

A cost–benefit analysis of slowing climate change

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This paper attempts to condense a mass of information relating to economic growth assumptions, carbon emissions forecasts, abatement cost estimates, and global warming damage functions and incorporate it into a cost–benefit analysis of slowing climate change. By these means it is possible to provide evidence on the extent to which society ought to incur control costs now in order to prevent future climate change using the rules commonly associated with project appraisal. In a business as usual scenario, the model predicts a temperature rise of 3.6°C above preindustrial levels by the end of the next century inflicting damage with a present value of US\$8.9 trillion. An optimal policy, however, seems to involve an immediate 12.7% cut in emissions and the establishment of 37.1 million hectares of forests. The optimal tax on carbon emissions for the year 2000 is estimated to be US\$16.84 per tonne and the optimal policy reduces temperature rise by 0.3°C relative to business as usual. By following the optimal policy, costs are reduced by US\$700 billion. It is also suggested that policies to halt deforestation and remove the subsidies paid to fossil fuel producers might reduce overall costs by a further US\$1.1 trillion.

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There are many conflicting views regarding the true dimensions of the climate change problem. Often these viewpoints are based on different estimates of key parameters. With little indication as to why these parameter estimates vary so much and which ones might be the more reliable, prospects for a coordinated strategy to tackle climate change appear dim. Little consensus has emerged, for example, regarding the costs of abating carbon emissions. Some take the view that considerable improvements in energy efficiency are available at negative cost by setting minimum efficiency standards for vehicles and domestic appliances (Mills *et al.*, 1991). Others regard the macroeconomic costs of even small reductions in carbon emissions as quite considerable (Manne and Richels, 1993). In the judgement of yet more researchers a significant proportion of carbon emissions arise purely as a result of institutional failings; either at a regional level in the subsidies paid to fossil fuel energy producers in the erroneous belief that this promotes economic growth (Shah and Larsen,

1994), in failure to deal with air pollution (Glomsrod *et al.*, 1992) and vehicle congestion in urban areas (Hughes, 1991), or at a global level in failing to make appropriate transfers to those countries whose forests contain rich biodiversity which we would wish to preserve (Pearce, 1991).

But differences in opinion over the costs of abatement are minor in comparison to the disagreements relating to the potential damage if significant cuts in emissions are not made. A recent survey of expert scientific opinion (Nordhaus, 1994), indicates enormous uncertainty regarding the impact of climate change. Some see a few degrees' temperature increase spread over a century as something which would hardly be noticed, perhaps even benefiting colder countries in the north (Schelling, 1992). Others emphasize the allegedly beneficial impact of elevated CO₂ concentrations on plant growth (Bolin *et al.*, 1986). Many ecologists, however, point to the painfully slow migration rates for some ecosystems and argue that mass species extinction would be inevitable if

rapid global warming were to occur (Fankhauser, 1993). The frequency of tropical storms could increase in line with sea surface temperatures resulting in devastation to areas prone to those kind of events (Emanuel, 1987). Some studies point to flooding of low lying island states in the Pacific Ocean and uncomfortably high temperatures in the mid latitudes (IPCC, 1990a).

Even the impact of escalating emissions of greenhouse gases on the climate is a matter of some debate. The influence of the elevated concentration of CO₂ in the atmosphere can only be resolved by reference to the temperature record. But in the opinion of some, the temperature record is itself in doubt due to thermal pollution from cities despite attempts to correct for this. In any case, the observed temperature record is consistent both with the hypothesis of no climate change as well as with a 2.5°C rise (IPCC, 1990b). None the less, researchers using different methods claim to have detected a statistically significant role for CO₂ concentrations (Tol and de Vos, 1993). Recently, Charlson and Wigley (1994) have argued that sulphate aerosols have the ability to mask the onset of climate change and that a warming rate higher than that currently predicted is likely. Some have rejected the IPCC's views altogether. For example; a poll of US meteorologists (Lindzen, 1992) showed that none believed that any global warming had occurred so far. It has also been difficult to decide the extent to which changes in sea levels reflect the thermal expansion of sea water rather than vertical movements in the surface of the land following the last ice age (see Bolin *et al* (1986) for a survey).

Confronted with such uncertainty regarding the costs and benefits of slowing anthropogenic climate change and even uncertainty regarding the processes underlying any observed changes it is hardly surprising that different authorities have drawn opposing policy conclusions. Some see the costs of emissions abatement as being insignificant or even negative and advocate a rapid transition to a low-carbon economy (Greenpeace, 1993). Others regard immediate reductions in carbon emissions as headlong and strongly oppose drawing resources away from more pressing concerns just to prevent a 'slight' change in climate to which mankind could probably adapt (Beckerman, 1994).

Most economists have cast the problem of global environmental change in terms of an exercise in cost-benefit analysis. A number of such analyses have appeared in the literature, for example, the CETA model of Peck and Teisberg (1992). In a separate cost-benefit analysis of arresting climate change, Cline (1992) considers the desirability of a 4 Gt C emissions ceiling compared with business as usual. Both emissions reductions and sink enhancement are considered as a means of achieving this goal. Nordhaus has developed an elegant

optimal control model of GHG abatement entitled DICE (1992). This model is based around a Ramsey-type model of economic growth in which all climate damage has a market impact cutting income and reducing emissions. For many environmentalists, however, the considerable uncertainties regarding the response of the planet are reason enough to reject any attempt to balance the costs and benefits of slowing climate change. Instead they propose a 'carbon budgets' approach in which an historical analogue is sought for threatened rapid changes in climate (for example Krause *et al*, 1989). Annual carbon budgets are set to ensure that a maximum rate of change is not exceeded. In the view of the author, however, linking decisions to a particular historical analogue seems rather arbitrary.

