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Estimating The Costs Of Global Warming - Comparative Static And Dynamic Approaches

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ESTIMATING THE COSTS OF CLIMATIC CHANGE - COMPARATIVE STATIC AND DYNAMIC APPROACHES

There is considerable scientific evidence to suggest that human activity will lead to significant climatic change over the next fifty years. The most important example is the 'greenhouse effect' which, it has been predicted, will lead to an increase in global mean temperature of up to 4° *C* over the next fifty years[1].

As a result of these predictions there have been numerous calls for policy action aimed at reducing the degree of global warming, primarily by reducing net emissions of the 'greenhouse gases' (primarily carbon dioxide (CO_2), carbon monoxide (CO), nitrous oxide (NO) methane (CH_4) and chlorofluorocarbons (CFCs)). Some of these proposals, most notably reductions in CFC emissions, involve relatively low costs and have additional benefits, such as reduced damage to the atmospheric ozone layer, sufficient to justify them even in the absence of concerns about global warming. Others, such as reductions in emissions sufficient to stabilize the current atmospheric stocks of CO_2 and CH_4 would involve substantial economic and social costs.

In order to assess the desirability of such proposals, it is necessary to formulate some estimates of the likely costs of climatic change. The simplest approach, adopted in much of the popular debate on the topic, is to catalog likely adverse effects such as the submersion of some Pacific islands, increased severity of monsoons and hurricanes in tropical and sub-tropical areas and the conversion of currently fertile areas into desert. It does not appear that any attempt has been made to convert such a qualitative assessment into an estimate of economic costs. Costs estimated in this fashion would be large.

[1] The use of the phrase "up to" is significant. There is considerable debate over the likely extent of warming. A minority of scientists claim that there is insufficient evidence to justify any prediction of the likely trend in temperature.

However, such an estimate would be meaningless because of the failure to take into account offsetting benefits. To take the simplest example, the increased severity of monsoons would raise rainfall in many arid areas. Land that is currently desert would become fertile. It is not clear whether the total area of desert would expand or contract.

After seeking to take account of both costs and benefits, economists such as Nordhaus (1991) and Schelling (1991, 1992) have produced estimates suggesting that the net costs of climatic change will be quite small, at least for developed countries such as the United States. Nordhaus estimates the quantifiable net damages at 0.26 per cent of GNP. After quadrupling this estimate to allow for unmeasured costs, he concludes that the cost-justified mitigation policy involves the elimination of most CFC emissions and a 2 per cent reduction in CO_2 emissions relative to their baseline (increasing) trend. The virtual elimination of CFC's has already been ensured because of concerns about their potential effects on ozone depletion. Hence, Nordhaus' conclusion is that no significant new action to mitigate global warming is justified.

Schelling comes to the same conclusion as far as the presently developed countries are concerned. He suggests however, that impacts on less developed countries may be substantial. (Nordhaus avoids consideration of this issue by assuming that the world economy in 2050 will be similar to the US economy today, with agriculture playing a minor role).

These estimates are implicitly derived from an exercise in comparative statics. Climate is treated as an input into production inseparably associated with land in a given region. Other factors such as labor and capital are combined with land and climate to produce goods and services. In long run equilibrium, labor and capital are allocated across regions (and industries) so as to maximize the net value of output. A global change in climate changes the productive characteristics of land in each region. The procedure adopted by Nordhaus and Schelling is, in essence, to estimate the change in the long run equilibrium value of output associated with a climatic change, assuming current endowments of land, capital and technology.

An alternative procedure, more theoretically satisfying, but much more difficult, would be to make a dynamic estimate of the costs and benefits associated with the transition from the current climate (and the associated allocation of resources) to a new long run equilibrium. The difficulties associated with deriving such an estimate are exacerbated, in two ways, by the considerable uncertainty about the likely extent of the rise in global mean temperature and the even greater uncertainty about the pattern of local climatic change. This creates difficulties in choosing the parameters for any dynamic estimate. There is a more fundamental difficulty, however. In modelling the transition path, it is necessary to take account of the fact that decision-makers who determine the allocation of resources are themselves subject to considerable uncertainty concerning the future path of climate.

Given the difficulties associated with the derivation of a dynamic estimate incorporating uncertainty, an effort in this direction could be justified only if there were grounds for supposing that the relatively simple comparative static estimates were systematically biased. The object of the present paper is to show that there are such grounds. First, it is shown that, under reasonable assumptions about the economic role of climate the application of the comparative static method must yield a mean estimate of zero. Second, it is shown that, under the same conditions, dynamic estimates of losses must always be positive.

The central result is that losses will be positive whenever the rate of adjustment required to adapt capital stocks (interpreted broadly to include natural resource stocks) to changing climate is more rapid than the 'natural' rate of adjustment associated with processes such as the depreciation of old capital items and their replacement with new, optimally located, items. In addition, uncertainty about global warming is shown to involve positive costs in the dynamic framework, but not in the comparative static framework.

The damage estimates presented by Nordhaus may be assessed in the light of these results. It is shown that Nordhaus' mean estimate is non-zero solely because they deviate from the comparative static approach in estimating costs associated with sea level changes. A consistent application of the comparative static approach to the available data would yield a mean estimate of zero damage associated with global warming.

