should use distributional weights, i.e., value costs falling on the poor higher than costs falling on the rich. As Johansson-Stenman (2005) points out, distributional weights were actually the norm in project appraisal documents, such as Dasgupta, Marglin, and Sen (1972); Little and Mirrlees (1974); and Squire and van der Tak (1975). Drèze and Stern (1987) and Drèze (1998) have also been proponents for the use of distributional weights. However, most BCAs do not use distributional weights. Instead, it has become the norm for BCA "to focus on efficiency" and to compare a dollar of costs with a dollar of gains at a one-to-one exchange rate—no matter who is gaining or losing—which in practice amounts to setting η equal to zero.

Although distributional weights are seldom used in practice, there is one big exception, where distributional weights turn up under another name: *discounting*! By setting η higher than zero, distributional weights are in fact applied to future generations.

Is it reasonable to use welfare weights only when we want to argue that we should do nothing today and leave the costs to future generations? This happens to be a case when the use of the curved utility function is in our interest. In all other cases—educational or nutritional programs for the poor, development assistance, or progressive taxation—we choose to disregard the curvature of the utility function. Real business is often conducted as if η were zero, and most economists use zero in all other contexts. Thus, it is ironic that Stern has been accused of using too low a value for η when he has used a value of one.

If we use the discount rate to lower the estimates of the costs from climate change that our descendents will face, based on the argument that they will be so much richer and the utility function is so curved, then we should logically give extra weight to any low-income people affected—such as the coastal dwellers of Bangladesh who appear doomed to become environmental refugees as their lands are inundated.[2] Although the *Stern Review* does discuss the uneven distribution of climate change impacts at length, its analysis simply refers to others who have estimated 25- to 50-percent increases in damage costs if equity weights are used. This is one area where we think the *Stern Review* could have been a bit tougher: by applying equity weights as an integral part, rather than a possible extension, of the analysis.

[2]Some authors argue that future costs will be smaller than predicted due to adaptation. Thus, for instance, people will not wait passively until they are inundated. We have no doubt that the people of coastal Bangladesh will want to move. However, we do have concerns about whether other countries will be prepared to admit these very large numbers of future refugees.

The Rate of Growth

The final factor in the Ramsey formula is the growth rate of the economy. In Stern's case, per capita consumption is projected to grow from \$7,600 to \$94,000 by the year 2200. This raises a number of fascinating issues: Can growth go on for so long? What about the material and ecological sustainability of this growth?

To account for the idea that growth cannot "go on forever," Azar and Sterner (1996) assumed that growth would continue only until we became ten times richer and that then income would level off. This simple assumption leads to declining discount rates, which increase the present value of any future cost. Azar and Sterner were also early in disaggregating those affected into rich and poor. This implies, as discussed above, that damages are strongly increased particularly if the marginal elasticity of utility is high. In effect this amounts to an explicit welfare weighting of the poor affected (for instance in lowland Bangladesh) that increased the damages dramatically. They thus found that the shadow value of carbon increased substantially compared to analyses by others (e.g., Nordhaus 1993).

However, the "Malthusian" notion that there are limits to growth is quite discredited. The counterargument is that there are no bounds to human imagination. However, we should not let this point pass too easily. Clearly, there is some logic to the notion that the planet is finite and that on any finite surface, eternal exponential growth must represent a problem. These two notions can be reconciled by recognizing that the argument against unlimited growth applies only to certain aspects of *physical* activity. For example, although the steel, cement, and oil industries cannot grow forever, this does not imply any practical limitation on the development of, say, music or electronic communication and computation, which require quite trivial physical resources. An immediate corollary to this is, however, that continued economic growth over a period of centuries also necessarily implies a dramatic change in the *composition of the economy* and thus in *relative prices*, the issue to which we now turn.

Substitutability, the Content of Growth, and the Role of Relative Prices

We have two central concerns with the *Stern Review*. First, we are concerned that it may not be giving sufficient weight to nonmarket damages, a topic to which we return in the subsequent section. Our second concern, and the main theme of this article, is that the effects of the changing composition of the economy and changing relative prices are not analyzed. The mechanism of changing relative prices is brought up on several occasions in the text, but it never enters the analysis.