This paper attempts to condense a diverse body of information relating to economic growth assumptions, carbon emissions forecasts, abatement cost estimates, and global warming damage functions, and incorporate them into a model which weighs up the costs and benefits of halting climate change. The paper does not seek to resolve the large uncertainties associated with virtually every aspect of the climate change problem. Rather, it asks what conventional assumptions about the size of the problem imply. In a later paper, the model might be used to illustrate how changes in those assumptions affect the optimal policy. Questions regarding how one should proceed under uncertainty and what is the value of information can also be addressed within this relatively simple framework, but these too are deferred to a later paper.

The model takes baseline economic output and GHG emissions as given. According to the statistically estimated model of the carbon cycle used, only two-thirds of these emissions are ever removed so atmospheric concentrations of carbon dioxide emissions are, in the absence of policy interventions, set to increase. Average global temperatures respond to elevated CO₂ concentrations via a process of lagged adjustment. This rise in temperature is taken as an index of global environmental change which is assumed to cause economic damage. Such losses are quantified in terms of a damage function. The warming process can be delayed by reducing emissions from the baseline (which incurs a cost) or, alternatively, emissions can be offset by terrestrial sink enhancement, ie planting forests to absorb carbon from the atmosphere. But afforestation has a lagged impact on the atmospheric concentration of CO₂ which ceases once the forests have grown to maturity. Reforestation programmes are also constrained by the costs of permanently removing land from other productive uses. The interesting question is the extent to which society ought to be willing to incur control costs now in order to prevent future climate change using rules commonly applied to project appraisal.

Clearly, the model is in many ways highly stylized neglecting potentially important feedbacks and interdependencies. This is inevitable: the construction of a fully integrated model is a huge undertaking and, in the view of the author, this kind of 'synthetic' modelling exercise will continue to enjoy an important role in policy analysis.

The remainder of the paper is organized as follows. The next section describes the model in more depth giving details of the data sources for the estimated equations and the properties of the equations whose role it is to describe the response of the climate to anthropogenic carbon emissions. The following section describes the results of the model when it is run using conventional assumptions regarding future economic growth rates and carbon emissions. The results contrast the present value costs of permitting unchecked carbon emissions with those associated with the optimal policy. The paper calculates the tax rates necessary to secure the optimal level of abatement activity and compares them with the estimates made by other researchers. A variety of other GHG protocols are evaluated including measures aimed at institutional reform to halt deforestation and end the payment of subsidies to fossil fuel producers. Finally the paper concludes with a discussion of the role of uncertainty and a consideration of the scope for further simulations of the model.

The model

The model takes the form of a dynamic non-linear programme whose objective is to minimize the present value costs associated with climate change policy. In essence, the model evaluates the trade-off between abatement activity and the costs of climate change related damage taking emissions reductions and sink enhancement as the control (choice) variables. This model is driven by exogenous input assumptions for economic growth and carbon emissions. The economic growth assumptions in Table 1 follow the Stanford Energy Modeling Forum specifications which suggest a slowly declining rate of economic growth over the next century (Gaskins and Weyant, 1993). The emissions assumptions in Table 2 are taken from the IPCC 'best guess' scenario IS92a (IPCC, 1992). Only the emissions of carbon are considered. Carbon dioxide, being the main GHG, is taken as a proxy for all GHGs. These trends in economic growth and emissions are projected forward to the year 2250 which is the terminal date used in this analysis.

The implications for atmospheric concentrations of CO₂ of these carbon emissions depend upon the dynamics of carbon in the atmosphere and the carbon cycle. The econometrically estimated model of the carbon cycle used here posits the existence of a long-run equi-

Table 1 Baseline GNP assumptions (US\$ trillion)

Year	Gross world national product
1990	22.92
2000	30.97
2010	39.77
2020	51.06
2030	66.55
2040	81.94
2050	100.89
2060	122.73
2070	149.31
2080	180.64
2090	217.35
2100	261.52

Source: Stanford Energy Modeling Forum, private communication.

Table 2 Business as usual annual global carbon emissions (Gt C)

Year	Energy and other	Deforestation
1990	6.2	1.3
2000	7.2	1.3
2010	8.8	1.2
2020	10.3	1.1
2030	11.6	1.0
2040	12.7	0.9
2050	13.7	0.8
2060	15.0	0.6
2070	16.4	0.4
2080	17.7	0.3
2090	19.1	0.1
2100	20.4	-0.1

Source: Scenario IS92a, IPCC International Panel on Climate Change) (1992).

librium relationship between the end-of-period change in the atmospheric concentrations of CO₂ and the flow of carbon emissions into the atmosphere. A polynomial distributed lag (Almon, 1965) was used to represent the manner in which emissions are removed from the atmosphere. The equation was deliberately overfitted and tested down (Hendry, 1993).

The data used for this exercise are drawn from a variety of sources. Atmospheric CO₂ concentrations are constructed from the Siple ice core record (Friedli *et al.*, 1986) for the period 1744–1958 and the direct measurements taken at Mauna Loa for the period 1959 to present day. The record of carbon emissions is taken from Keeling (1991) for the period 1860–1949 and from Boden *et al.* (1991) for the period 1950–90. These records are incomplete in that they exclude carbon emissions from land-use changes which are largely unknown. In order to deal with this problem, the equation was estimated with an intercept to represent a constant rate of increase in atmospheric concentrations arising from land-use changes. The intercept was estimated to have the value 1.147 and indicates that each decade the atmospheric concentration of CO₂ increased by a little over 1 ppm independently of fossil fuel emissions. Given that

the equation also suggests that ultimately 36% of emissions are retained in the atmosphere, it is possible to calculate that average annual carbon emissions from deforestation and other non-energy emissions of carbon were approximately 0.7 Gt C per annum. Although a crude calculation, this figure agrees surprisingly well with the deconvolution of ice core data by Siegenthaler and Oeschger (1987), who estimate biospheric emissions at 0–0.9 Gt C per annum. In the equation presented below, the intercept is dropped because emissions from land-use changes are explicitly included:

