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Costs of adjustment to climate change*

John Quiggin and John Horowitz†

The present paper argues that the costs of climate change are primarily adjustment costs. The central result is that climate change will reduce welfare whenever it occurs more rapidly than the rate at which capital stocks (interpreted broadly to include natural resource stocks) would naturally adjust through market processes. The costs of climate change can be large even when lands are close to their climatic optimum, or evenly distributed both above and below that optimum.

1. Costs of adjustment to climate change

There is considerable scientific evidence to suggest that human activity will lead to significant climatic change over the next 50 years. The most important example is the 'greenhouse effect'. The Intergovernmental Panel on Climate Change (IPCC) has projected that human-induced climate change will produce an increase in global mean temperature of between 0.5°C and 2.5°C over the next 50 years and between 1.4°C and 5.8°C over the next 100 years (IPCC 2001). It is also predicted that sea levels will rise by between 0.09 and 0.88 metres over the next 100 years.

In response to these predictions a large number of countries signed the Kyoto Protocol in 1997. The Protocol is aimed at mitigating global warming, primarily by reducing net emissions of the main 'greenhouse gases': carbon dioxide (CO_2), carbon monoxide (CO), nitrous oxide (NO), methane (CH_4), and chlorofluorocarbons (CFCs).

Many proposals have been put forward aimed at achieving the reductions in emissions proposed under the Protocol. Some of these proposals, most notably those aimed at reducing 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

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† John Horowitz is with the Department of Agricultural and Resource Economics, University of Maryland, College Park, MD, USA. John Quiggin is an Australian Research Council Federation Fellow with the Schools of Economics and Political Science, Faculty of Business, Economics and Law, University of Queensland, Brisbane, Australia.

global warming. Others, such as sufficient reductions in emissions to stabilise the current atmospheric stocks of CO_2, would involve substantial economic and social costs.

The governments of the USA and Australia have announced their intention not to ratify or implement the Kyoto Protocol. In part, this decision reflects the view that the costs of global warming are less than the costs of any action to reduce greenhouse emissions (Moore 1998), and that the optimal responses to climate change involve mitigating and adapting to its effects.

An assessment of the effects of climate change requires an appropriate framework for the analysis of adjustment to change. Mendelsohn *et al.* (1994, 1999) criticise previous work on the costs of climate change, such as that of the IPCC (1990), for failing to take proper account of opportunities for adjustment. Quiggin and Horowitz (1999) argue that the effects of climate change depend primarily on the rate of change, so that assessments of the impact of some given change (say, an increase of 1°C in global temperatures), as undertaken by Mendelsohn *et al.* (1994, 1999) are unlikely to be satisfactory.

The main purpose of the present paper is to provide a formal analysis of the impact of climate change, demonstrating that the rate of change is the crucial variable. The analysis will deal primarily with agriculture, the sector of the economy most directly affected by climate change. Many of the issues raised by consideration of the effects of climate change on agriculture are also relevant in assessing the effects on natural ecosystems. However, whereas human-induced changes in the environment may have both positive and negative effects on agriculture, it will be argued that the effects of human-induced environmental changes on natural ecosystems are generally negative.

The present paper is organised as follows. First, we review the issues raised in the literature on assessing the costs and benefits of climate change. Next, we consider the concept of a globally optimal climate and the implications for estimates of the costs and benefits of global warming. Third, we consider the formal properties of a dynamic model. Fourth we consider estimates of adjustment costs, with special emphasis on agricultural capital stocks and natural resources. Finally, we examine issues associated with uncertainty and climatic variability.

2. Assessing the costs and benefits of climate change

In considering the economic impacts of global climate change, the earliest approach, still in use, was to catalogue likely adverse effects such as the submersion of some Pacific islands, increased severity of monsoons and hurricanes in tropical and subtropical areas, higher air-conditioning costs, increased prevalence of tropical diseases and reduced agricultural yields or, at an extreme, the conversion of currently fertile areas into desert. In response, critics such as Nordhaus (1991) and Schelling (1991) argued that an estimate based on these effects would be incomplete because of the failure to take into account offsetting benefits. To take the simplest example, agricultural yields could rise in cool areas with short growing seasons. Hence, critics argue, it is not clear whether worldwide growing conditions would improve or deteriorate. Nordhaus estimated the quantifiable net damages from climate change for the USA at 0.26 per cent of gross domestic product, and Schelling reached a similar conclusion without presenting quantitative estimates.