In the second part of the paper, a preliminary attempt is made to quantify some of the sources of loss associated with global climatic change in a dynamic framework. Particular attention is paid to capital stocks associated with agriculture and to natural resources.

The Comparative Static Approach

The basis of the comparative static argument for a small net impact from global warming may be summarized as follows. Human productive activity is possible under a wide range of climatic conditions. Hence there is no reason to suppose that a change in climate will have substantial negative effects except in areas that are already marginal because of high temperatures or monsoons. These latter negative effects will be offset by positive effects in areas which are currently marginal because of low temperatures. In order to formalize this argument it is necessary to set out the comparative static approach in more detail.

Assume an aggregate capital stock K and labor force N. There are m regions. In each region, two classes of productive activity may be undertaken. The first class of activity is independent of climate and yields an output $f(K_{i1}, N_{i1})$ in region i, where K_{i1} and N_{i1} are the capital and labor used in region i for the first class of activities. The second class consists of activities that are dependent on climate.

The potential contribution of land area i to production is given by a function $L_i(T)$

where T_i is an index of the climate in region i (which may be taken, in the simplest case, to be summarized by mean temperature). The function L_i is assumed to be concave in T_i with a maximum $\bar{L}_i$ at some T_i^*. Further L_i approaches zero for sufficiently large and sufficiently small T_i. That is, both extremely hot and extremely cold regions are of negligible productive value.

Total output produced in region i is given by

(1) $$Y_i = f(K_{i1}, N_{i1}) + g(K_{i2}, N_{i2}, L_i(T_i))$$

where K_{i2}, N_{i2} are the capital and labor used in region i for activities in the second class. Note that all differences between regions are assumed to be captured by L_i so the functions f, g are the same for all regions.

Under either optimal planning or a competitive equilibrium there exists a set of capital and labor allocations K^*, N^* such that $Y = \sum_{i=1}^{n} Y_i$ is maximized subject to the constraints $\sum_{i=1}^{n} K_{i1} + K_{i2} = K$, $\sum_{i=1}^{n} N_{i1} + N_{i2} = N$.

The value of this optimal outcome depends on the distribution of temperature. It also depends on the aggregate factor endowments but these will be treated as fixed.

(2) $$Y = \phi(L_1, L_2 \dots L_m) = \phi(T_1, T_2 \dots T_m) = max_{K^*, L^*} \sum_{i=1}^{n} Y_i$$

If all of the regions 1, 2 ... m are identical (except for differences in climate) then Y will depend only on the set $\mathbf{T} = \{T_i : i \in 1, 2 \dots m\}$. In particular, it may be of interest to focus on the increasing rearrangement of this set, the sequence $(T^1, T^2 \dots T^m)$ such that $T^1 \leq T^2 \dots \leq T^m$. By the concavity of L, the contribution of climate to production will be least for the extreme values of I and greatest for the intermediate values.

Suppose for simplicity that the elements of T are evenly spaced, that is $T_{i+1} = T_i + \Delta$, $\forall\ i$. Then the effect on $\mathbf{T}$ of a uniform increase in all temperatures by Δ may be obtained by deleting T^1 and replacing T^m with $T^m + \Delta$. This effect will be small. In particular suppose that $L(T^1) = L(T^m) = 0$ *i.e.* that both the hottest and coldest regions are of negligible economic value. Then

Proposition 1: A small uniform change Δ will have no effect on Y

More generally we may consider the case where land quality and climate are assumed to vary in a more or less continuous way. In this case the distribution of climate may be represented by a probability distribution $F(T)$. If the distribution F is uniform and both the hottest and coldest regions are of negligible economic value, a small uniform change Δ will have no effect on Y.

This reasoning is not affected by uncertainty. Suppose that there is uncertainty represented by a set of independently and identically distributed random variables η_i about the values of each of the T_i in the discrete case. Suppose once again that the means of the T_i are evenly spaced and that $L(T) = 0$ for all T in the support of both $T^1 + \eta^1$ and $T^m + \eta^m$. Then the effect of a shift ε is zero, exactly as in the deterministic case.

Similarly, it does not matter that the change in temperature is unlikely to be uniform. Some areas will have a greater than average increase in mean temperature, others a lower than average increase, or even a decrease. Provided there is no systematic pattern to this variation, the argument presented here remains valid. The only important possibility is that global warming might act to increase (or decrease) the variation in the distribution of temperatures as would occur if warming is greatest (least) at the Equator, and least (greatest) in high latitudes.

The type of shift that is likely to occur in the new equilibrium may be estimated using the following back-of-the-envelope approach. From the isotherms observed under the existing temperature distribution, a rise in mean annual temperature of about 3° C is associated with a move of about 4.5 degrees of latitude or 500 km[2] towards the equator.

[2] In calculations of this kind, the fact that the metric system is based on the earth's circumference makes the back-of-the-envelope approach easy. The arc from equator to pole is 10 000 km, so that 1 degree of latitude = 111 km.

Conversely, if global mean temperatures were to rise by a uniform 3°, climates would migrate towards the poles, on average by about 500km. The exception is that the extremely cold climate currently prevailing at the poles would disappear and that a new high temperature climate would prevail at the equator.