$$CONC_t = CONC_{t-10} + 0.00446EM_{t-10} - 0.00158EM_{t-20} - 0.00118EM_{t-30} \quad (1)$$

where $CONC_t$ is the concentration of CO_2 measured in ppm and EM_t is the annual flow of carbon emissions measured in Gt C. The equation suggests that by the end of 10 years approximately 94% of emissions are still air borne. At the end of 20 years, this has fallen to 61% and after 30 years to 36% after which time the process becomes so slow that it may for all practical purposes be taken as complete. This equation has a number of properties in common with more complex representations of the carbon cycle, eg the model of Maier-Reimer and Hasselmann (1987). The concentration of a pulse excess of carbon into the atmosphere does not go to zero even in the long-term and there is a period of extremely rapid elimination of carbon to begin with in both models. In the model of Maier-Reimer and Hasselmann, however, only 15% of the carbon emissions are ultimately retained but this process requires a period of several hundred years to complete.

Actual warming is calculated by fitting a polynomial lag with zero end point restrictions to the global temperature record constructed by Jones *et al* (1991) covering the period 1854–1990. This temperature record is not corrected for the ENSO phenomenon and all factors having a transitory impact on the climate, such as solar cycles and volcanic eruptions, are ignored. Once again, the order of the polynomial and the length of the lag are exaggerated before testing down. The final equation suggests that the response of the climate to heightened radiative forcing is complete within 40 years and can be represented by a polynomial of order 2; Tol and de Vos (1993) reach an identical conclusion. The full impact of a doubling of CO_2 concentration leads to an estimated temperature rise of 3.5°C. However, because CO_2 is being used as a proxy for all greenhouse gases, this figure should be reduced by around 39% before comparing it to the IPCC estimate for equivalent CO_2 doubling.¹ Once this has been done, the forecast equilibrium

response of 2.1°C is quite close to the IPCC's prediction of 2.5°C. The fact that the temperatures in the data series are measured as deviations from the 1950–79 average means that in order to calculate the temperature rise from preindustrial levels, it is necessary to adjust the intercept slightly such that equilibrium warming for preindustrial carbon concentrations is zero. The suggested temperature rise $WARM_t$ for the year 1990 is a shade under 0.8°C:

$$WARM_t = -28.00 + 1.49 \ln CONC_{t-10} + 1.99 \ln CONC_{t-20} + 1.49 \ln CONC_{t-30} \quad (2)$$

The damage function, $DAMAGE_t$, takes this temperature rise as an index of global environmental change, calculates the amount of economic damage and scales it to GNP. Only a handful of research papers have attempted to place economic values on the impact of climate change. None of these papers indicates the extent to which damage depends upon the rate of warming but instead focus upon an equilibrium climate change as it would effect the present-day economy. It must be admitted that our knowledge in this area is dreadfully weak.

The results of a survey of expert opinion conducted by Nordhaus (1994) suggest a loss of 3.6% of GNP for a 3°C temperature rise while a taxonomy of climate change impacts prepared by Cline (1992) for the USA points to much smaller losses of 1.1% for a 2.5°C rise and damage increasing by a power of 1.3 with temperature rise. Fankhauser (1993) arrives at an estimate of 1.5% for a 2.5°C rise relative to preindustrial levels. Titus (1992) uses an estimate of a 2.5% loss of US GNP for a 4°C rise in temperature. Ideally one would also wish to make damage depend upon the rate of change of temperature but no estimates are available yet. The model follows Fankhauser in assuming a loss of 1.5% for a 2.5°C temperature rise, it takes a damage function exponent of 2, and the following equation is calibrated:

$$DAMAGE_t = 0.0024 WARM_t^2 \quad (3)$$

In order to avoid global temperature rises it is necessary either to abate emissions of carbon or to reabsorb the carbon once it has been emitted. While the cost of greenhouse gas abatement has been the subject of a considerable research effort there does not yet appear to be a consensus on what the costs actually are (Maddison, 1994).

Gaskins and Weyant (1993) report that the carbon tax required to reduce US emissions to 80% of their 1990 levels by the year 2020 ranges from between US\$50 to US\$300. The costs of achieving the same reduction in emissions ranges from between 0.9% to 1.7% of GDP. This implies a reduction in the average annual growth rate of 0.05%. These losses can be significantly reduced by using the revenues to reduce existing distor-

¹According to the IPCC (1990b) CO_2 has been responsible for 61% of the increase in radiative forcing to the year 1990.

tionary taxes. Dean and Hoeller (1992) conduct a similar exercise for the OECD using six different models run under common input assumptions. They consider the marginal costs of abatement curves for the years 2000, 2020, 2050 and 2100. As expected, the marginal cost of abatement curves are highly non-linear. Important differences emerge when later years are considered. The explanation offered is that the existence of a backstop technology in some models implies that once the backstop technology becomes economically viable, further reductions in CO₂ are available at constant marginal cost.

Interesting though these comparisons may be, they give no indication as to which model provides the most credible results. Even if standardized input assumptions could eliminate all the disparities between the different models (and the results suggest that they cannot) this does not validate any of the models. All could be wrong together. Given that it will be a long time before we possess models which can be tested against the data (rather than against each other) and that the need to make policy is immediate, how should we make the best of the results that we have? One approach is to combine the results from several different models using regression analysis and to regard the resultant 'meta-model' as being preferable to those from any one source. Unfortunately, there is no reason to believe that the 'errors' made by the different models are normally distributed with zero mean. Nevertheless, while there is no justification for attaching any special significance to the results of this exercise, the approach continues to find favour. It is effective in placing less weight on 'extreme' findings and 'conveniently summarizes' the information contained within these models in just a single reduced form expression.