Stern is not alone in his approach to relative prices. In most discussions on discounting and climate change policy, changing relative prices and the effect this could have on real discount rates is acknowledged and then left aside (see for example, Arrow, Cline, and Mäler 1996; Nordhaus 1997; see also Lebègue et al. 2005 and Gollier 2007). In this section, we examine and explain the effect of changing relative prices and conclude that this effect implies that long-run damages from climate change should be taken much more seriously.

Implicit in all integrated assessment models (IAMs) used in the analysis of climate change policy—e.g., the PAGE model used by Stern (see Hope 2006 for a model description) and the models used by some of his critics (e.g., Nordhaus's DICE model [Nordhaus 1994; Nordhaus and Boyer 2000] and Tol's FUND model [Tol 1999])—is the assumption of *perfect* *substitutability*. Perfect substitutability implies that detrimental climate change impacts can be balanced on a one-to-one basis with increased consumption of material goods: one dollar's worth of climate damages, regardless of the kind, can be compensated by a dollar's worth of material consumption. This implies that despite climate impacts, we will be richer and enjoy a higher level of welfare in the future.

However, if there are limits to the substitutability between, for example, consumption of material goods and environmental services, then our analysis of climate change needs to take into account the content of future growth. Unbalanced growth, where consumption of some goods or services grows more slowly, would be expected to cause relative prices for those goods or services to rise as they become relatively more scarce.

The effect of increasing scarcity on relative prices can be quite drastic, as illustrated by the following example. One or two centuries ago, a share of the population—say 5 percent—employed domestic labor such as maids. However, despite increasing average incomes, the number of people who employ maids has not gone up! The main reason for this is, of course, that the price of such labor has gone up at about the same rate (if not faster) as average income.

When it comes to environmental amenities, like access to water, biodiversity, or other essential ecosystem services, a similar point can easily be made. For example, global agriculture is said to represent 24 percent of global GDP (*Stern Review*, p. 67). A 1-percent loss of agricultural output might be estimated to reduce global GDP by .24 percent. Basic logic, however, tells us that a 50-percent loss of agricultural production would reduce global GDP by much more than 12 percent, and a 100-percent loss would reduce GDP by more than 24 percent of GDP. *The mechanism behind this would be escalating food prices*: As food became more and more scarce, its relative price would rise so fast that the dwindling food supplies would crowd out everything else and approach 100 percent of total GDP.

In a recent paper, Hoel and Sterner (2007) analyze a conceptual model of the economy consisting of two sectors with different growth rates.[3] This model can be used to analyze an economy where one (conventional) sector grows "forever" and the other (let us call it environmental services) sector is constant (or maybe even declining due to pollution). The model shows that due to rising relative prices, the environmental sector can see its share of the economy grow in value terms in spite of becoming physically smaller relative to the growing sector.

The most important implication is that, when valuing damage to the environmental sector, discounting should be supplemented with changes in relative prices. These changes in relative prices may more than counteract the effect of discounting, so that the net effect is higher rather than lower values. Thus, we would argue that future costs should not only be discounted, but also "revalued" to reflect their expected prices in the future.

Discount Rates and Relative Prices—A Numerical Illustration

To illustrate the effect of different discount rates and, most importantly, changing relative prices on the economics of climate change, we utilize DICE, a well-established benefit-cost

[3]We recently found that there is a similar model in Guesnerie (2004). Also, Lebègue (2005) and Philibert (1999) mention changing relative prices as an important factor in connection with (and sometimes as a motivation for) lower discount rates.

model of climate change.[4] We amend the DICE model so that utility is dependent not only on the consumption of material goods, but also on nonmaterial, or environmental, goods.[5] We assume that today people derive a modest 10 percent of their utility from these environmental goods and services. Put another way, this assumption implies that if the environmental services were goods that could actually be purchased in the market, people would allocate 10 percent of total expenditures to this consumption.

The substitutability between market and nonmarket, or environmental, goods is expressed by the elasticity of substitution, here assumed to be 0.5. This implies that if, hypothetically, the relative price of the environmental good increased by 1 percent, then the purchase of environmental goods would decline by 0.5 percent relative to the purchase of other goods. This means that the value of the environmental goods as a share of total consumption would be expected to rise with increasing scarcity, much as the value of food would rise in the case of famines mentioned earlier.