Only two assumptions in the analysis leading to Proposition 1 do not appear entirely robust. The first is that $L(T^1) = L(T^n) = 0$. In practice, nearly all regions of the earth are subject to some form of economic activity that is affected by climate. The assumption of zero economic value is reasonably accurate for the high latitudes (near the poles) where activity is constrained by low temperatures. On the other hand, some Equatorial areas yield considerable economic value. The violation of the assumption $L(T^1) = 0$ implies that the comparative static procedure should yield positive net estimates of benefits, since the area of usable land will actually be expanded by global warming.

The second assumption, implicit in the argument presented above, is that the total land area is constant. This is invalid, since global warming is generally expected to lead to a rise in sea levels. A rise of about 1 meter is expected as a result of expansion following rising water temperatures, combined with some melting of glaciers. A much greater rise (about 6 meters) would occur if the Antarctic ice sheet melted. Current scientific opinion is that this will not occur as a result of the warming anticipated over the next fifty years. These issues are discussed further in EPA (1989, Ch 7).

The process of adjusting to rising sea level may involve considerable economic costs. However, these are dynamic in nature, and will therefore be considered in the following section. The relevant consideration for comparative static analysis is the likely reduction in the world's land area. For a 1 meter sea level rise, the loss of land area is trivially small. For the US, EPA (1989) suggests that coastlines will move inwards by less than 0.5 km in most areas, implying a reduction in US land area of less than 0.1 %. Hence, this effect may be disregarded, except for a few very vulnerable countries (notably

Bangladesh, the Netherlands and some island states).

On the basis of these modifications of Proposition 1, it seems reasonable to conclude that any consistent application of the comparative static approach, using the consensus predictions of likely climatological impacts, must yield the conclusion that global warming will have zero (or perhaps slightly negative) net costs. No such consistent analysis appears to have been presented. As will be argued below, most published estimates involve a mixture of dynamic and comparative static reasoning.

The Dynamic Approach

The key difference in the dynamic approach lies in the treatment of capital stocks. In the comparative static approach, the capital stock is completely homogenous, both in form and in its allocation across regions. In the dynamic approach, capital is heterogeneous and location-specific. The basic approach is that of the 'putty-clay' model. Divergences in the marginal product of capital, arising in the present context from climatic change, call forth adjustment in the form of new investment in areas where the marginal product is high. In areas where the marginal product is low, the capital stock declines as a result of depreciation or, in extreme cases, scrappage. To provide a simple comparison with the comparative static approach, it will be useful to consider first the case when total capital stock is constant (new investment = depreciation in every period).

The production technology for region i is given by

$$Y_{it} = f(K_{i1t}, N_{i1t}) + f(K_{i2t}, K_{i3t}, \dots K_{imt}, N_{i2t}, \dots N_{imt}, L_i(T_{it})) \tag{3}$$

where K_{ijt} represents the stock of the j-th type of capital in region i at time t. As in the comparative static model, K_{i1t} represents the capital stock associated with activities that are independent of climate. The capital stock associated with climate-dependent activities has been disaggregated into stocks of $(m\text{-}1)$ specific classes of capital. A similar disaggregation has been undertaken for labor.

Capital stocks evolve subject to the constraints that

(4) $$\sum_{i=1}^{n} \sum_{j=1}^{n} K_{ijt} = K_{\cdot t}$$

and

(5) $$K_{ijt} \geq (1 - \gamma_{ij}) K_{ij(t-1)}$$

where

γ_{ij} is the rate of depreciation for the j-th type of capital in region i.

Suppose that the time path of climate T_{it} is known in advance for all i, t. The planning problem is to maximize an objective of the form

(6) $$V = \sum_{t=1}^{T} e^{-rt} \sum_{i=1}^{n} Y_{it}$$

subject to the constraints (4), (5). We shall denote the initial distribution of temperature by T_{i0} $i = 1 \ldots n$. As in the previous section, we assume that in the initial distribution, the areas of extreme temperature are valueless, so that $L_1(T_{10}) = L_n(T_{n0}) = 0$. Under appropriate uniformity conditions a small change in temperature will therefore have no effect on the total quantity of usable land, though it will alter the regional distribution. The initial stocks of capital and labor by K_{ij0}, $i = 1..n$, $j = 1..m$ and N_{i0} $i = 1 \ldots n$. It will be assumed that the system is initially in equilibrium so that the initial stocks of capital and labor are equal to the optimum derived in the previous section.

We now suppose that temperature increases by a constant amount δ per period. Thus, a comparative static analysis could be undertaken by fixing some τ (for example, the doubling time of global CO_2 stocks) and undertaking the analysis of the previous section with $\Delta = \delta\tau$. As we have seen, for moderate values of Δ, a zero net impact is derived.

We now turn to a dynamic analysis. Denote by K, N the time paths of the regional allocations of capital and labor and let

(7) $$V^*(\delta) = Max_{K,N}\, V$$

where V is defined as in (6) and K satisfies the constraints (5). Our key result is

Proposition 2: Under the stated conditions V is a concave function of δ with maximum at zero.