The most comprehensive analysis along these lines with respect to agriculture was that of Mendelsohn *et al.* (1994, 1999), who concluded that the net costs of climatic change will be quite small, at least for developed countries, and that climate change may even be beneficial. Mendelsohn *et al.* (1994, 1999) estimated that a 2.8°C increase in mean temperatures will yield changes in USA farmland rents ranging from a 4.9 per cent loss to a 1.2 per cent gain.

As Quiggin and Horowitz (1999) observed, estimates of this kind may be interpreted using the concept of a climatic optimum. For a typical specification of agricultural technology, as employed in these models, there exists an optimal configuration of seasonal temperatures and rainfall. Climate change will be costly (or beneficial) if, on average, climatic conditions move further away from (or closer to) the climatic optimum. Cool areas are ones that are below their climatic optimum. They will benefit from an increase in average temperature. Areas that are already hot are above their climatic optimum and will suffer from an average temperature increase.

Quiggin and Horowitz (1999) showed that the (1994, 1999) model was not well-behaved, in that the optimal values for climatic variables were either implausible (an optimal July temperature of −55°C) or nonexistent, because the returns function was not concave. Hence, although the equations estimated by Mendelsohn *et al.* (1994, 1999) fit the data reasonably well, they will not, in general, be well-behaved for data points lying outside the range of the data set used in estimation. Similar criticisms were made by Darwin (1999). Mendelsohn *et al.* (1999) stated that revised versions of the model display the necessary concavity properties for the existence of a well-behaved optimum.

Several questions arise from consideration of the concept of a climatic optimum. If such an optimum exists, what are its characteristics? Are agricultural areas in general above or below this optimum? Does the concept of a climatic optimum adequately capture the potential effects of climate change? The primary focus of the present paper will be on the last of these questions.

In particular, we argue that the costs of climate change are primarily adjustment costs, which are necessarily missing from any approach that relies, implicitly or explicitly, on the concept of a climatic optimum. Thus, the main effects of climate change would not be measured by distance from the climatic optimum or whether the change is toward or away from the optimum, but rather the speed of the change in climate.

The central result is that climate change will reduce welfare whenever it occurs more rapidly than the rate at which capital stocks (interpreted broadly to include natural resource stocks) would naturally adjust through market processes. Furthermore, the magnitude of the welfare loss from adjustment costs is unrelated to the difference between the initial climate and the climatic optimum.

The distinction between static measures of the equilibrium costs of climate change and dynamic measures of adjustment costs is important because the equilibrium effects tend to cancel out. Adverse effects of warming in areas where temperature is already above the climatic optimum will be offset by benefits in areas where the temperature is initially below the optimum. Hence the aggregate effect is a residual, equal to the difference between costs and benefits. By contrast, adjustment costs are strictly positive. Furthermore, in a world in which areas are found equally on either side of the climatic optimum (or are close to the optimum), benefits and costs will be roughly equal. Hence, the aggregate effect of climate change will be determined primarily by adjustment costs. This argument is formalised in the analysis below.

3. The optimal climate approach

The notion of an optimal climate is implicit in many studies of the costs and benefits of global warming. However, different procedures for estimating the optimum yield different outcomes. Comparisons of income per person generally support the view that a temperate climate similar to that of Northern Europe is optimal.

Horowitz (2001) argued that one way of gauging how global warming will affect an economy is to look at the economic performance of countries that are warmer. He examined the income–temperature relationship for a cross-section of 156 countries in 1999. After separating Organisation for Economic Cooperation and Development (OECD) countries and accounting for historical factors (which would not be affected by temperature change), he estimated that a temperature increase of 1°C would result in a 2.8 per cent decrease in world gross domestic product (GDP). If climate change delays the transition from a non-OECD to an OECD-type economy, the costs of climate change would be much larger.