Following the approach in the *Stern Review*, we assume that nonmarket impacts are equal, in economic terms, to the impacts on material consumption. In the *Stern Review*, including nonmarket impacts roughly doubles the total loss in consumption. That is, for a temperature increase of 2.5°C, the loss in material consumption increases from 1.05 percent of GDP, in the original DICE model, to 2.10 percent. To isolate the effect of relative prices, we run the model in two ways: one where the nonmarket damage costs are perfectly substitutable for market goods and consequently are included in consumption directly, as in the analyses by Stern, Nordhaus, and others, and one where the damages are attributed to the environmental good, whose relative price is rising over time due to limited substitutability.

The sensitivity of our results to these assumptions—the share of environmental amenities in total consumption and the elasticity of substitution between man-made and environmental goods and services—are discussed below. The cost estimates for the nonmarket impacts are discussed separately in the sixth section.

The Impact of the Discount Rate

Figure 1 shows the resulting emissions scenarios from the amended DICE model described above, under two different assumptions regarding the discount rate[6]: using the *Stern Review*'s low pure rate of time preference (δ being 0.1 percent) and using Nordhaus's high pure rate of time preference (δ starting at 3 percent, decreasing slowly over time).[7] The difference in the "optimal" level of emissions shown in Figure 1 clearly illustrates the importance of the

[4]We have used an updated version of the DICE model, developed by Nordhaus in connection with his critique of the Stern Review (Nordhaus 2007). For a full description of the original model, see Nordhaus (1994) and Nordhaus and Boyer (2000).

[5]For a more technical discussion, see Appendix A.

[6]The third emissions scenario displayed in Figure 1, using a high discount rate but an increasing relative price for the environmental good, is discussed under the section "The Impact of Changing Relative Prices" below.

[7]As the endogenous growth rate in per capita consumption initially is 3.3 and 2.2 percent/yr, respectively, in the Stern and Nordhaus cases (decreasing to 1.5 percent/yr by the year 2100 in both cases), the resulting discount rates are 3.4 and 5.2 percent, respectively (decreasing to 1.6 and 3.8 percent, respectively, in the year 2100).

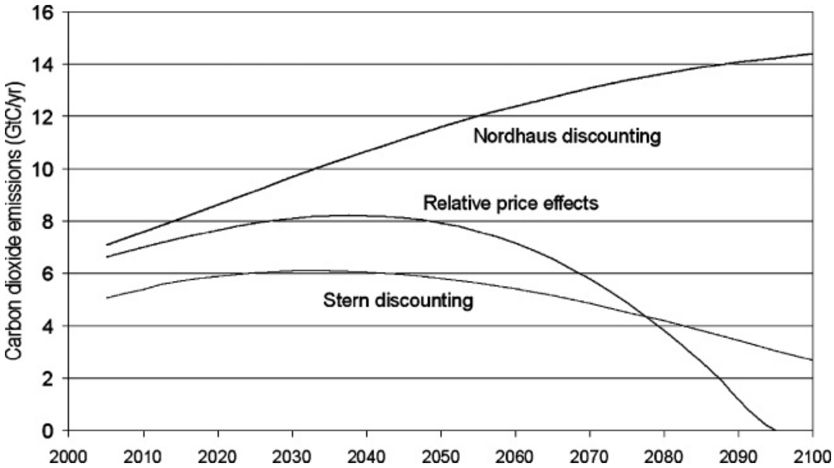

Figure 1. Optimal carbon dioxide emission paths in amended version of the DICE model, showing how conclusions concerning abatement depend crucially on assumptions regarding discounting and relative prices. Note: Emissions paths are shown for three different cases: a high discount rate case (upper line—labeled Nordhaus discounting), a case utilizing the lower discount rate argued for in the *Stern Review* (the lower line—labeled Stern discounting), and a run with the high discount rate, but where the nonmarket impacts are attributed to the consumption of a representative environmental good whose relative price is rising over time (middle line—labeled Relative price effects). See text for further explanation.

assumptions about the discount rate, as discussed above and as also shown by Nordhaus (2007) and others.