Proof: By the initial equilibrium assumption, the optimal path when $\delta=0$ has $K_{ijt} = K_{ij0}\ \forall\ i, j, t$. Define the unconstrained optimal path for arbitrary δ by $K^{**}(\delta)$, and the associated return by $V^{**}(\delta)$. Then $V^{**}(\delta) \geq V^*(\delta)$. This inequality will be strict whenever any of the constraints is binding. By Proposition 1, $V^*(0) = V^{**}(\delta)$, so V^* takes its maximum at zero. Concavity follows from the properties of the production function.

It follows that the estimate of zero loss derived in Proposition 1 is, in fact, a lower bound. Under certainty the lower bound will be attained if and only if all of the required capital stock adjustments are consistent with the constraint (5). That is, in any region i where the stock of capital j is required to contract as T changes, the rate of adjustment needed to maintain optimality must be less than γ_{ij}.

This implies that there exists a range of rates of temperature change for which the net damage is zero. These rates of change are sufficiently slow that all relevant capital stocks can be costlessly adjusted to the changed distribution of climate, so that the comparative static analysis of the previous section applies. The faster is the rate of climatic change, the greater the number of classes of capital that cannot be adjusted in this optimal fashion and the greater the net costs.

Comparison of the two approaches

From the analysis above, the adoption of a dynamic approach yields a number of changes in the assessment of the costs of global warming. Most importantly, the comparative static approach yields zero mean estimates of costs under plausible assumptions (and possible net benefits under slightly more realistic assumptions). The dynamic approach implies the existence of unambiguously positive costs. Also, cost estimatesderived from comparative static methods are typically linear in emissions of greenhouse gases (see, for example, Nordhaus Figure 3). Dynamic cost estimates are a convex function of the rate of climate change. The operation of carbon 'sinks' means that the rate of climate change is likely to be a convex function of cumulative emissions and hence also a convex function of annual emissions. The damage function associated with annual emissions is thus derived from the composition of convex functions and is therefore convex.

The comparative static approach is based on differences between the current climate and that predicted to prevail with higher concentrations of greenhouse gases. The most common approach has been to project forward to the point at which atmospheric CO_2 concentrations are double the present level. This approach reflects the fact that present climatic models describe static equilibria. Thus, they can produce estimates of the climate arising from given concentrations of greenhouse gases. They cannot, however, predict the path of climatic change arising from a given initial situation and inputs of greenhouse gases. Economists using the comparative static approach have simply analyzed the problem in the obvious form posed by the output of climatic models.

By contrast, the dynamic approach focuses attention on the rate of change of temperature and other climatic variables rather than on their level at any given time. What matters is whether the rate of adjustment of capital stock required to maintain optimality is greater than that which would arise through the standard mechanisms of depreciation and obsolescence.

An estimate of the average rate of change of climate can be derived using the same model results as those on which comparative static cost estimates are based. A full dynamic representation of the process would, of course, be preferable. However, as will be shown below, an analysis based a constant, geographically uniform and predictable change in temperatures yields a lower bound estimate of damages.

In some ways, the dynamic approach simplifies the task of economic modelling. Users of the comparative static approach must not only select an estimate of the rate of change of temperature, but also an arbitrary cut-off date at which to make the static comparison. Prediction of the point at which greenhouse gas concentrations are likely to stabilize is even more difficult than climatic modelling. Hence, users of the comparative static approach are forced to pick an arbitrary stopping date. This will produce either non-comparable estimates (if different stopping dates are chosen) or an unjustified focus on a particular date.

This point is illustrated by Cline's (1991) comments on Schelling (1991). Schelling follows the convention of considering effects of a doubling of CO_2, and concludes that costs for more developed countries will be negligibly small. Cline, also using a comparative static approach, observes that there is no reason to suppose that CO_2 emissions will stop at the point of doubling, and suggests examining the implications of temperature increases of up to $10°$ *C*. Within the comparative static framework, there is no way of choosing between these suggestions without first predicting the point at which CO_2 stocks will stabilise.

This has particularly important implications for discounting. The comparative static analysis implies the need to compare present costs of mitigation against higher mean temperatures in the future. In order to make such comparisons, it is necessary to decide how to discount future benefits. The choice of discount rate has a dramatic impact on the benefits of mitigation. For example, Nordhaus (1991) assumes that current emissions will be reflected in higher mean temperatures in 30-50 years time. On this assumption, the use of a 1 per cent discount rate reduces cost estimates by a factor of four. A 4 per cent discount rate reduces cost estimates by a factor of twenty-five.

These difficulties are greatly reduced by the adoption of a dynamic framework. The lag assumed by Nordhaus refers to the time between increased emissions and the completed increase in temperature. In a dynamic framework what matters is the lag between changes in emissions and changes in the rate of growth of temperature. This lag will be much shorter, and the effect of changes in the discount rate will be correspondingly smaller.

Improvements in climatic modelling capacity would be beneficial for both approaches. However, the comparative static approach would benefit only from more detailed regional projections of climatic changes. Damage estimates using a dynamic framework would be improved by the use of estimates of the time-path of climatic change, as well as by the provision of greater regional detail. In addition, as will be discussed below, the dynamic approach could incorporate the effects of uncertainty.

