CONFERENCE PROCEEDINGS

The Economics of CO_2 Sequestration Scenarios Using Ocean Nourishment

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Abstract

With the aid of a dynamic, general equilibrium model of the global economy, the optimum economic path of carbon dioxide abatement in the atmosphere can be predicted. The "*optimum*" sequestration path is defined as that which minimizes the economic damage caused by climate change while costing no more than the economic benefits. The prediction depends strongly on the magnitude of the assumed economic damage as a result of climate change.

Ocean Nourishment is the purposeful introduction of nutrients into the ocean to sequester atmospheric carbon dioxide and increase the sustainable fish stocks. The feed stock today is natural gas but in the future could be coal. It has been found that carbon credits could be offered to the carbon market at price less $25 (1995 US $) /tonne CO_2 avoided, allowing for a typical return on capital and assuming coal prices are stable (in current dollars). The potential of Ocean Nourishment generated carbon credit has been compared with the optimal trajectory carbon tax calculated from different energy models that ignore Ocean Nourishment. This comparison has been done for two emission reduction scenarios, *optimum sequestration* and *Kyoto forever*.

Following the *optimum sequestration* path as predicted by the DICE economic model requires about 100 Ocean Nourishment plants to be constructed each decade assuming each plant sequesters 10 Mt of carbon dioxide per year in the ocean. Sensitivity studies show that the number of Ocean Nourishment plants is proportional to the magnitude of the climate change damage function. The Ocean Nourishment option has benefit-cost ratio of 2.75 compared with 1.0 (by definition) of the *optimum sequestration*.

Climate damage to the economy is most severe in the Low Income countries and the economic model has been used to estimate the future cost in this group of countries. Assuming that their population is predetermined, the accumulated economic advantage of mitigating the climate change is $6.2 trillion (1995 US $) accumulated by 2100. The total cost of Ocean Nourishment, is estimated to be $2.5 trillion (1995 US $).

The potential of Ocean Nourishment to meet the Kyoto protocol net emissions has also been studied. It has been found that in order to implement a *Kyoto forever* scenario, about of 150 Ocean Nourishment plants are needed with a total cost much less than the current alternative abatement strategies.

Introduction

The increasing global population and the rising standard of living of many people has led to increasing carbon dioxide emissions into the atmosphere despite an improvement in the intensity of carbon used in producing GDP. The process can be modeled by considering both the climate damage to the economy and the dependence of climate change due to greenhouse gas emission, on the economy. The economic model from Yale University, known as DICE provides such a tool.

It is possible to reduce the net emissions of carbon dioxide by sequestering some of the carbon used by society either before its release into the atmosphere or by taking carbon from the atmosphere using biological sinks. These processes have a cost to the economy but also may have benefits. For example, growing trees can absorb CO_2 and the resulting timber is of economic benefit.

Another way to manage the emissions is by imposing a tax on CO_2 emissions. By taxing the emissions over some quota, emitters are encouraged to switch from carbon intense fuels or to capture the CO2 or to generate sinks. The level of taxation (price) is dependent on the carbon mitigation technology available. It can be expected to change with time. The imposition of a tax has a cost to the economy.

In this paper we are seeking the *optimum* strategy that minimizes the economic damage caused by climate change while costing no more than the economic benefits. This strategy can be implemented by imposing a tax. It is the alternative strategy of using Ocean Nourishment that is considered here. This new technology is described in detail in Jones and Otaegui (1997) and Jones (2004).

We wish to compare the tax predicted by Nordhaus et al (1999) DICE model with the cost of meeting the goal by Ocean Nourishment. Ocean Nourishment is the concept of purposefully introducing nutrients into the upper ocean to sequester atmospheric carbon dioxide and increasing the sustainable fish stocks.

We can assume that Nordhaus did not know the cost of producing a carbon sink by Ocean Nourishment in 1999 when they prepared the curve of the cost of controlling net CO_2 emissions.. This cost of Ocean Nourishment depends upon the cost of capital and the cost of energy to produce reactive nitrogen. The DICE model suggests the cost of capital varies little so our modeling has concentrated on estimating the cost of coal and natural gas.

The DICE model of the economy

The DICE model (the Dynamic Integrated model for Climate and Economy) has been presented by Nordhaus et al (1999) in order to capture the impact of climate change on future global economic growth. The key goal of the DICE model is to predict the standard of living of people now and in the future. The economic output in the DICE model is calculated based on a number of behavioral assumptions, such as the *pure rate of time preference* (which represents the trade off between the consumption now and in the future) and economic expressions that converts the capital stock, productivity and population numbers into economic output (GDP).