In the emissions scenario utilizing the Stern discount rate, the CO_2 concentration in the atmosphere is stabilized at just under 450 parts per million (ppm) at the end of this century—in line with the climate target of 450–550 ppm CO_2 equivalents endorsed by the *Stern Review*—and the global mean temperature increase stays almost below 2°C, the climate target set by the EU (although this does not hold if the climate sensitivity is increased). On the other hand, in the emissions scenario using the high discount rate, CO_2 concentrations reach over 600 ppm by the end of the century and the temperature eventually increases by more than 3.5°C.

The Impact of Changing Relative Prices

Figure 1 also shows the resulting emissions scenario for a high discount rate, but where the increasing relative price of the nonmarket good is taken into account. Although at the beginning, emissions abatement is lower than in the Stern discounting case, in the longer run, as the relative price of the environmental good increases, abatement is tightened, bringing emissions to even lower levels than in the Stern discounting case. The climatic effects are similar to the Stern discounting case: CO_2 concentrations reach about 450 ppm in the year 2100, and the temperature increase only slightly overshoots 2°C, before starting to recede again in response to the very low emissions level.

These results illustrate that accounting for relative price changes can have an effect on necessary abatement that is on the same order of magnitude as changing the discount rate. There are, of course, huge uncertainties here regarding the share of utility derived from nonmarket goods, the elasticity of substitution and the level of nonmarket impacts. The principle is, however, very important. Nordhaus (2007) and others argue that the *Stern Review*'s results depend on low discount rates. While we do not necessarily agree that these discount rates are too low, we have shown that there is an alternative approach that builds on high discount rates and still yields results that are similar to the *Stern Review*. If we were to use both low discount rates and changing relative prices, we would find even stronger support for firm and immediate abatement measures.

Sensitivity Analysis

To test the sensitivity of our results, we increase the share of environmental goods and services in today's consumption to 20 percent. This implies that emissions peak 10 years earlier and at a lower level than in our base case with relative price effects (see Figure 1), and that emissions have already reached zero in the year 2075. The resulting CO_2 concentration in 2100 is 400 ppm. If, on the other hand, we increase the substitution possibilities between the man-made and environmental good by setting the elasticity of substitution to one, then relative prices have virtually no effect at all, and emissions are similar to the Nordhaus case. Thus, if substitution away from the environmental good is easy (elasticity of one or more), then the effects of changing relative prices are weakened substantially.

It is hard to provide a good empirical estimate for the elasticity of substitution at this level of aggregation (with only two, representative goods) and particularly hard to say how it would evolve over time. In a model with many goods, the elasticity would vary considerably from one environmental good or service to another (as well as varying over time with scarcity and between individuals). What we want to illustrate, however, is the fact that some natural ecosystem services are inherently very hard to replace.

Furthermore, if there is a range of goods and services with different elasticities of substitution, then the relevant aggregate number is very likely not going to be the average of those elasticities. It is the goods or services with low elasticities that will dominate the calculation, since these will be the ones with increasing shares in utility. This goes for clean water, pollination services, and many other subtle aspects of the ecosystem that we take for granted as long as they are plentiful. As shown already in Dasgupta and Heal (1979), when one approaches thermodynamic or other minimum input levels, then the elasticity of substitution becomes very small.[8]

Underestimating Nonmarket Impacts

The discussion and numerical example above put the nonmarket impacts of climate change at center stage, since it is precisely the prices of these goods and services that we expect to rise over time. The nonmarket impacts from climate change can take many forms: biodiversity and ecosystem loss; effects on human well-being (human amenity, loss of lives, and air pollution); impacts from natural disasters, such as extreme weather events, droughts, hurricanes or floods (Manne et al. 1995); as well as socially contingent consequences, such as migration and risk for conflicts. The *Stern Review* does a great job of presenting many of these, the consequences of which could become very severe over the coming century: billions of people could suffer water shortages while billions of others run the risk of being flooded; tens to hundreds of millions are at risk of hunger, diseases like malaria, and coastal flooding (Parry et al. 2001).