The critical new information required for the dynamic approach concerns the rate at which capital stocks of various kinds can be adjusted. In the following section, some illustrative estimates are provided.

Dynamic losses

From the discussion above, dynamic losses from climatic change will arise if capital stocks

(i) are dependent on climate for their optimal location; and
(ii) depreciate more slowly than is required to permit easy adjustment to changing climate.

Two main categories of capital stock might satisfy these conditions. The first is that of long-lasting 'infrastructure' investments, such as harbors, dams and irrigation systems and grain handling facilities.

Consider first the example of grain handling. Suppose that climatic change over the next fifty years results in a mean global temperature increase of 3°. As shown above, this increase has the effect of shifting the zone of grain production 500 km further from the

Equator. Comparative static estimates would imply a zero effect, since the area of potentially arable land is unaffected by this change.

A dynamic estimate yields different results. Assuming, for the moment, a uniform rate of warming yielding a 3° increase over 50 years, the annual change of 0.06° per year implies a shift of 10 km per year in the zone of wheat production. Although his shift appears small, it is large enough to imply significant capital losses in grain handling. Quiggin and Fisher (1988) estimate the optimal service radius for Australian grain handling facilities at 25 km. Hence facilities initially at the margin of the wheat production zone will be sub-optimally located after 2.5 years of warming at a rate of 0.06° per year. By contrast, the normal service life of vertical and horizontal storage facilities is several decades. In areas currently close to the margin, this implies a capital loss, as grain production ceases before the facilities end their useful life. In areas currently well away from the margin, but within the 500km range, it is likely that existing facilities will require replacement before grain production ceases. Since it would be uneconomic to replace long-lived storage facilities, it will be necessary to resort to methods such as bunker storage with lower capital costs and higher operating costs. Thus, even though no loss is incurred in relation to the existing capital stocks, the process of global warming will impose continuing costs.

A similar analysis applies to harbors, beachfront houses, and other capital goods whose value is derived from a seafront location. In this case, the central variable is the rate of rise of sea levels. Assume that the rate of sea level rise is 2 cm /year (implying a 1-meter rise over 50 years) and that this implies an inward shift in the natural coastline of 10 meters/year. In relation to existing capital stocks, three options are available. First, they may be modified to cope with higher sea levels. Second, they may be dismantled and moved inward. Third, they may be abandoned.

Once again, there are continuing losses over and above those associated with the existing capital stocks. New capital investments must be modified to take account of shorter lifetimes and higher maintenance costs. Consider the example of beachfront housing. If we interpret the beachfront as the area within, say, 50 meters of the high water-mark, a beachfront house will have a natural life of 5 years. After this, it must be built up, at steadily increasing cost, or abandoned. This dilemma is already being faced in areas of the coastal US with naturally shifting shorelines[3].

In both of the cases described above, damages are related fairly directly to the rate of change. As shown in Proposition 2, the damage will be a convex, rather than a linear, function of the rate of warming. Nevertheless, it should be relatively straightforward, having derived cost estimates for some predicted mean rate of warming, to adjust those estimates to take account of new information or more detailed regional forecasts.

Rather different problems arise when we consider facilities such as dams, irrigation systems and hydro-electric power generation. The value of these facilities depends on a number of climatic factors including precipitation in the catchment areas, evaporation rates and the suitability of the irrigated areas for growing different crops. All of these will be affected by climatic change. Most of the relevant effects are unpredictable on the basis of present knowledge[4]. The only thing that can be predicted with certainty is that the optimal location of these systems will change and that this change will be costly.

The distinction between the dynamic and comparative static approaches is particularly clear in the case of dams. The evidence available at present gives no grounds for supposing that the distribution of rainfall and hydrological systems resulting from global climatic change will be any more or less suitable for irrigation or hydro-electricity than the present

[3] A similar analysis applies to buildings lying in the flood plain of rivers. By contrast with the case of sea levels, there is no reason to expect a general expansion of flood plains. However there is a cost asymmetry between the expansion of flood plains to include existing built-up areas and the contraction of flood plains to permit new building in areas taht would previously have been unsafe.

[4] It seems reasonable to suppose that evaporation rates will generally increase with higher temperatures.

distribution. Hence a comparative static analysis must yield a net cost estimate of zero.

From the dynamic perspective the critical point in favor of the current rainfall distributions is that our existing infrastructure is designed to exploit it. Either an increase or a decrease in rainfall in the catchment area for an existing dam will impose losses if the change is sufficiently large. A decrease in rainfall will reduce the economic value of the services provided by the dam. An increase in rainfall increases the severity of the flood events (conventionally measured by 50 and 100 year floods) the dam must withstand. This creates the possibility that the dam will require costly modifications or even replacement if safety standards are to be maintained.