The CO_2 emission is related directly to the economic output using the prescribed declining carbon intensity. Intensity is a measure of the amount of carbon dioxide emission per unit of Gross Domestic Product (GDP). A carbon cycle model is utilized in the DICE model to translate the continuous atmospheric CO_2 build-up into an increase in the average surface temperature. Climate change impact studies are used to relate the increase in the average surface temperature to the percent loss in economic output due to such an increase in the average surface temperature. In the DICE model, two environmental factors will affect the future GDP. The climate change damage to the economy and the cost of CO_2 mitigation.

Climate damage cost in the DICE model

The loss of economic output as a result of changing average surface temperature (and the other environmental factors such as rainfall) has been predicted through many climate-economy models. Nordhaus et al (1994) have used a quadratic expression to relate the loss in the economic output to the increase in the average surface temperature. Nordhaus et al (1999) have developed a climate damage function that generates a net benefit on a world basis until the predicted increase in the average surface temperature reaches 1.4 ^{0}C. In this paper, the climate change damage function proposed by Nordhaus et al (1994) has been used rather than the function utilized in Nordhaus et al (1999). The climate change damage function in Nordhaus et al (1994) is consistent with other estimations which use quadratic formula (e.g., Tol (2000) & Cline (1990). The damage of climate change to the economy is predicted by an aggregation procedure that adds up the expected damage in different sectors such as agriculture, water resources and species loss.

Mitigation cost in the DICE model

Engineering studies have provided an estimation of the cost of reducing the percentage of carbon dioxide emission from industry. There are substantial uncertainties in predicting this cost in the future. Here we have used the DICE model cost estimation as well as a high cost and a low cost expression. The percentage reduction in the industrial carbon dioxide emission required is called the *CO_2 control rate*.

A carbon tax in the DICE model is designed to reflect the cost to the economy of the reduction in the CO_2 emission as a function of the required *CO_2 control rate*. Thus the carbon tax represents the marginal cost- in units of $/ avoided tonne CO_2 emission. Nordhaus et al (1999) has described the relation between the *CO_2 control rate* and the carbon tax required to achieve that rate. This task has been done by analyzing the relation between the carbon tax and the amount of CO_2 mitigation calculated by nine different economists. Most of these studies are fundamentally energy models that have been extended to include the CO_2 emission. The cost estimates in these models are carried out taking into account the shape of the demand and supply function of the carbon market services in terms of the observed prices and quantities. Using mathematical programming, these models provide for the optimal prediction of economic output, fuel mix and technologies.

Nordhaus et al (1991) have carried out regression analysis to obtain one expression that characterizes the relation between the carbon tax and the *CO_2 control rate* presented in different models. The role of declining carbon intensity is also included in the carbon tax trajectory. The DICE model estimation for the relation between the carbon tax and the CO_2 control rate required to achieve different emission targets is shown in Figure (1) and also includes the high and low mitigation cost estimations from different energy sector models.

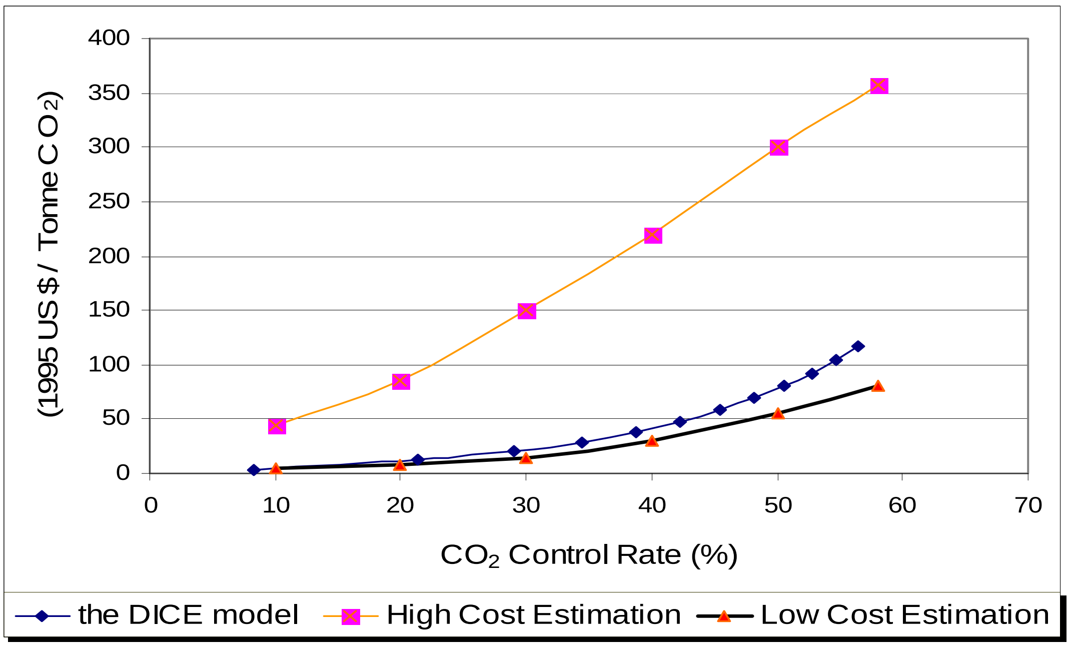

Figure (1): the carbon tax required to achieve a certain control rate for a high and low cost estimation. The DICE model estimation used intermediate cost estimation.