[8] See also the discussion on weak versus strong sustainability in Gerlagh and van der Zwaan (2002).

As rightly pointed out by the *Stern Review*, the patchy (at best) coverage of these impacts in the current IAMs is something that seriously undermines the validity of their results. For example, the largest contribution to global impacts from climate change in the FUND model of Tol (1999) comes from the extra cost of installing air-conditioning equipment in developing countries, primarily in Africa (Warren, Hope, and Mastrandrea [2006]). In the original DICE model, nonmarket impacts for a 2.5°C warming actually amount to a small net *benefit*. Thus, when examining the damage estimates used in today's IAMs of climate change, one can not avoid getting the feeling that the effects of climate change on human lives are being trivialized (Parry et al. 2001).

Even if the climate damages in the DICE model used in the numerical exercise above are doubled to account for a wider range of nonmarket impacts, following the results in the *Stern Review*, we would argue that these impacts are still comparatively low. As discussed above, total damages in our modified DICE model amount to just over 2 percent of GDP, for a temperature increase of 2.5°C. As noted by Manne et al. (1995), US *expenditures* (which should be smaller than averted damages) on environmental protection totaled about 2 percent of GDP in 1995. Thus, the suggestion of current IAMs that we should be willing to spend much less on climate protection, one of the biggest environmental problems facing humanity, seems implausible.

We believe that it is exactly the nonmarket effects of climate change that are the most worrisome. If we focus on the risk for catastrophes, as Weitzman suggests, then we believe the main effect of climate change will not be to stop growth in conventional manufacturing, but rather to damage our ability to enjoy some vital ecosystem services.

As also acknowledged in the *Stern Review*, the steps taken in their analysis to rectify the limitations in the literature concerning the estimates of nonmarket impacts are only partial: the PAGE2002 model used by Stern adopts a 0.7-percent benchmark for nonmarket impacts on global GDP from a 2.5°C warming, with an uncertainty span from 0 to 1.5 percent. However, social impacts are not included at all. Yet social impacts—in the widest sense of the word—have the potential to make the already serious climate damages much worse.

For instance, conflicts triggered by disagreements on policy, resource wars, or migration of environmental refugees could become very serious. If, in the term "social services," we include the absence of such societal disruptions induced by climate change, then it seems reasonable to assume a very low "substitutability" with material consumption. Thus, to give a sensible picture of the cost of climate change, and the benefits of mitigation, these impacts should also be taken into account, together with their expected increase in relative valuation over time.

Summary and Conclusion

The *Stern Review*'s estimate of the economic significance of climate change damages is an order of magnitude higher than earlier estimates. It is thus natural that the *Stern Review* is being hotly debated and criticized. It is perhaps surprising that the reactions have not been even stronger, but this may be due to several factors: Stern's stature as an economist; the recent research indicating that climate change may be faster and more severe than previously thought; the strong political backing for the report, primarily in Britain; and finally, the clearly changing tide of opinion in the United States.

Still, there has been serious criticism that risks undermining the important message of the *Stern Review*. First, the report has been accused of causing some misunderstandings through its unusual and somewhat drastic approach to presenting the climate damage costs. While there may be some truth to this, we believe that this criticism is exaggerated.

Second, some have suggested that the report is a political document (see, for example, Nordhaus 2007). While we would not disagree with this statement, we would argue that this is also true for other analyses that have tried to perform the same task as the *Stern Review*: weighing the costs and benefits of climate change mitigation in order to provide policy-makers with some advice for addressing the problem. Although there is a lot of science and economics involved in trying to weigh the costs and benefits, we have argued in this article that ethics, value judgments, and thus politics, are an inherit part of the picture.

Third, the *Stern Review* has been accused of assuring high damage numbers by using low discount rates. In this article, we have traced the discount rate back to its basic components and discussed them in turn. Although Stern's choices concerning the marginal elasticity of utility and the pure rate of discount are low compared to many others, we believe they are well within the realm of reasonable and defensible.

We have also argued that nonmarket damages are probably underestimated in the *Stern Review* and that future scarcities, caused by the changing composition of the economy and climate change, will lead to rising prices (or willingness to pay) for certain goods and services. This price escalation should raise the estimated damage of climate change, counteracting the effect of discounting. In fact, when we considered the likely future scarcity values for (nonmarket) environmental assets, we obtained high damage figures even when we used high discount rates.