Natural capital

The second main category is that of 'natural capital' including forests and ecosystems valued for tourism, or in their own right. Forests valued primarily for the production of one or a few timber species may be treated in much the same manner as human-made capital. The main difference is that the adjustment mechanism cannot be represented in terms of exponential decay taking place at a constant rate. Rather, adjustment occurs when trees are felled in one area and replaced in another. Typical rotation periods in plantation forestry range from 20 to 40 years. In order for production of a given species to be feasible in a given area, it is necessary that the climate in that area should, throughout the rotation period, be consistent with the survival and growth of the species in question. Global warming implies that, on average, the zone in which climate is suitable will move northward by about 500 km during this period[5]. Hence, many existing forests with limited capacity for adaptation to climatic change will suffer tree decline and dieback. A further implication is that reafforestation will be constrained by the need to choose replacement species, such as the Ponderosa pine, that are capable of flourishing in a wide

[5] This back-of-the-envelope estimate agrees, on average, with the detailed model estimates presented by EPA (1989).

range of climatic conditions.

EPA (1989) estimates that the loss in healthy woodland area in the US could be made up by a reafforestation program costing about $0.5 bn/year. It is not clear whether this estimate includes the capital losses associated with the dieback of existing forests. Also, if forests suffering dieback are not cleared, there is an increase in the land devoted to forestry with no corresponding increase in output. The opportunity cost of this land needs to be taken into account. Other aspects of the problem, such as the fire hazard associated with large stand of dead or dying trees, do not appear to have been addressed.

It is likely that losses in timber production would represent only a small part of the social loss associated with large-scale dieback. Losses in recreation values arise from dieback in existing forests and their replacement by monocultures of highly adaptable species. These losses could be estimated using hedonic pricing and travel cost methods (see eg McConnell and Bockstael 1979). Deeper social concerns about large-scale forest decline are more difficult to quantify. However, forest decline resulting from acid rain has been a major social concern in both Europe and North America. The argument presented here suggests that the negative effects of global climatic change on forests will be comparable to those of acid rain.

Whole ecosystems require a different treatment within the dynamic framework. In place of the notion of depreciation, it is natural to think in terms of the rate of ecological succession arising in response to a disturbance in the environment. If the process of succession is more rapid than the rate of climatic change, ecosystems will migrate away from the Equator as temperatures rise, and the overall distribution will be essentially stable. However, if the process of succession is insufficiently rapid at a given point, the ecosystem will be in an unstable state. Some species will become extinct and others will multiply to pest proportions. Many of the ecological succession processes that have been observed proceed at rates of meters per year, rather than the kilometers per year required for adjustment to anticipated global warming.

A closely related point may be made by comparing the time scale of global warming with previous examples of climatic change, for which some evidence on the pattern of ecological adjustment is available. The anticipated rate of increase in mean temperatures is considerably more rapid that any which has occurred as a result of natural climatic processes. Hence there is no reason to expect that the mechanisms of ecological succession developed as a result of previous evolutionary pressure will be sufficiently flexible to permit adjustment to these changes.

As in the case of forests, large-scale extinctions will involve economic losses associated with declining recreational values, loss of scientific value, loss of potentially useful species and so forth. It seems clear, however, that this list of economic losses comes nowhere near capturing the concerns of many citizens about the impact of large-scale extinction. The way in which concerns not associated with consumption of goods or services should be incorporated into economic analysis has been the subject of considerable controversy recently. One approach is based on the notion of existence value (Krutilla 1964). Since, for most people, no market transactions are associated with the preservation or extinction of species, existence values must be assessed using direct questioning methods such as the contingent valuation method (Mitchell and Carson 1989). This approach has been criticized on various grounds (Kahneman and Knetsch, Nelson and Rosenthal, Quiggin).

An alternative approach may be used to obtain a fairly robust lower bound. It seems reasonable to conclude that the rates of ecological loss associated with global climatic change at the rates estimated on the basis of median predictions of global warming will be greater than those prevailing in the developed countries prior to the passage of the extensive environmental legislation of the 1960s and 1970s. It has been estimated (Denison 1979a, 1979b) for the US that over the period 1975 to 1978 the cumulative impact of this legislation was to reduce measured GNP by 0.6 per cent. Extrapolation over the period 1970-90 suggests a cumulative impact of around 2.5 per cent of measured GNP

If it were true that

(i) the net benefits of the legislation are deemed to exceed the costs

(ii) the potential ecological benefits of mitigating global warming are at least as large as those from the earlier legislation

(ii) the legislation was solely directed to the preservation of natural ecosystems

the cost actually incurred to reduce ecological loss in the past would serve as a lower bound estimate for the increased losses associated with global warming. Assumption (i) does not seem problematic. Sentiment in most developed countries appears to favor strengthening rather than relaxation of environmental laws. The arguments presented above suggested that assumption (ii) is also valid. Assumption (iii), however, is not valid. Environmental laws are directed to human health objectives as well as to ecological concerns. Other (eg aesthetic) concerns may also be important. Hence an application of this estimation procedure requires a finer partitioning of the social costs of existing legislation than is available at present.

For illustrative purposes, I will suppose that one-third of past environmental expenditures have been motivated by ecological concerns, and (following Nordhaus) that the experience of the US is representative of that of the more developed countries as a group. It follows that mitigation of ecological damage associated with global warming would justify annual expenditures by these countries of at least 0.8 per cent of GDP.