The cost implied in Figure (1) is paid by switching from using cheap and highly intense carbon energy into expensive and low intensity carbon services.

Seeking the optimum path

Many studies have searched for the path of optimum emission reduction over time in the face of imperfect information. Manne et al (1995) in the MERGE model have presented the concept of the *Buying green house gas insurance* to draw the track of the optimum sequestration path based on the projected market and non-market climate change damage for each geopolitical region. Nordhaus et al (1999) has presented an optimum sequestration path, determined when the benefit-cost ratio in terms of the present value of consumption is the highest. Two concepts are used in this context:

- Total abatement cost which is the difference between the present value of consumption in the base case (no mitigation) and the present value of the consumption under the abatement policy assuming that the policy will have no effect on the temperature path.
- Environmental benefit which is the sum of the abatement cost and the net economical impacts of the policy

Thus, the benefit-cost ratio is: Environmental Benefit / Total Abatement Cost.

Nordhaus et al (1999) have determined the CO_2 sequestration path that is required to maximize the benefit-cost ratio. The time horizon suggested by Nordhaus et al (1999) is relatively long and many aspects of the climate change problem are expected to be resolved before that time. Thus, another optimum sequestration path is used here.

The DICE model has been used to predict both the accumulative cost and benefit for the proposed optimum sequestration path as \$2.5 Trillion (US 1995 \$) with a decrease of 0.35 ^{0}C below the projected increase in the average surface temperature in the absence of any mitigation policy. The cost is calculated using the relation:

$$\text{Cost} = \sum_{t=2005}^{2100} \text{carbon tax}(\mu, t)\ \mu(t)\ E(t)$$

where t is the time, μ is the *CO_2 control rate* and E (t) is the projected CO2 emission. The DICE model has been used to estimate the carbon tax, the *CO_2 control rate* as well as the CO_2 emission.

And the benefit is calculated using the relation:

$$\text{Benefit} = \sum_{t=2005}^{2100} \text{Climate change damage under the base case (t) - climate change damage under the adopted strategy.}$$