For the agricultural sector, consideration of current agricultural technology gives rise to rather different results. Early studies such as the first assessments undertaken by the Intergovernmental Panel on Climate Change (1990) and the National Academy of Sciences Panel on the Policy Implications of Global Warming (1992) modelled the effects of climate change on crop yields under the assumption that existing patterns of land use would remain unchanged. This procedure does not involve the assumption of a unique climatic optimum, since the optimum will, in general, be different for every land use.

Mendelsohn *et al*. (1994) and Mendelsohn and Dinar (1999) criticised the approach of the IPCC (1990) as a 'dumb farmer' model since it assumed that farmers would not adjust their land use in response to climate change. A less tendentious description might refer to the IPCC model as a 'no adjustment' model.

Mendelsohn *et al*. (1994) observed that land rents provide a measure of the value of land in its most valuable use, and then considered the impact of climate on land rent. Under standard assumptions, discussed below, this procedure involves the assumption of a unique optimal climate. A similar implicit assumption is central to the analysis of Nordhaus (1991) and Schelling (1991), and is carried over into critical responses such as those of Cline (1991). We will refer to the approach used in these studies as the 'optimal climate model'. Both the 'optimal climate model' and the 'no adjustment' model are based on a comparative static approach.

The distinction between the two models is illustrated in figure 1. In this figure, the heavy curve, graphed against the horizontal (T) and vertical (V) axes represents the long-run relationship between temperature and the value of aggregate output, with a maximum at the climatic optimum T^*. By contrast, the dotted curve, graphed against the vertical (V) axis and third (t) axis represents the average value associated with temperature t on the assumption that the capital stock is optimised for the current temperature T_0. This curve has its maximum at or near T_0, where it coincides with the long-run value curve. Therefore, the 'optimal climate' model is represented by the heavy curve and the static model, without adjustment, by the dotted curve.

4. A formal model

To consider the global optimum approach in more detail it is useful to introduce some formal notation. The value of production in land area i, with capital and other inputs chosen optimally for the current climate, is given by a function $v_i(T_i)$ where T_i is an index of the climate in region i, which may be taken, in the simplest case, to be summarised by mean

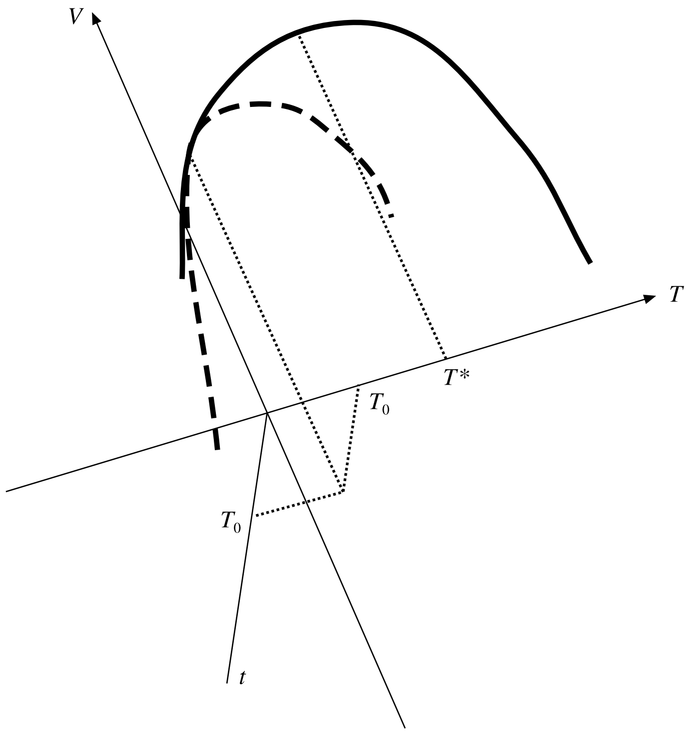

Figure 1 Static models of climate change.