These results appear to contradict the arguments of Schelling (1991). He suggests that willingness to pay for environmental protection *per se* is very limited. This claim is made primarily on the basis of the observation that proposals to tax gasoline in the US have had hardly any success. Schelling's argument would be convincing if it were true that the policy debate over gasoline taxes in the US was a representative example of the political trade-off between direct economic benefits and the environment. In fact, the US gasoline tax debate is an extreme case. Most developed countries have in fact imposed high taxes on gasoline. Further, the US has adopted a number of costly measures aimed at achieving reductions in gasoline consumption (such as corporate automobile fuel economy standards) and the pollution associated with automobile use (as in the 1991 Clean Air Act). Many of the goals of these measures could have been achieved at lower social cost through a tax on gasoline. Finally, it may be observed that the resistance to gasoline taxation was equally vigorous when the good sought was not an imporvement in the environment but a reduction in vulnerability to disturbances in oil supplies from the Middle East. In this case, again, the US preferred to seek the goal through an alternative, apparently more expensive, route - the creation, deployment and use of a military capability to ensure the free flow of oil.

All of this leads to the conclusion that there is strong resistance to the taxation of gasoline in the US. This is a problem for policymakers seeking to develop proposals for global reductions in CO_2 emissions. However, it cannot be regarded as a representative illustration of the willingness of citizens in developed countries to trade off economic welfare for environmental protection.

Variability and uncertainty

It was shown above that uncertainty about the extent, pattern and timing of global warming has no effect on comparative static cost estimates. This is not true for dynamic estimates. It is useful to distinguish between damage associated with predictable variations in the degree and rate of warming and damage associated with pure uncertainty.

The costs of predictable variability arise from the fact, demonstrated in Proposition 2, that damages are a convex function of the rate of warming. This means that the expected damage level is greater than the damage associated with the expected rate of warming.

Similarly, the convexity of the damage function implies that damages will be greater the more uneven is the rate of warming. Hence, cost estimates derived from the impact of the mean rate of warming will be biased downwards to the extent that rates of warming are higher in some areas than in others (assuming, as in the section on comparative statics, that this variation is uncorrelated with the existing temperature).

The same analysis applies to the distribution of warming over time. Most available projections imply a gradual and uniform increase in temperature. This is an artifact of the modelling techniques that are used. In fact, the rate of warming is likely to be highly non-uniform. One reason is simply statistical. The warming trend due to the build-up of greenhouse gases is super-imposed on ill-understood cyclical climatic fluctuations of varying periodicities (up to decades). During the period 1940 to 1980, a cyclical downturn was sufficient to offset the underlying trend presumed to be associated with the buildup of CO_2. Conversely, in periods when an upward cyclical fluctuation is superimposed on the upward secular trend the rate of warming will be above the long run mean.

In addition to this statistical point it is likely that the climate system involves a wide range of non-linearities and threshold effects that are not captured by the climate models now available. These will also imply fluctuations in the rate of increase of temperature, particularly at the local level.

All of these effects arise on the assumption that the time-path of warming, though variable, is known with certainty. Uncertainty implies losses over and above those associated with the convexity of the damage function. The optimal outcome V^* in (6) above was derived on the assumption that the time-path of climatic change was known in advance at every point. The fact that the effects of global change are highly uncertain, especially at a local level, implies losses that are independent of risk-aversion or convexity of the damage function. In the presence of uncertainty, individuals will take actions in response to climatic change that turn out, *ex post*, to have been sub-optimal. These sub-optimal decisions may represent either a failure to take sufficient measures to deal with climatic change or excessive investment which turns out to have been unnecessary.

For example, farmers faced with a run of dry seasons must choose whether to continue to make investments in agriculture or to sell and move elsewhere. If *ex post*, the run of dry seasons turns out to have been a random fluctuation, those who sold will have made a costly error. Conversely if the climate has undergone a permanent change, those who persevered will regret their decision.

Another way of looking at this is that the information held by economic actors about the climate becomes more diffuse, and hence less valuable in the presence of a new source of uncertainty. Thus climate change may be regarded as destroying information. This information may in some cases be represented by formal probability distributions over temperature and rainfall derived from historical records. More frequently, it is the informal knowledge of particular local climates that is acquired by attentive individuals over a long period. Once again this is a dynamic and not a comparative static issue.

These considerations relate to moderate variations in the rate of global warming. It is necessary, in addition to consider the possibility of an 'apocalyptic' outcome arising from unforeseen interaction effects. Such outcomes might include the melting of the Antarctic ice sheets or the diversion of the Gulf stream away from Northern Europe. Although the probability of such outcomes is low, the costs would be very large. In assessing such disastrous events, it is necessary to take account of risk-aversion. For example, suppose that there is a 1 per cent probability of a disastrous outcome leading to a 50 per cent reduction in per capita GNP. Simple arithmetic would imply an expected cost of 0.5 per cent of GNP. However, depending on the degree of risk-aversion, willingness to pay to prevent such an occurrence might be significantly larger.

The Nordhaus-Schelling analysis

In their analyses of the likely costs and benefits of global warming, Nordhaus (1991) and Schelling (1991, 1992) do not make an explicit distinction between comparative static and dynamic estimates. In fact, the estimates they present are a mixture of the two. I will consider first the detailed estimates presented by Nordhaus, derived primarily from the work of the EPA (1988).