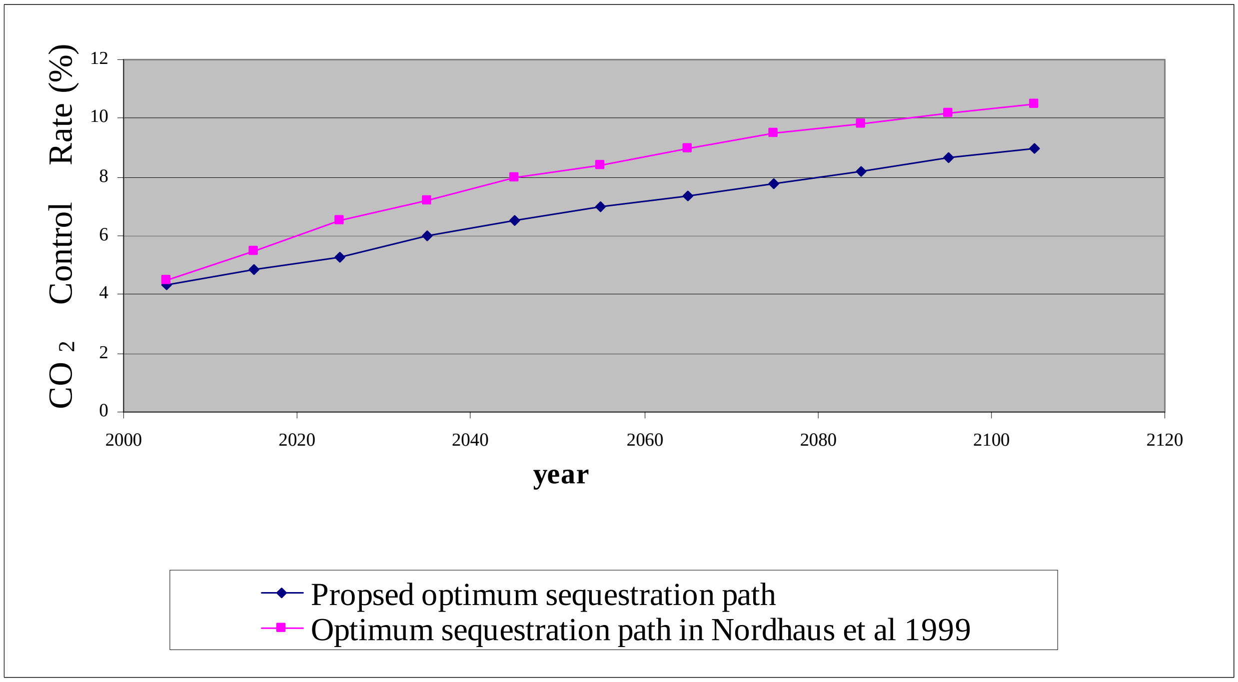

Figure (2): Required CO_2 control rate for both the *optimum sequestration path* and Nordhaus et al (1999) sequestration path. The CO_2 *control rate* is the percent of the sequestered industrial emission.

The DICE model has been used to set the parameters of this new *optimum sequestration path*. Figure (2) shows the required control rate for both the new sequestration path and the Nordhaus et al (1999) optimum sequestration path. Because of the shorter time horizon the *CO2 control rate* can be less.

Carbon credit from Ocean Nourishment

The cost of the Ocean Nourishment consists of the capital cost plus the fuel cost. Shoji and Jones (2001) have presented the following formula to calculate the carbon credit from Ocean Nourishment by using natural gas:

Carbon credit (1995 US $/tonne CO_2) by natural gas= [43+2.7 I +30 E] / 12
Where I is the interest rate and E is the fuel price in (1995 US $) /GJ

while carbon credit from a Ocean Nourishment plant is calculated by using coal:

Carbon credit (1995 US $/tonne CO_2) by coal = [75.3+5.4 I +45 E] / 12
Where I is the interest rate and E is the fuel price in (1995 US $) /GJ.

One can observe from these formulas that the capital cost for an Ocean Nourishment plant that is operated by coal is higher than that operated by natural gas while the fuel price is variable over time. The cost of producing an Ocean Nourishment carbon credit from natural gas is expected to exceed one generated from by coal around the year 2035, based on the assumption that the natural gas price will increase by 1.5% p.a. (based on the American energy outlook (AEO2003) for the Natural Gas Price Forecast 2004). The cost of coal is not expected to change due to the size of the world coal reserves and the increasing demand for coal can be met without an impact on price (based on the World Energy Review 2001). A relatively high return on equity capital is assumed supported by interest on loan funds of (2 + Interest rate in the DICE model %). Its is assumed that there would be switching from the use of natural gas to coal, seeking for the lowest possible cost for the carbon credit. Figure (3) shows the predicted carbon tax offered by Ocean Nourishment.

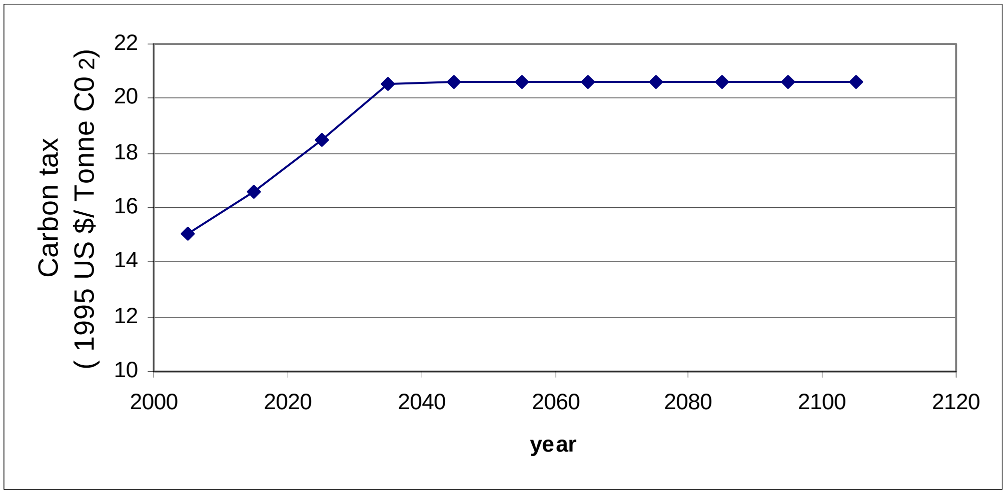

Figure (3): The cost of carbon credits offered by Ocean Nourishment. Due to the rapid predicted increase in the natural gas price, coal is assumed to replace natural gas about the year of 2030. The price of coal is assumed to be constant.