temperature. Note that $v_i(T_i)$ captures both the area of region i and the value added per unit area. There are m regions. World climate is the set $\boldsymbol{T} = \{T_i\}$. Total agricultural value is given by:

$$V = \Sigma_i v_i(T_i). \tag{1}$$

Now consider a small change in climate such that, in each region, the climate index increases to $T_i + \delta_i$. Assume $\delta_i > 0 \; \forall \; i$. The function v_i is assumed to be concave in T_i with a maximum at some T_i^*. Let I_+ denote the set of regions for which $T_i > T_i^*$ and I_- denote the set of regions for which $T_i < T_i^*$. Therefore, the impact on agricultural value of the change ΔV is given by:

$$\Delta V = \Sigma_- \{v_i(T_i + \delta_i) - v_i(T_i)\} - \Sigma_+ \{v_i(T_i) - v_i(T_i + \delta_i)\} \tag{2}$$

where Σ_- denotes the sum of gains taken over the regions in I_-, and Σ_+ denotes the sum of losses taken over the regions in I_+. Both sums are positive. Therefore the net effect ΔV is the difference between the benefits accruing to areas that are initially colder than the optimum and the losses accruing to areas that are initially warmer than the optimum.

If the value added per unit area is a symmetric function around T^* and land areas are roughly equal for each region i, then the net effect, ΔV, of global warming is a residual which will be small in relation either to the gains experienced in the I_- regions or the losses in the I_+ regions. Hence, estimates derived in this way will inevitably be small in relation to total agricultural output.

To illustrate this point, consider the case when the elements of T are evenly spaced, that is $T_{i+1} = T_i + \delta$ for all i. Suppose that the temperature–value relationship is the same in all regions, given by the function $v(T_i)$. The effect on $\boldsymbol{T}$ of a uniform increase in all temperatures by δ may be obtained by deleting T_1 and replacing T_m with $T_m + \delta$. Thus, the change in V will be simply $v(T_m + \delta) - v(T_1)$. That is, the gain of new warm-temperature agriculture minus the loss of some former cold-temperature agriculture. The sign of this expression may be either positive or negative.

The shift that is likely to occur in the new equilibrium may be envisioned 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 kilometres towards the equator. Therefore, if global mean temperatures were to rise uniformly by 3°C, climates would migrate towards the poles, on average by about 500 kilometres. The exceptions are that the extremely cold climate currently prevailing at the poles would disappear and that a new high temperature climate would prevail at the equator.

Because ΔV is a residual, estimates of its sign will be sensitive to variations in modelling assumptions. For example, a conclusion that the impact of warming is negative could be reversed either by an upward revision of the estimated optimal temperature T^*, which increases $v(T_m + \delta)$ and decreases $v(T_1)$, or by changes in estimates of the pattern of warming, leading to more warming at higher latitudes and less warming at lower latitudes.

The introduction of uncertainty has only a second-order effect on this reasoning. Suppose that there is uncertainty about δ. Taking expectations with respect to a linear approximation of V, the expression ΔV derived above is still an unbiased estimate of the net impact of warming, assuming that the underlying model is valid. Observe that since $\partial v/\partial T_i$ is positive in some regions, negative in others, and close to zero on average, the linearised estimate will be unbiased. Therefore, to a first-order approximation, uncertainty about changes in absolute temperature does not matter. Of course, because of the concavity of the value functions, uncertainty will have a negative second-order effect which may be significant if the uncertainty is great enough.

Similarly, it does not matter, to a first-order approximation, 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 up to a first-order approximation. 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.