Using this technique, Cline (1992) estimates a linear relationship between a percentage reduction in emissions away from the baseline and a cost in terms of a percentage of GNP using a survey of published abatement cost estimates. Notwithstanding a number of problems,² his results seem to indicate that reducing carbon emissions by a further 10% decreases GNP by 0.9% and that delaying the cutback by 10 years reduces GNP costs by 0.25%. Cline at a later stage reduces these estimates even further to account for the recycling of the tax revenue and associated benefits from reduced air pollution. Clearly, the manner in which Cline condenses the available cost estimates to incorporate in his cost-benefit analysis raises a large number of questions, among other

Table 3 Global CO₂ abatement cost modelling studies

Model	% cut in CO ₂	% GNP cost	Year
Anderson and Bird (1990)	68	2.8	2050
Barns <i>et al</i> (1992)	26	0.74	2005
	45	1.62	2020
	59	2.43	2035
	78	4.07	2050
	83	4.67	2080
	87	5.05	2095
Burniaux <i>et al</i> (1992)	18	0.2	2000
	26	0.4	2005
	33	0.6	2010
	46	1.0	2020
	55	1.2	2030
	69	1.9	2050
Goldemberg <i>et al</i> (1987)	50	0.0	2020
Manne (1992)	89	7.49	2100
Manne and Richels (1993)	75	4.0	2100
Mintzer (1987)	88	3.0	2075
Nordhaus (1990)	50	1.0	2100
Perroni and Rutherford (1991)	23	1.0	2010
Whalley and Wigle (1991)	50	4.4	2100

things the extent of zero cost emissions reductions, the assumed linearity of the abatement cost curve, and inclusion of cost savings from revenue recycling. On the other hand it is easy to sympathize with Cline because the abatement cost literature is in so many respects deficient. In these situations, expert judgement is required.

The abatement cost estimates used to generate the regression equation used in this exercise are summarized in Table 3. All abatement cost estimates are drawn from simulations in which it is assumed that emissions trading occurs so that costs are kept to a minimum. After some experimentation with a more general polynomial abatement cost curve, a cubic equation was found to provide the best overall fit. The equation was estimated without a constant term such that the abatement cost curve passes through the origin. In other words, the equation denies the existence of any 'free lunch' reductions in carbon emissions. The scope for cost-free reductions from institutional reform are considered separately. The estimated equation is:

$$ABCOST_t = 0.081CUT_t^3 \quad (4)$$

What this equation actually entails in terms of the GNP costs of carbon emissions reductions is shown in Table 4 and a measure of the fit of the equation to the data points can be gleaned from Figure 1. It is most important to understand that the estimated equation has no particular statistical significance in the usual sense. Adding the results from many different models does not obviously result in a 'better' cost curve. Furthermore, the abatement cost estimates generated by the equation reflect the

²The estimated regression has a negative intercept term which suggests that the initial cutbacks in emissions are available at negative cost – emphatically not a property of the models contained in his survey. This occurs because the equation is constrained to being linear.

Table 4 The GNP costs of carbon emissions reductions.

Percentage reduction	Percentage GNP costs
0	0
10	0.01
20	0.07
30	0.22
40	0.52
50	1.01
60	1.75
70	2.78
80	4.15
90	5.90
100	8.10

Source: See text.

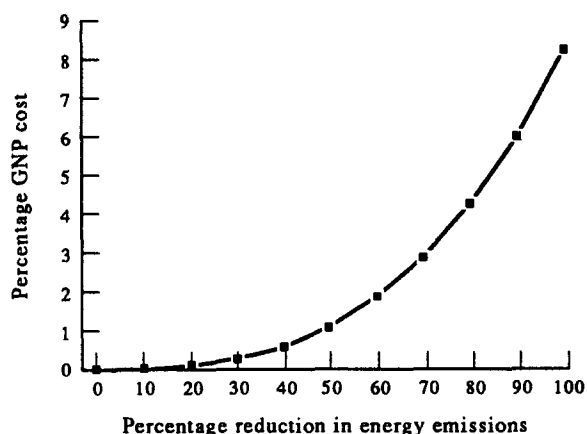


Figure 1 The GNP costs of carbon emissions restrictions

costs of reducing by a given fraction emissions of CO₂ from the consumption of fossil fuel and not total emissions which include emissions from deforestation.

Turning now to the reabsorption method, there has been considerable discussion regarding the potential for reforestation to sequester carbon dioxide from the atmosphere as an alternative to reducing emissions (Cooper, 1983; Marland, 1988; Sedjo and Solomon, 1989). The key aspect of this afforestation is that only a growing forest absorbs carbon. Once forests reach maturity, there is no further contribution to carbon fixation. Carbon fixation is typically modelled as being a cumulative process which is completed within 40 years.

The fundamental parameter in forestry models is the quantity of carbon contained within a hectare of mature forest minus, of course, the carbon content of the vegetation currently occupying the land which is to be reforested. Marland (1988) estimates that 500 million hectares (Mha) of rapidly growing forests would sequester 5 Gt C annually. Woodwell (Cited in Sedjo and Solomon, 1989) calculates that 300 Mha remove 1.5 Gt C annually. Sedjo and Solomon claim that

Table 5 Carbon annually sequestered by reforestation

Study	Carbon sequestered (t C/ha/year)
Marland (1988)	10.0
Woodwell (cited by Sedjo and Solomon)	5.0
Sedjo and Solomon (1989)	6.2
Nordhaus Tropical (1991)	1.6
Nordhaus Temperate (1991)	0.8
Moulton and Richards (1990)	4.5–7.1
This study	4.65