When Nordhaus et al (1999) carried out their survey seeking the optimum relation between the carbon tax and the control rate, the concept of Ocean Nourishment had not been developed. The relation between the carbon tax and the *CO_2 control rate* in Fig 1 does not take account of the potential of the Ocean Nourishment concept to provide the market with carbon credit at a cheap price.

Using the Ocean Nourishment concept to achieve the optimum sequestration

As pointed out above, the Ocean Nourishment approach has a potential to reduce the abatement cost. Shoji and Jones (2001) pointed out that one Ocean Nourishment plant with sequestration capacity of 2.5 Mt C/year requires about 19,800,000 GJ of fuel with a capital cost of $340 (M 19995 US $). Based on these figures, Table (1) shows the results of using Ocean Nourishment to provide the CO_2 control to follow the *optimum sequestration path.* It shows that one can increase the number of Ocean Nourishment plants steadily over the next century and achieve the same reduction as assumed by taxation.

Table (1): the required number of Ocean Nourishment plants to follow the proposed *optimum sequestration path.*

Year	Number of ON plants	Sequestrated CO_2 Mt C/ year	Total capital $ Billion (1995 US $)	Required Coal PJ/year	Required fuel (% of fuel consumption in 2000)	Required fuel (% of world fuel consumption in that year
2015	150	375	51	2970	12.5	3.2
2035	265	663	90.1	5247	6.7	4.7
2055	340	850	290	6732	8.6	5.2
2075	400	1000	136	7920	10.13	4.95
2095	510	1275	173.4	10098	12.9	5
2105	560	1400	190.4	11088	14.18	5.2

Note 1: fuel before 2035 refers to natural gas while after 2035 it refers to coal.

Note 2: figures in the last column are based on McFarland et al (2004) assumption of 1% pa increase in the world coal consumption in the next few decades and the (AEO2003) price forecast for natural gas.
Note 3: 1 tonne C = 0.27 tonne CO_2)

Such a construction of Ocean Nourishment plants as in Table (1) will sequester about of 95 Gt C (4 X Gt CO_2) from the atmosphere as an accumulative reduction until year 2100. This amount is equal to the amount of CO_2 that would be sequestered by constructing 100 Ocean Nourishment plants by 2015, increasing by 100 plants each decade, ending with 400 plants in 2045. One can assume - without loss of generality - that constructing 400 Ocean Nourishment plants before the middle of this century could provide sinks to achieve the *optimum sequestration path*. This assumption is supported by Figure (4).

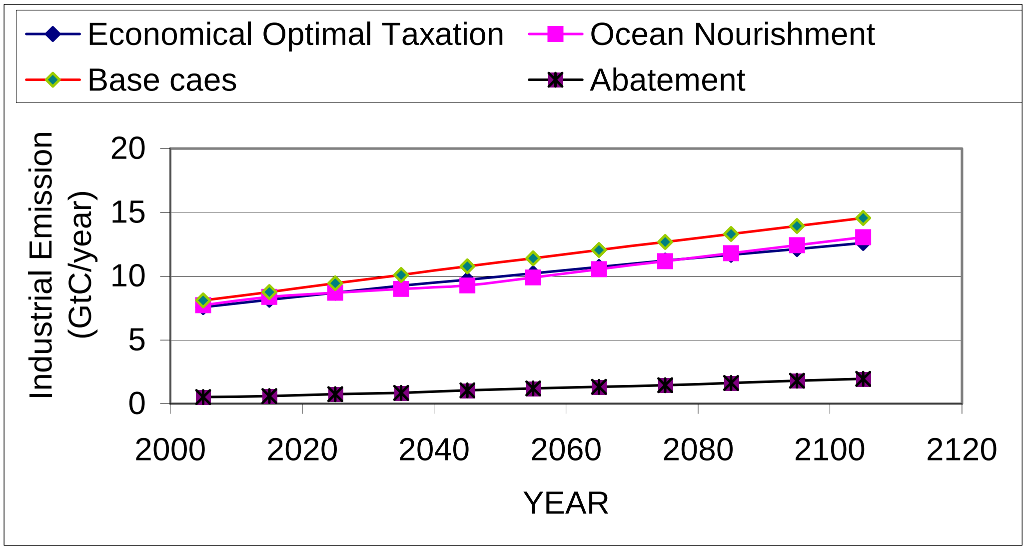

Figure (4): Net Emissions with a 100 Ocean Nourishment plants by 2015 increasing by 100 plants each decade, ending with 400 in 2045. This scenario will follow *the new optimum sequestration path*.

The total cost of this approach is estimated to be 1.9 $ trillion (1995 US $). This cost includes capital cost and the cost of the fuel. The generated benefit for this approach is 4.8 $ trillion (1995 US $) in terms of the reduction in the economical damage that might be caused by global warming, assuming the central damage case, as in the DICE model.