Nordhaus follows the comparative static approach described above fairly closely. He first partitions GNP into climate-dependent and climate-independent activities, finding that only about 13 per cent of US GNP is climate dependent. The next step is to present comparative static estimates of the likely change in annual output in the climate dependent sector given a 3° C rise in mean temperatures.

Nordhaus estimates possible gains and losses in agriculture, energy and real estate. Estimates for agriculture range from a loss of $10.6 bn/year to a gain of $9.7bn/year (all estimates are in $US 1981). A mean estimate near zero is also obtained by netting out the effects of increased electricity demand for air-conditioning and reduced demand for space heating. Nordhaus suggests there will be a positive (but unquantified) impact on the construction industry because of a longer period of warm weather. For some other activities (recreation and water transport) there are mixed, but unquantified effects - cold regions will gain while hot regions may lose. All of these estimates are derived using a purely comparative static approach and the results (suggesting if anything a small positive benefit from global warming) are entirely consistent with Proposition 1 and the associated discussion.

The only area where a clear loss is incurred is in real estate. Actual losses of land due to rising sea levels are estimated at $1.55 bn (for a total loss of 4000 square miles over 50 years). In addition, annual costs of protection against rising sea levels are estimated at $3.74 bn. As noted above, the loss of land area is correctly included in a comparative static estimate. However this loss alone would be insufficient to justify any significant mitigation policies.

The remaining estimates represent a mixture between comparative static and dynamic reasoning. Defensive expenditures are necessitated only because the existing capital stock is located in areas which will be inundated as sea levels rise. In a stable equilibrium with higher sea levels (the correct basis for comparative static analysis) no such expenditures would be necessary. On the other hand, the estimate is lower than that which would be derived from a properly dynamic analysis. There is no accounting for the reduced returns to new investment arising from the fact that sea levels are rising over time.

In summary, the comparative static procedure on which Nordhaus' estimates are based is guaranteed to yield the result he obtains - that the costs of climatic change are very close to zero and that no significant mitigation policies are justified.

Schelling's treatment of the problem comes closer to a dynamic analysis. He argues that, even under high estimates of the impact of greenhouse gases, the process of climatic change will be so gradual as to be imperceptible to the average citizen. For example, many people, particularly in the US, will experience greater climatic changes from shifts in residence than from the entire process of climatic change.

Schelling makes a similar point regarding estimates of damage and mitigation costs. Viewed in the context of a fifty-year time-span even fairly high estimates of the costs of global warming[6] look small. Damage equal to two per cent of GDP would merely imply that the standard of living otherwise attainable in 2050 would not be attained until 2051. Conversely, as he observes, the same perspective makes the costs of large-scale mitigation programs look small.

Having shown that the direct individual impacts of climatic change will be imperceptibly small, Schelling argues that economic activity in the developed countries, with the exception of agriculture, is essentially independent of climate. Agriculture (narrowly

[6] This point does not apply to apocalyptic damage estimates such as those arising from the melting of the Antarctic ice sheet.

defined to include only those activities taking place on farms) defined contributes only about 3 per cent of US GDP. Hence, he suggests that any large-scale costs of climatic change will be concentrated in less-developed countries, where the ratio of agriculture to GDP is high.

This argument is faulty. The damage estimates given above include some on-farm losses associated with increased uncertainty. However, the main losses related to agriculture will be incurred in activities such as grain handling and water supply. These are not counted in the agricultural sector for the purpose of computing contributions to GDP. Other losses described above would arise in housing and construction, electricity generation, tourism and transport. Only a small proportion of the activity in each sector would be affected. For example, only that part of the housing stock for which value is derived from a seafront location would be reduced. However, there is no way to derive a simple upper bound on damages from the GDP statistics. First there is the difficulty of computing the proportion of each sector that might be affected. Second, the loss is related, not to current annual output but to capital stocks.

These difficulties could be avoided by consistently applying the same reasoning used by Schelling in his treatment of the direct impacts on individuals. The relevant question in each part of the analysis is whether the change arising from global warming is rapid relative to the changes arising from other sources. In the case of direct individual impacts, the answer is "No" and global warming may be disregarded. In other cases (beachfront houses, grain handling, natural ecosystems) the answer is "Yes" and the costs must be analyzed in detail.

Concluding comments

The derivation of a dynamic estimate of the costs of global warming is beyond the scope of the present paper. However, the adoption of a dynamic approach implies reductions in measured GNP larger than the 0.26 per cent estimated by Nordhaus. In addition, costs associated with ecological damage (not measured in GNP) are likely to be equivalent to at least a 1 per cent reduction in GNP. Hence Nordhaus' 'maximum' estimate of a 2 per cent reduction in GNP might more reasonably be regarded as a low range estimate. Also, the adoption of a dynamic approach yields the recognition that the costs associated with a changing climate are already occurring and should not be subject to discounting.

It follows that a significant reduction in CO_2 emissions is justified. Nordhaus' high damage scenario implies that a 20 per cent reduction in CO_2 emissions is optimal. Concern with possible disastrous outcomes might lead to a preference for a larger reduction in emissions. On the other hand, optimistic estimates of the flexibility of (man-made and natural) capital stocks might imply a smaller reduction.

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