465 Mha sequesters 2.9 Gt C annually. Nordhaus (1991) assumes that the average annual rate of removal of carbon from the atmosphere is 1.6 t C/ha in the tropics and 0.82 t C in temperate areas. For the USA Moulton and Richards (1990) point to annual sequestration rates of 4.5–7.1 t C/ha. This study assumes that net storage of 186 t C/ha can be achieved in both tropical and temperate regions and that the impact of afforestation is exhausted after 40 years have elapsed (since by then the trees are fully grown). The annual sequestration rate over that period is 4.65 t C/ha – close to the average figure found in the literature (see Table 5). A figure of 186 t C/ha points to somewhat higher storage of carbon than could be achieved by converting fallow land into natural forests even in temperate regions (Brown, 1992), but this reflects the assumption that the forests would be managed specifically with a view to sequestering carbon. Obviously there are questions to be answered regarding the productivity of the land and how intensively the land is managed before much more can be said about the potential for reforestation. The average annual quantity of carbon sequestered by forests $SEQUEST_t$ is estimated to be 0.00465 Gt C/Mha during the 40 years following planting ($PLANT_t$ is the area measured in million hectares planted at time t) and zero thereafter. Hence:

$$SEQUEST_t = 0.00465PLANT_t + 0.00465PLANT_{t-10} + 0.00465PLANT_{t-20} + 0.00465PLANT_{t-30} \quad (5)$$

Several studies into the potential for afforestation have sought to determine the cost per tonne of carbon sequestered by dividing total establishment costs for a hectare of forests by the net carbon carrying capacity. This is usually done with the intention of comparing the relative merits of carbon sequestration versus emissions reductions. Sedjo and Solomon (1989), for example, cite estimates that the plantation costs of forests are US\$400/ha everywhere but the opportunity cost of the land required is determined by its location. Cline (1992) conservatively estimates the costs of absorbing a tonne of carbon as US\$5 for tropical regions and US\$20 for

Table 6 The present value costs of afforestation

Area (Mha)	Land cost (\$/ha/yr)	Management cost (\$/ha/yr)	Plantation cost (\$/ha)	Present value cost (\$/ha)
100	20	10	400	1000
100	20	20	450	1250
100	50	10	400	1600
100	100	10	400	2600
100	100	20	450	2850
100	200	20	450	4850

Source: Nordhaus (1991).

temperate regions. Even in the USA a considerable quantity of carbon could be absorbed at a cost of less than US\$20 per tonne (Moulton and Richards, 1990).

Unfortunately, making a direct cost comparison between absorption through reforestation and emissions abatement is not so easy. Reforestation absorbs carbon slowly over a period of time and the present value of a tonne carbon absorbed in 40 years' time is likely to differ considerably from the value of a tonne of carbon absorbed today. Studies which seek to equate the marginal costs of emissions abatement with the cost per tonne of carbon sequestered through afforestation are in effect not comparing like with like. But by explicitly modelling sequestration as a lagged function of plantation, the analysis presented here avoids miscalculation.

Table 6 calculates the present value costs of reforestation as a function of total land reforested. Estimates of land availability, the cost of land, management cost and plantation cost are taken from Nordhaus (1991). Given net carbon storage of 186 t C/ha these estimates suggest that the present value costs of removing a tonne of carbon range from US\$5 to US\$26. These costs are annualized and expressed as a fraction of GNP. The different geographical options are ranked in terms of increasing cost and then integrated in order to obtain the total annual cost of reforestation in terms of GNP as a function of the area planted. Regression analysis is once more used to fit a smooth curve to the abatement cost function (see Figure 2) which yields the following equation:

$$REFCOST_t = 9.935 \times 10^{-7} AREA_t + 9.132 \times 10^{-9} AREA_t^2 \quad (6)$$

$REFCOST_t$ is the annual opportunity cost of reforestation expressed in terms of GNP as a function of the area covered, $AREA_t$ measured in million hectares. It is assumed that the plantations are permanent.

Despite all this effort, it must be admitted that little is known regarding the current opportunity cost of land in less developed countries and how this might change in response to large-scale reforestation.³ There

³In private communication, Pearce has suggested that the rents gained from deforestation are zero for 80% of land conversion. In other words, the opportunity cost of reforestation is very low.

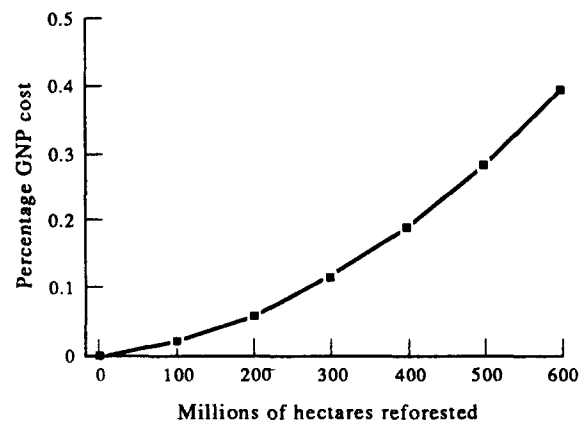


Figure 2 The GNP costs of reforestation

are important but unanswered questions regarding the environmental costs of large-scale reforestation programmes as well as the prospects for cost recovery at some later stage.⁴ It has even been suggested that large-scale reforestation might change the albedo of the planet and that this would offset some of the benefits from sequestering the carbon (Cline, 1992). All this makes it difficult to assess the cost-effectiveness of reforestation programmes in the manner we would wish.

This concludes the specification of the model which is subsequently solved in step intervals using the GAMS software (Brooke *et al.*, 1992). Further details regarding the specification of the model are available from the author upon request.

Results

This section outlines the results which emerge from the model when it is run using the input values described above and a 5% discount rate. Results are reported only up to the year 2100 to avoid any problems associated with the existence of a terminal date.