4.1 The dynamic approach

To understand the dynamic aspects of the problem, it is necessary to model the production technology in more detail. Suppose there are n classes of productive activities that may be undertaken. Some of these may be independent of climate; others are dependent on climate, such as agriculture. Let K_{ijt} and N_{ijt} be the capital and labour used in region i for activity j at time t.[1] Let K_{it} and N_{it} represent the corresponding vectors. In general, we can write the total value of output produced in region i, given factor allocations, as:

$$v_{it}(K_{it}, N_{it}; T_{it}) = f(K_{i1t}, \dots K_{i(p-1)t}, N_{i1t}, \dots N_{i(p-1)t}; T_{it}) \\ + g(K_{ipt}, \dots K_{int}, N_{ipt}, \dots N_{int}; T_{it}). \quad (3)$$

We have arbitrarily divided the factors into those whose productivity is affected by climate ($j = 1, \dots, p - 1$) and those who productivity is not. Conditional on factor allocations, all differences between regions are assumed to be captured by T_i, so the functions f, g are the same for all regions.

We next consider values over the long run. Suppose that the time path of climate T_{it} is known in advance for all i and t. The planning problem is to maximise an objective of the form:

$$\max_{K_{ijt}, N_{ijt}} \sum_{i,t} e^{-rt} v_i(K_{it}, N_{it}; T_{it}). \quad (4)$$

[1] Here the term capital is taken to encompass all those inputs to the production process that can be regarded as fixed in the medium term, including agricultural systems based on established crop practices, irrigation systems, tillage plans and so on. Capital also includes inherent properties of soils and topography that may constrain the range of land uses feasible in a given region. Conversely, labour is taken to include all inputs that are variable in the short term, such as levels of fertiliser input and use of other agrochemicals.

subject to constraints on capital stock adjustment described below. To provide a simple comparison with the optimal climate approach, it will be useful to consider the case when total capital stock is constant (new investment = depreciation in every period), both before and after climate change. Thus, capital stocks evolve subject to the constraints:

$$\Sigma_i \; \Sigma_j \; K_{ijt} = K \; \forall \; t. \tag{5}$$

We now suppose that temperature increases by a constant amount δ per period. Define the value function $V^*(\delta)$ by:

$$V^*(\delta) = \max_{K_{ijt}, N_{ijt}} \sum_{i,t} e^{-rt} v_i(K_{it}, N_{it}; T_{i0} + \delta t) \text{ subject to (5).} \tag{6}$$

Note that this is identical to a series of static maximisations. Therefore, the effect of δ can be calculated using the previous formula, ΔV. Alternatively, a comparative static analysis could be undertaken by fixing some time interval τ (for example, the doubling time of global CO_2 stocks) and undertaking the analysis of the previous section with total change $\delta\tau$. As we have seen, for moderate values of δ, a zero net impact is derived.

We now turn to a more realistic treatment of the evolution of the capital stock, the crucial feature of the dynamic approach. In the static approaches, the capital stock is homogenous, both in form and in its allocation across regions, and therefore costlessly adjusted. 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, of being scrapped.

The capital adjustment constraint is now written:

$$K_{ijt} \geq (1 - \gamma_{ij}) \; K_{ij(t-1)} \tag{7}$$

where γ_{ij} is the rate of depreciation for the j-th type of capital in region i. The value function is:

$$V^{**}(\delta) = \max_{K,N} \Sigma_{i,t} \; e^{-rt} \; v_i(K_{it}, \; N_{it}; \; T_{i0} + \delta), \text{ subject to (5) and (7).} \tag{8}$$

Our key result is:

Proposition 1: Suppose $\Delta V = 0$. Then V^{**} is a concave function of δ with a unique global maximum at $\delta = 0$.

Proof: By the initial equilibrium assumption, the optimal path when $\delta = 0$ has $K_{ijt} = K_{ij0}\ \forall\ i, j, t$. Therefore, constraint (7) does not bind. Therefore, $V^*(0) = V^{**}(0)$. For $\delta > 0$, we have $V^*(\delta) \geq V^{**}(\delta)$. This inequality will be strict whenever any of the constraints is binding.