A most crucial point in this context is the extent to which the world will be affected by climate change. Qualitative estimates of damage are extremely tentative. The *optimum sequestration path* depends on the extent of climate change damage. Thus altering the damage function of climate change will result in a change in the path of the optimum sequestration. To examine the sensitivity of the approach, two climate damage shape functions have been examined in addition to the central damage case (the DICE damage shape function):

- The high damage case where the climate change damage function equals (1.5 X DICE formula). The benefit of the Ocean Nourishment sequestration is 7.23 $ trillion (1995 US $). In this case 150 Ocean Nourishment plants each decade ending with 600 in 2045, are needed to follow *the new optimum sequestration path* with total cost of 2.642 $ trillion (1995 US $).

- The low damage case: where the damage function equals (0.5 X DICE formula), the accumulated benefit of the Ocean Nourishment sequestration is 2.3 $ trillion (1995 US $). In this case 50 Ocean Nourishment plants each decade are needed to follow the *new optimum sequestration path* with a total cost of 0.8 $ trillion (1995 US $). Table (2) shows the sensitivity analysis result for the climate change damage shape function.

Damage case	Low damage	Central damage	High damage
Damage estimation	0.5 X DICE formula	1.0 X DICE formula	1.5 X DICE formula
Accumulated benefit ($ trillion 1995 US $)	2.3	4.8	7.23
Accumulated cost carbon tax revenue ($ trillion (1995 US $)	2.3	3.5	7.23
Benefit-cost ratio	1.0	1.0	1.0
Accumulated cost Ocean Nourishment ($ trillion (1995 US $)	0.8	1.76	2.64
No of plants	200	400	600
Benefit-cost ratio	2.875	2.7	2.73

Table (2): Using Ocean Nourishment instead of tax increases the benefit-cost ratio, from 1.0 for the *optimal sequestration path*, to 2.8, 2.7, and 2.7 for the cases of low, central and high damage respectively. It also shows that the number of Ocean Nourishment plants needed depends strongly on the predicted climate damage function. The cost of Ocean Nourishment does not take account of the benefit of enhancing fish catch that is predicted to occur with Ocean Nourishment.

One can assume that these Ocean Nourishment plants will be uniformly distributed among the coastlines of the world. The sinks do not need to be located next to the sources as the atmosphere is an efficient transporter of CO_2. The concentration of CO_2 differs by just 5% across the globe. Thus in the high damage case where 600 Ocean Nourishments plants are needed, the plants on the average be one plant each 1420 Km of the world coastline. (Note: the total world coastline is $84X10^4$ Km).

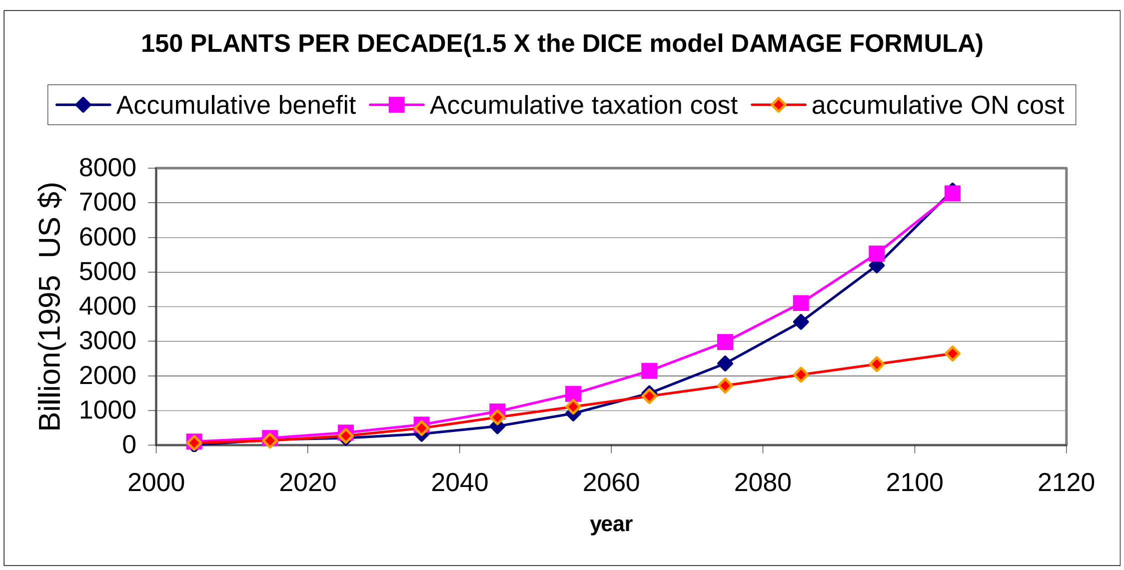

Figure (5) the accumulated cost and benefit of taxation for the high damage case for the *optimum sequestration path*. 600 Ocean Nourishment plants in the year 2045 are needed to follow the *optimum sequestration path.*

The impact of the proposed Ocean Nourishment sequestration path on low income countries

Low-income countries such as India and the African countries are more vulnerable to the effect of climate change than developed countries because their economy depends mostly on climate–related sectors such as agriculture that has an average GDP share of the economy of low-income countries of about 25%. The agricultural sector for USA, Australia and the European Union is 1.4%, 3.3% and 2% respectively (World Organization trade annual: report 2003).