⁴Read links afforestation and carbon abatement measures. His idea is that as well as providing a sink for carbon, biomass can also replace fossil fuel as a source of energy. See Read (1994).

Table 7 The impact of controls on the climate

Year	No controls warming (°C)	Optimally controlled warming (°C)
1970	0.5	—
1980	0.6	—
1990	0.8	—
2000	1.0	1.0
2010	1.2	1.2
2020	1.4	1.4
2030	1.6	1.6
2040	1.9	1.8
2050	2.2	2.0
2060	2.5	2.3
2070	2.7	2.5
2080	3.1	2.8
2090	3.3	3.0
2100	3.6	3.3

Source: See text. Temperature rise is relative to preindustrial levels.

Table 8 The present value costs of different protocols (US\$ trillion)

Policy	Present-value cost
Business as usual	8.9
Optimal control	8.2
Optimal control, end subsidies and deforestation	7.1
Wait twenty years	7.2
Stabilize emissions	11.9
Stabilize concentrations at 450 ppm	10.5

Source: See text. Present-value costs are in 1990 US dollars discounted back to 1995.

In the business as usual scenario, temperature (measured against preindustrial levels) rises from 0.8°C to 3.6°C (see Table 7). The present-value cost of the greenhouse problem (see Table 8) itself is estimated to be US\$8.9 trillion. This cost includes both abatement costs plus residual damage and is the amount that we should be prepared to pay for information leading to a cost free solution to the global warming problem.

In the optimal control scenario, the optimal cutback in carbon emissions appears to be 12.7% by 2000 rising to 22.9% by the end of the next century (see Table 9). These controls on carbon emissions seem rather modest.

Table 9 Optimal reduction in fossil fuel emissions and forest planting

Year	% emissions reduction	Forest planting (Mha)
2000	12.7	37.1
2010	14.2	0
2020	15.4	0
2030	16.1	0
2040	17.8	9.2
2050	18.8	0
2060	19.7	0
2070	20.5	0
2080	21.4	0
2090	22.1	0
2100	22.9	0

Source: See text.

Similarly, the option of sink enhancement is a cost-effective one but constrained by the availability of low-cost land. It appears that those forests which are established have a present value cost of much less than US\$1000/ha. Although the plantation of forests appears to be erratic, the lagged impact they have on net carbon emissions leads to an amount equal to 170 Mt of carbon per annum sequestered over the coming decades. It should be remembered that there are no constraints upon the rate of afforestation. However, in scenarios where a much greater cutback in emissions is called for (because damages are deemed to be high or the climate more sensitive to radiative forcing) then afforestation might have a more significant role to play.

With so little abatement being desirable, the temperature change associated with the optimal climate policy looks very similar to the BAU temperature change (see Table 7). In fact, the optimal control and BAU paths for temperature rise look identical to begin with and only start to diverge significantly by the year 2040 (see Figure 3). At the end of the next century the difference in temperature is still only 0.3°C less than in the BAU scenario. The optimal tax rate (Table 10) necessary to push the economy along this path rises quickly through time. In the year 2000 the optimal tax on carbon is US\$17/t C rising to US\$22 by 2010. But if one wished to evaluate a project like afforestation which would remove carbon at points of time in the future, it would be necessary to discount these values and it is the need to do this which substantially reduces the attractiveness of long-term carbon removal schemes. Even when applying the optimal control, very little can be done to retrieve the losses. The present-value costs associated with following the optimal policy are US\$8.2 trillion (see Table 8). Following the best policy available to us, we can save a sum equal to US\$700 billion. The remedy is, as they say, almost as bad as the disease.

If in the model energy based emissions of carbon are reduced by 9.5% in each period to represent the removal of subsidies to fossil fuel energy producers (Shah and

Table 10 Carbon tax rate (\$/t C)

Year	Optimal tax rate (US\$/t C)
2000	16.84
2010	22.13
2020	28.52
2030	36.27
2040	45.71
2050	56.93
2060	70.25
2070	86.02
2080	104.67
2090	126.71
2100	152.76

Source: See text. Tax rates are in 1990 US dollars.

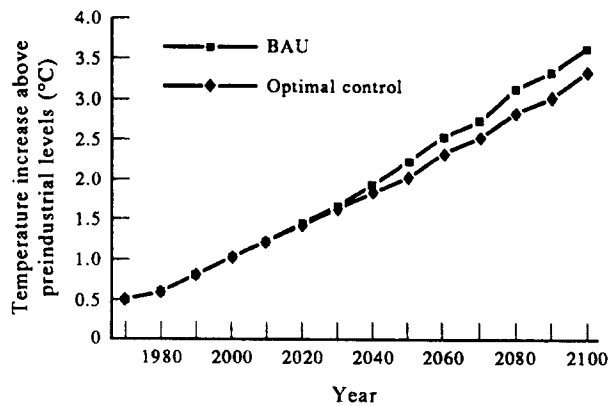


Figure 3 The impact of controls on the climate

Larsen, 1994) and deforestation is halted by institutional reform then the present value costs fall to US\$7.1 trillion (see Table 8). In other words, regulatory policy failure might be responsible for additional present value costs of US\$1.1 trillion. By introducing further constraints into the model, it is possible to examine the present-value future income associated with various other protocols which have been proposed from time to time. First of all, it is perhaps surprising to see that delaying the optimal policy by twenty years increases costs by only US\$100 billion relative to starting with the optimal policy today. On the other hand, seeking to stabilize global emissions at their 1990 levels, partly by eliminating subsidies and halting deforestation, incurs costs of US\$11.9 trillion while seeking to stabilize concentrations at their current levels is almost as bad, costing US\$10.4 trillion. Both of these protocols are much worse than the 'do nothing' option. Very high carbon tax rates amounting to several hundreds of dollars are necessary to achieve these outcomes and large additional areas of land are required for afforestation.