The cost of climate change is $V^{**}(0) - V^{**}(\delta)$. Since $V^*(0) = V^{**}(0)$, this cost can be written as $\{V^*(0) - V^*(\delta)\} + \{V^*(\delta) - V^{**}(\delta)\}$; in words, the equilibrium costs plus adjustment costs. The first term is ΔV, the estimate of loss derived in the previous section. Since adjustment costs are non-negative, this is 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 (7). 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}. Otherwise (7) binds and $V^*(\delta)$ will be strictly greater than $V^{**}(\delta)$.

Proposition 1 is critical to understanding the issues related to global warming because it encapsulates the distinction between the dynamic approach and the comparative static approach. In the case where the long-run costs and benefits of climate change, captured by a comparative static analysis, sum to zero, the aggregate effects of climate change are exactly equal to the adjustment costs, which are necessarily positive, and increasing in the rate of climate change. Thus, in general, it is the rate of climate change and not the final equilibrium temperature that should be the focus of analytic attention.

The dynamic approach is represented in figure 2 for the general case when ΔV is small, but not necessarily equal to zero. The horizontal axis is

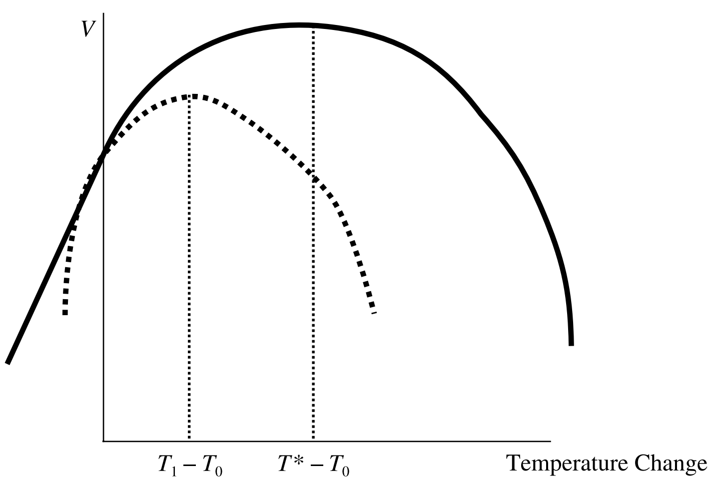

Figure 2 Static and dynamic models of climate change.

taken to represent the change in temperature over some fixed period of time, say 10 years. The intercept with the vertical axis corresponds to no change from the original temperature T_0.

The heavy curve is the long-run value curve as in figure 1. The dotted curve is the average cost curve, taking adjustment costs into account. As drawn, the temperature is initially below the long-run climatic optimum. A small increase in temperature will increase output value. However, an increase beyond T_1 will reduce value because capital stocks will adjust more slowly than temperature.

5. Adjustment costs

From the discussion above, costs of adjustment to 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: long-lived infrastructure investments and natural capital.

5.1 Long-lived infrastructure investments

Long-lived infrastructure investments include harbours, dams and irrigation systems, and grain handling facilities. Consider first the example of grain handling facilities. Suppose that climatic change over the next 50 years results in an increase of 2.5°C in mean global temperature. As described above, this increase has the effect of shifting the zone of grain production 500 km further from the equator. In the optimal climate approach, the impact would depend on the area of potentially arable land at different latitudes.

A dynamic estimate yields different results. Assuming a 2.5°C increase over 50 years and a uniform rate of warming, the annual increase of 0.05°C per year implies a shift in the zone of grain production of 10 km per year away from the equator. Although this shift appears small, it is large enough to imply significant capital losses in grain handling. Fisher and Quiggin (1988) estimate the optimal service radius for Australian grain handling facilities at 25 km. Hence facilities initially at the margin of the grain production zone will be suboptimally located after three years of warming at a rate of 0.05°C 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 500 km 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, the process of global warming will impose continuing costs.

An imprecise estimate of the proportional increase in costs could be obtained on the basis of the assumption that grain handling facilities last for 50 years and that half of them would be within the 500 km range requiring early replacement during this period. This would imply a 50 per cent increase in the effective rate of depreciation, and therefore in long-run capital costs. (These estimates would need to be reduced to the extent that technological change permitted a continuing expansion in the zone of grain production).