The RICE model (the Regional version of the DICE model as developed by Nordhaus et al 1999) has been used as a tool to examine the impact of the *optimum* sequestration path on low-income countries. The RICE model has predicted that low-income countries would lose about 6% of their economic output in the year 2100 due to the daunting effect of global warming. Based on the RICE model base line, it has been found that utilizing Ocean Nourishment plants to follow the *optimum sequestration path* would save the low-income countries about $6.3 (trillion 1995 US $) as an accumulated benefit in the year 2100. This is equivalent to the projected economic output for this group for one year in the middle of this century. The accumulated total cost of the Ocean Nourishment plants is $1.76 (trillion 1995 US $) with a net benefit of $4.54trillion.

The assessment of the impact of climate change on low-income countries is extremely tentative. For example, the ability of this group to adapt to climate change is still emerging and producing much controversy. Another important factor is the economic growth rate. The RICE model assumes a relatively rapid increase in the economic output of low-income countries in the next few decades. This rapid economic growth is expressed in the fact that the RICE model has predicted that the GDP per capita for low income countries in 2105 is seven times as much as in 1995. This finding is not consistent with the situation now where some low-income countries are getting poorer than in the past. For example GDP per capita for Kenya, Kingston and Venezuela has dropped from $335, $745, $3750 (1995 US $) respectively in 1990 to $320, $476 and $2654 (1995 US $) in 2000 respectively (based on the World Bank figures 2004).

Does the impact of carbon sequestration by Ocean Nourishment depend on an assumed growth in productivity? To answer this question, the economic growth for the low income countries in the RICE model has been taken as a reference and the impact on low-income countries has been studied assuming different rates of economic growth (different productivity growth rates). The increase in the GDP per capita from the 1995 value of $450 induced by Ocean Nourishment for the *optimum sequestration path* has been used as an indicator. Table (3) lists the three productivity rates considered. One can see that the impact of Ocean Nourishment sequestration is low (as a percentage change) when a high rate of growth is assumed. This is primarily due to the fact that a relatively rapid economic growth rate in low income countries would reduce the impact of global warming on the standard of living.

Assumed productivity growth rate	High	Middle	Low
The assumed productivity growth rate (% per decade)	12	6	2
GDP per capita (the base case in 2100)	$3270	$1460	$850
GDP per capita (Ocean Nourishment sequestration 2100)	$3320	$1500	$910
Increase of GDP per capita with Ocean Nourishment sequestration	1.4%	2.3%	6.85%

Table (3): shows the impact of the proposed Ocean Nourishment sequestration path on the low-income countries as a percent increase in the GDP per capita. Note: the RICE model used for GDP per capita for the low income countries in 1995 is $450 (all prices are in 1995 US $)

Abatement cost in the Kyoto protocol framework

Among the different solutions that have been proposed to slow climate change, the Kyoto Protocol represents the only international policy adapted to date. The key element of the Kyoto Protocol is its obligatory formula which states that Annex I countries should individually or on average reduce their emission of GHG by 5% less than the 1990 level within the period of 2008-2012. In this section, the cost-benefit dimensions of the Kyoto Protocol have been studied within the framework of the Ocean Nourishment regime, assuming that the Kyoto Protocol will be applied for ever (*Kyoto forever*).

The RICE model (Regional Version of the DICE model) has predicted the CO_2 emission for different regions of the world and the emission for Annex I members are shown in Table (4).

Year	USA	Europe	OCED	R&EE	Annex I
1995	1.44	0.85	0.58	0.83	3.7
2015	1.73	0.91	0.62	0.82	4.07
2065	1.83	0.0.71	0.54	0.81	3.97
2105	1.87	0.75	0.51	.91	4.07

Table (4) shows the predicted Annex I emission in Gt C per year (by the RICE model). R&EE is Russia and East Europe, OCED is the other high income countries such as Australia and Canada.