It is interesting to compare the findings which emerge from this model with those from the DICE model (Nordhaus, 1992). The DICE model suggests that the net benefit from pursuing the optimal policy rather than continuing with business as usual is only US\$199 billion. The optimal cutback in carbon emissions in 1990 is 10% and a carbon tax rate of US\$5/t C is required to achieve this. Stabilizing emissions at 1990 levels incurs a net cost of US\$5.2 trillion whereas stabilizing the climate involves a net cost of US\$30 trillion. In many respects then the results from the DICE model and the model offered here are quantitatively similar although this should not be interpreted as a reason to feel confident about the policy prescriptions which emerge from the two models. An important limitation of both analyses is that they proceed by replacing the uncertain parameters with their modal values. The models therefore address the question of what

would be the optimal policy to follow if all the parameters were known with perfect certainty. Since it is absolutely not the case that all parameters are known with perfect certainty the results of these exercises are not strictly policy relevant and may yield poor advice.

Conclusions

This paper has presented a 'synthetic' model of the optimal control of global warming. The model can demonstrate how differing assumptions regarding the costs of abatement and the damage potential from global warming translate into particular policy implications. It is important to emphasize the tentative nature of these findings and the fact that they rest upon a specific set of viewpoints which do not enjoy universal support. None the less, it is suggested that exercises of this kind might play a useful role in focusing the minds of those who have to take policy decisions on our behalf.

Notwithstanding certain shortcomings, the model is used to estimate the optimal cutback in emissions and the controlled rise in temperature. This paper incorporates both emissions reductions and sink enhancement as choice variables and demonstrates that an optimal policy requires the use of both. Following the optimal strategy reduces the overall costs associated with climate change by about US\$700 billion. However, this result depends on, among other things, the shape of the abatement cost function and the damage function. If the reduction in carbon emissions yields significant secondary benefits or if the costs of a carbon tax can be offset by reducing other distortionary taxes then a much greater degree of abatement may be desirable.

It would not be wrong to regard global climate change as in part a result of institutional failure. In the scenario in which deforestation and subsidies to fossil fuel producers are halted, the enhanced greenhouse effect to some considerable extent resolves itself reducing costs by a further US\$1.1 trillion. Perhaps surprisingly, delaying the use of costly measures by 20 years increases overall costs by US\$100 billion. Other policy objectives fare less well. Stabilizing emissions at 1990 levels and stabilizing atmospheric concentrations at 450 ppm, even if they are partly achieved by zero cost institutional reform, are both much worse than continuing with business as usual. The message of this admittedly simple model seems to be that it matters little whether carbon emissions are cut or not only that protocols to stabilize emissions or concentrations are avoided.