If we were to combine the low discount rates in the *Stern Review* with rising relative prices, the conclusions would support even higher levels of abatement than recommended by the *Stern Review*. This would even lead us to consider some of the levels of carbon content that Stern deems unrealistic, i.e., aiming for a target below 450 ppm of CO_2 equivalents.

The most obvious prices that need to change dramatically are the relative prices of fossil fuels themselves (see Sterner 2007). Conventional price elasticities (1 for income and −.65 for fossil fuels) and the *Stern Review*'s estimates of emissions falling 1 to 5 percent per year as incomes grow at 2 percent imply real price increases of 5 to 10 percent per year! Still, we do not believe that the need for increases in energy prices comes across clearly enough in the *Stern Review*. The report appears to be banking on rapid technical progress to lower the future costs of nonfossil technologies. This may indeed happen, but it would be unwise to persuade people that climate change is important if it is done at the cost of making them believe that fossil fuel and energy prices do not need to rise very much. In fact, the rising price of fossil fuels is the most important motivating factor for the research and implementation of other technologies that are needed.

In a more thorough evaluation of the effect of relative prices, changes in relative prices would be broken down and assessed by sector (e.g., agriculture, water). These and some other ecosystem services have particular importance for the very poor, and the climate change damages suffered by the poor are particularly important for welfare. This is yet another area where more work should be done. In the *Stern Review*'s baseline scenario without climate damages, it is assumed that average per capita incomes will rise by some thirteen times in the next 200 years. But we need to better understand how this growth will be distributed and, in particular, what growth the poorest will experience—with and without climate change.

Although these would be interesting extensions of our article, we end by coming back to the main issues raised in this article: Society in the future will be not only a lot richer, but also very different in other ways. An integral part of increasing income is that growth is uneven and that some of the sectors that decline or do not grow will have a strong tendency toward rising prices. Climate change is likely to damage some of these nonmarket sectors seriously. If we take into account these changes in relative prices, the cost estimates of future climate damages become higher, which supports the argument for stronger abatement now. Moreover, if the low discount rate of the *Stern Review* were combined with the increases in relative prices associated with ecosystem damages identified in this article, even stronger abatement measures would be justified.

Appendix A: Incorporating Relative Prices into DICE

To allow for changes in relative prices between market and nonmarket (or environmental) goods in the DICE model, we have made two changes in Nordhaus's (2007) version of the model: we have changed the utility function equation, and we have included an extra equation that determines how consumption of the environmental good changes over time, in response to climatic change.

The original DICE model maximizes total discounted utility using a *constant relative risk aversion* (CRRA) function

$$U(C) = C^{1-\alpha}/(1-\alpha),$$

where utility, *U*, is dependent on per capita consumption, *C*, and the elasticity of marginal utility of consumption, α. To include the effect of changing relative prices in the DICE model, we replaced the one aggregate consumption good in this function with a constant elasticity of substitution (CES) kernel while keeping the overall CRRA properties:

$$U(C) = [(1-\gamma)C^{1-1/\sigma} + \gamma E^{1-1/\sigma}]^{(1-\alpha)\sigma/(\sigma-1)}/(1-\alpha),$$

where utility is dependent on the consumption of two goods, *C* and *E*, and where the latter represents nonmarket, or environmental, amenities. The elasticity of substitution is given by σ, and γ determines the share consumption of nonmarket goods in the utility function. As before, the elasticity of marginal utility of consumption is given by α.

We assume that the consumption of environmental amenities will be affected only by rising temperatures, i.e., in the absence of climate change, the environmental quality will neither deteriorate nor improve. We use a quadratic relationship between temperature change, T(t), and nonmarket damages, so that

$$E(t) = E_0/[1 + aT(t)^2],$$

where *a* is a constant and E_0 is the level of consumption of environmental amenities in year 2005. By normalizing the latter to the level of material consumption in 2005, the choice of γ will determine the share of environmental amenities in initial utility (see Hoel and Sterner 2007).

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