One can see from Table (4) that CO_2 emission from the USA is expected to increase by 0.4 Gt by 2065 while the emissions of Europe and the other high income countries are expected to fall by the time due to technological improvements which will lead to a decrease in the carbon intensity. European countries and other high-income countries are expected to meet the Kyoto Protocol at the middle of this century; this means that meeting the Kyoto protocol is very costly for USA, which is expected to carry the highest portion of emission reduction with regard to Kyoto protocol implementation. Figure (6) shows the carbon tax required to meet the Kyoto protocol.

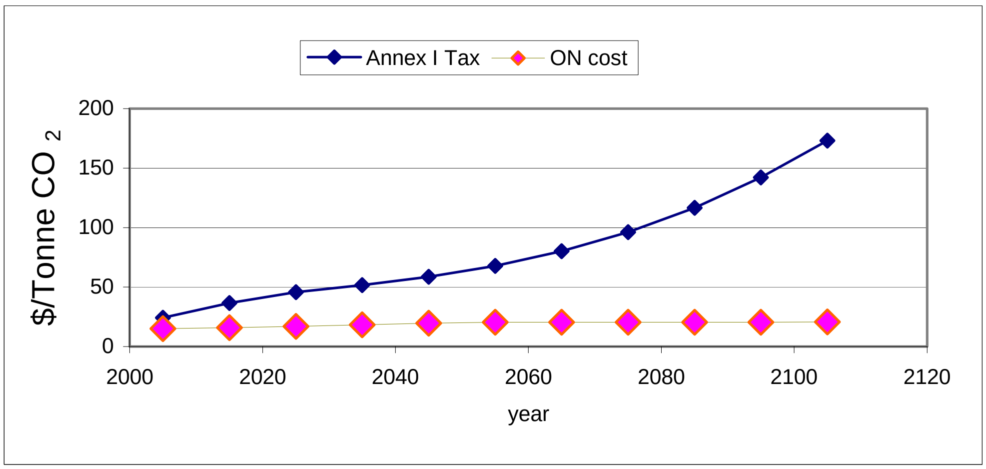

Figure (6): required carbon taxes for Annex I countries under *Kyoto forever*. Calculated using the RICE model by considering the sequestration control rate required by each group to meet the Kyoto Protocol. The higher the *CO_2 control rate*, the higher carbon tax (Cost in US $ for year 1995). The required carbon tax is compared with the carbon credit cost for Ocean Nourishment.

One can see from Figure (6) that the carbon credit offered by Ocean Nourishment is cheaper than that offered by an Annex I trade regime with a cost structure as used by Nordhaus et al (1994). For example in the year 2100, taxation of 180 (1995 US $) /tonne CO_2 is needed by Annex I regions compared with 22 (1995 US $)/tonne CO_2 using Ocean Nourishment. Table (5) shows the predicted required sequestration for the Annex I countries to meet the Kyoto protocol.

Year	Required sequestration (Gt C)
2015	0.39
2065	0.27
2105	0.39
Total	35.9

Table (5): the predicted required yearly CO_2 sequestration by the Annex I countries in order to meet the *Kyoto Protocol Forever* and the total reduction in 2105. (1 tonne CO_2 = 0.27 tonne C)

It can be concluded from Table (5) that 150 Ocean Nourishment plants are needed by Annex I countries to meet the Kyoto Protocol. Each one of these plants will sequester 10 Mt CO_2 (2.5 Mt C) (Shoji and Jones (2001)). Thus 150 Ocean nourishment plants have the potential to sequester 0.375 Gt C annually. These plants will use 2970 PJ (Peta Joule) of coal annually, which equals 4% of the world coal consumption in 2000.

Conclusions

The carbon tax needed to manage the climate by the DICE model has been developed without taking account of the potential of the Ocean Nourishment concept. In this paper we have argued that the carbon credits offered by Ocean Nourishment are more economical than the conventional carbon tax, which is imposed on the economic sectors to force them to reduce their carbon intensity. The cost of mitigation by the carbon tax is set against the benefit of mitigation with the time horizon of the year 2100 while costing is no more than the economic benefit. This framework is then compared with the Ocean Nourishment concept which has been found to be more economical than the taxation model by factor of 2.7.

It also has been found that seeking a CO_2 reduction path with a control rate of more than 10% CO_2 sequestration by the end of this century might not be economically advantageous without adapting the Ocean Nourishment concept. It has been found that the accumulative benefit of following the *optimum sequestration* by using Ocean Nourishment on low income countries may equal one year GDP in the middle of this century. The prediction of a relatively high economic growth – such as that proposed by the RICE model **-** for the low income countries might conceal the real impact of climate change on this group of countries, which is expected to carry the worst burden of climate change. It has also been found that meeting *Kyoto Protocol Forever* demands the construction of about 150 Ocean Nourishment plants. This scenario would provide carbon sinks which are a factor of 3-9 times cheaper than the carbon tax that is predicted in the Nordhaus model.

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