In this case, damages are related fairly directly to the rate of change. As shown in Proposition 1, 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 hydroelectric 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. 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 approach and the optimal climate approach 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 hydroelectricity than the present distribution. Hence an optimal climate analysis must yield a net cost estimate of zero.

From the dynamic perspective, however, the critical point in favour 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 years floods) that 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.

5.2 Natural capital

The second main category of capital stock with high adjustment costs 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 for any given species will move away from the equator by about 500 km during this period. That is, if a given species is initially best suited to locations 1000 km south of the equator before climate change, it will be best suited to locations 1500 km south of the equator after 40 years. Thus, trees growing in a location that is initially optimal will be 500 km away from their optimal location at the end of the rotation period. Hence, many existing forests with limited capacity for adaptation to climatic change will suffer tree decline and dieback (Shugart *et al.* 1986; Neilson *et al.* 1992). A further implication is that reafforestation will be constrained by the need to choose replacement species that are capable of flourishing in a wide range of climatic conditions.

These points are illustrated by the work of Sohngen and Mendelsohn (1998). Although climate change is modelled as having beneficial impacts on the steady state productivity of forests, these benefits are reduced when account is taken of adjustment costs, including forest dieback. Negative net effects arise in versions of the model with dieback and imperfect foresight.

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. For example, whereas the current US forestry system involves four major species, Sohngen and Mendelsohn (1998) show that, with an equilibrium adjustment to a temperature increase of 3°C, a single species, loblolly pine, is likely to dominate most US forestry.

Losses in recreational value could be estimated using hedonic pricing and travel cost methods (Bockstael and McConnell 1981). 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, as has the rate of clearance of forested land in Australia and elsewhere. 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 appropriate to consider 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.

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 than any that has occurred as a result of natural climatic processes (IPCC 2001). 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. However, this list of economic losses does not capture 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 1967). 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 criticised on various grounds (Kahneman and Knetsch 1992; Rosenthal and Nelson 1992; Quiggin 1993, 1998).

An alternative approach may be used to obtain a fairly robust lower bound. Rates of ecological loss associated with global climatic change are likely to 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 1979) for the USA that over the period 1975–1978 the cumulative impact of this legislation was to reduce measured gross national product (GNP) by 0.6 per cent. Extrapolation over the period 1970–1990 suggests a cumulative impact of around 2.5 per cent of measured GNP.

If: (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; and (iii) the legislation was solely directed to the preservation of natural ecosystems, then 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 favour 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. Aesthetic and other 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, suppose that one-third of past environmental expenditures have been motivated by ecological concerns, and (following Nordhaus 1991) that the experience of the USA is representative of that of other developed countries such as Australia. 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.

6. Climatic variability and uncertainty

It was shown above that uncertainty about the extent, pattern and timing of global warming has no effect on cost estimates derived using the optimal climate approach. 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 1, 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 above, 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 artefact 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 caused by the build-up of greenhouse gases is super-imposed on ill-understood cyclical climatic fluctuations of varying periodicities (up to decades). During the period 1940–1980, a cyclical downturn was sufficient to offset the underlying warming trend presumed to be associated with the buildup of CO_2. Conversely, in periods when an upward cyclical fluctuation in temperatures 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.

Uncertainty implies losses over and above those associated with the convexity of the damage function. The optimal outcome V^{**} in (8) 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 suboptimal. These suboptimal 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 problem.

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.

7. Concluding comments

Most assessments of the likely consequences of climate change have adopted a comparative static approach, in which the initial situation is compared to that which is expected to prevail after some given increase in temperature. Some assessments have been based on existing patterns of economic activity, thereby precluding adjustment. Going to the opposite extreme, Ricardian approaches incorporating the notion of a climatic optimum have, in effect, assumed that adjustment is costless.

The present paper has argued that the main costs of climate change will be costs of adjustment. Stocks of both natural capital and long-lived physical capital will be reduced in value as a result of climate change. This loss will be exacerbated if the process of climate change is variable and stochastic.

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