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References

- Almon, S (1965) 'The distributed lag between capital appropriations and expenditures' *Econometrica* **33** 178–196
- Anderson, D and Bird, C (1990) 'Carbon accumulations and technical progress: a simulation study of the costs' *Oxford Bulletin of Economics and Statistics* **54** (1) 1–29
- Barns, D, Edmonds, J and Reilly, J (1992) *Use of the Edmonds–Reilly Model to Model Energy-related Greenhouse Gas Emissions* OECD Working Paper No 113, Paris
- Beckerman, W (1994) Foreword in Bate, R and Morris, J *Global Warming: Apocalypse or Hot Air?* Institute for Economic Affairs Studies on the Environment
- Boden, T, Sepanski, R and Stoss, F (1991) *Trends '91: A Compendium of Data on Climate Change* Carbon Dioxide Information Analysis Center, Oak Ridge National Laboratory, TN
- Bolin, B, Doos, B, Warrick, R and Jäger, J (1986) *The Greenhouse Effect, Climatic Change and Ecosystems* SCOPE 29, John Wiley, Chichester
- Brooke, A, Kendrick, D and Meeraus, A (1992) *GAMS: A User's Guide* The Scientific Press, Redwood City, CA
- Brown, K (1992) *Carbon Sequestration and Storage in Tropical Forests* GEC Working Paper 92-24, University of East Anglia: Centre for Social and Economic Research on the Global Environment, Norwich
- Burniaux, J-M, Oliveria-Martins, J, Martin, J and Nicoletti, G (1992) *The Costs of Reducing CO₂ Emissions: A Comparison of Carbon Tax Curves with GREEN* OECD Working Paper No 118, Paris
- Charlson, R and Wigley, T (1994) 'Sulfate aerosol and climatic change' *Scientific American* February, 28–35
- Cline, W (1992) *The Economics of Global Warming* Institute of International Economics, Washington, DC
- Cooper, C (1983) 'Carbon storage in managed forests' *Canadian Journal of Forest Research* **13** 155–165
- Dean, A and Hoeller, P (1992) *The Costs of Reducing CO₂ Emissions: Evidence from Six Global Models* OECD Economics Working Paper, No 122, Paris
- Emanuel, K (1987) 'The dependence of hurricane intensity on climate' *Nature* **326** (2) 483–485
- Fankhauser, S (1993) 'The economic costs of global warming' in Kaya, Y, Nakićenović, N, Nordhaus, W D and Toth, F L (eds) *Costs, Impacts and Benefits of CO₂ Mitigation* CP-93-2, IIASA, Laxenburg, 85–105
- Friedli, H, Löttscher, H, Oeschger, H, Siegenthaler, U and Stauffer, B (1986) 'Ice core record of ¹³C/¹²C ratio of atmospheric CO₂ in the past two centuries' *Nature* **329** 403–408
- Gaskins, D and Weyant, J (1993) 'Model comparisons of the costs of reducing CO₂ emissions' *American Economic Review* **83** (2) 318–323
- Glomsrod, S, Vennemo, H and Johnsen, T (1992) 'Stabilization of emissions of CO₂: a computable general equilibrium assessment' *The Scandinavian Journal of Economics* **94** (1) 53–69
- Goldemberg, J, Johansson, T, Reddy, A and Williams, R (1987) *Energy for a Sustainable World* World Resources Institute, Washington, DC
- Greenpeace (1993) *Towards a Fossil Free Energy Future* Greenpeace International, Amsterdam
- Hendry, D (1993) *Econometrics: Alchemy or Science?* Basil Blackwell, Oxford
- Hughes, P (1991) 'The role of passenger transport in CO₂ reduction strategies' *Energy Policy* March, 149–160
- IPCC (International Panel on Climate Change) (1990a) *Strategies for Adaptation to Sea Level Rise* Ministry of Transport and Public Works, Tidal Waters Division, Rijkswaterstaat
- IPCC (International Panel on Climate Change) (1990b) *Climate Change: The IPCC Scientific Assessment* Cambridge University Press, Cambridge
- IPCC (International Panel on Climate Change) (1992) *Climate Change: The Supplementary Report to the IPCC Scientific Assessment* Cambridge University Press, Cambridge
- Jones, P, Wigley, T and Farmer, G (1991) 'Marine and land temperature data sets: a comparison and a look at recent trends' in Schlesinger, M (ed) *Greenhouse Gas Induced Climatic Change: A Critical Appraisal of Simulations and Observations* Elsevier Science Publishers, Amsterdam, 153–172
- Keeling, C (1991) 'Industrial production of carbon dioxide from fossil fuels and limestone' *Tellus* **25** 174–198
- Krause, F, Bach, W and Kooney, J (1989) *Energy Policy in the Greenhouse: Vol 1, From Warming Fate to Warming Limit* International Policy for Sustainable Energy Paths, El Cerito, CA
- Lindzen, R (1992) *Global Warming: The Origin and Nature of Alleged Scientific Consensus* OPEC Seminar on the Environment, Vienna
- Maddison, D (1994) *A Review of Greenhouse Gas Abatement Costing Methodologies* CSERGE working paper
- Maier-Reimer, E and Hasselman, K (1987) 'Transport and storage of carbon dioxide in the ocean and in organic ocean circulation carbon cycle model' *Climate Dynamics* **2** 63–90
- Manne, A (1992) *Global 2100: Alternative Scenarios for Reducing Carbon Emissions* OECD Working Paper No 111, Paris
- Manne, A and Richels, R (1993) *Buying Greenhouse Insurance: The Economic Costs of CO₂ Emission Limits* MIT, Cambridge
- Marland, G (1988) *The Prospect of Solving the CO₂ Problem through Global Reforestation* Report DOC/NBB-0082, US Department of Energy, Office of Energy Research, Washington, DC
- Mills, E, Wilson, D and Johansson, T (1991) 'Getting started: no regrets strategies for reducing greenhouse gas emissions' *Energy Policy* **19** (6) 526–542
- Mintzer, I (1987) *A Matter of Degrees: The Potential for Controlling the Greenhouse Effect* Research Report No 5, World Resources Institute, Washington, DC
- Moulton, R and Richards, K (1990) *Costs of Sequestering Carbon Through Tree Planting and Forest Management in the United States* US Department of Agriculture, Forest Service, Washington, DC
- Nordhaus, W D (1990) 'An intertemporal general-equilibrium model of economic growth and climate change' Paper presented to the workshop of Economic/Energy/Environmental Modelling for Climate Policy Analysis, Washington, DC, 22–23 October
- Nordhaus, W (1991) 'The cost of slowing climate change: a survey' *The Energy Journal* **12** (1) 37–65
- Nordhaus, W (1992) *Rolling the DICE: An Optimal Transition Path for Controlling Greenhouse Gases* Cowles Foundation Discussion Paper No 1019, Yale University
- Nordhaus, W (1994) 'Expert opinion on climatic change' *American Scientist* January–February, 45–51
- Pearce, D W (1991) 'An economic approach to saving the tropical forests' in Helm, D (ed) *Economic Policy Towards The Environment* Blackwell, Oxford 239–262
- Peck, S and Teisberg, T (1992) 'CETA: a model for carbon trajectory assessment' *The Energy Journal* **13** (1) 1–21
- Perroni, C and Rutherford, T (1991) *International Trade in Carbon Emission Rights and Basic Materials: General Equilibrium Calculations for 2020* University of Western Ontario, mimeo
- Read, P (1994) *The Economics of the Greenhouse Effect* Belhaven Press
- Schelling, T (1992) 'Some economics of global warming' *American Economic Review* January, 1–14
- Sedjo, R and Solomon, A (1989) 'Climate and forests' in Rosenberg, N, Easterling, W III, Crosson, P and Darmstadter, J (eds) *Greenhouse Warming: Abatement and Adaptation Resources For the Future*, Washington, 105–109
- Shah, A and Larsen, B (1994) *Global Warming, Carbon Taxes and Developing Countries* World Bank, Washington, DC, mimeo
- Siegenthaler, U and Oeschger, H (1987) 'Biospheric CO₂ emissions during the past 200 years reconstructed by deconvolution of ice core data' *Tellus* **39** 140–154
- Titus, J (1992) 'The costs of climate change to the United States' in Majumdar, S, Kalbenstein, L S, and Yarnal, B M (eds) *Global Climate Change: Implications, Challenges and Mitigation Measures* The Pennsylvania Academy of Science, Harrisburg, PA, 384–409
- Tol, R and de Vos, A (1993) 'Greenhouse statistics: another look at climate research' *Theoretical and Applied Meteorology* **48** 63–75
- Whalley, J and Wigle, R (1991) 'The international incidence of carbon taxes' in Dornbusch, R and Poterba, J (eds) *Global Warming: Economic Policy Responses*, MIT, Cambridge, MA