CARBON DIOXIDE SEQUESTRATION: WHEN AND HOW MUCH?

Klaus Keller[1], Zili Yang[2], Matt Hall[3], and David F. Bradford[4,5,6]

[1] Department of Geosciences,
The Pennsylvania State University,
University Park, PA, 16802-2714, kkeller@geosc.psu.edu,
phone: (814) 865-6718, fax: (814) 865-7823.
[2] Department of Economics, SUNY at Binghamton.
[3] Brookings Institution.
[4] Woodrow Wilson School of Public and International Affairs,
Princeton University
[5] Department of Economics, Princeton University.
[6] School of Law, New York University.

Center for Economic Policy Studies (CEPS) Working Paper No. 94
Princeton University
September 2003

Abstract

We analyze carbon dioxide (CO_2) sequestration as a strategy to manage future climate change in an optimal economic growth framework. We approach the problem in two ways: first, by using a simple analytical model, and second, by using a numerical optimization model which allows us to explore the problem in a more realistic setting. CO_2 sequestration is not a perfect substitute for avoiding CO_2 production because CO_2 leaks back to the atmosphere and hence imposes future costs. The "efficiency factor" of CO_2 sequestration can be expressed as the ratio of the avoided emissions to the economically equivalent amount of sequestered CO_2 emissions. A simple analytical model in terms of a net-present value criterion suggests that short-term sequestration methods such as afforestation can be somewhat ($\approx$ 60 %) efficient, while long term sequestration (such as deep aquifer or deep ocean sequestration) can be very ($\geq$ 90%) efficient. A numerical study indicates that CO_2 sequestration methods at a cost within the range of present estimates reduce the economically optimal CO_2 concentrations and climate related damages. The potential savings associated with CO_2 sequestration is equivalent in our utilitarian model to a one-time investment of several percent of present gross world product.

1 Introduction

Anthropogenic greenhouse gas emissions are projected to change future climates and to cause non-negligible economic damages [*Munasinghe et al.*, 1996; *Weyant et al.*, 1996]. Efforts to mitigate the greenhouse gas problem have traditionally focused on avoiding the production of carbon dioxide (CO_2) by reducing fossil fuel use (typically referred to as "CO_2 abatement") [*Nordhaus*, 1992; *Tol*, 1997]. One alternative to CO_2 abatement would be to capture CO_2 emissions and sequester them in carbon reservoirs such as deep aquifers, deep oceans, or minerals [*Lackner et al.*, 1995; *Herzog and Drake*, 1996; *Hoffert et al.*, 2002]. However, large-scale sequestration presents considerable scientific, engineering, and economic problems. One economic problem is that CO_2 sequestration is not a perfect substitute for avoiding CO_2 production. This is because sequestered CO_2 may leak back into the atmosphere and impose future climate damages. In contrast, avoiding CO_2 production would not impose the legacy of CO_2 leakage.

Whether or not CO_2 sequestration should be considered as a viable alternative to CO_2 abatement is an open and much debated question [*Kaiser*, 2000]. Previous studies addressing CO_2 sequestration develop elegant analytical expressions to analyze the tradeoff between CO_2 sequestration and CO_2 abatement (*e.g., Richards* [1997], *van Kooten et al.* [1997], *Herzog et al.* [2003]) or analyze the optimal use of CO_2 sequestration in numerical models (*e.g., Swinehart* [1996], *Biggs et al.* [2000], *Lecocq and Chomitz* [2001]). While breaking important new ground, these studies are silent on important policy questions. For example, the analytical models typically neglect the feedback effects caused by the availability of the CO_2 sequestration technology on future carbon taxes. Also, most numerical models focus on afforestation (which can only play a minor role in reducing climate change [*Nilsson and Schopehauser*, 1995; *Adam*, 2001]). Studies analyzing more powerful sequestration methods ($e.g.$, deep-ocean or deep-aquifer injection) assume negligible marginal costs [*Nordhaus*, 1992], neglect cost reductions as technologies mature, [*Biggs et al.*, 2000; *Herzog et al.*, 2003]), or neglect CO_2 leakage [*Ha-Duong and Keith*, 2002].

Here we expand and improve on the previous work in two respects. First, we refine and apply an analytical model [*Richards*, 1997] by estimating the relevant model parameters and estimating the efficiency factor of CO_2 sequestration. Second, we expand an optimal economic growth model [*Nordhaus and Yang*, 1996] by adding CO_2 sequestration, learning-by-doing, and technological inertia. We use the numerical model to analyze the optimal use of CO_2 sequestration methods and the effects of optimal carbon dioxide levels. Specifically, we ask five questions: (i) What is the tradeoff (or the ratio of marginal benefits) between CO_2 sequestration and CO_2 abatement? (ii) What is the optimal use and timing of sequestration? (iii) How does CO_2 sequestration change the optimal tax path? (iv) How do technological inertia and endogenous learning affect the optimal use of sequestration? and (v) What is the present value of a technology that would provide sequestration in the future?

We propose an economic framework to measure the efficiency of CO_2 sequestration. Specifically, we estimate the net present value of sequestered CO_2, in terms of avoided abatement costs, to meet a specific atmospheric concentration constraint. CO_2 sequestration can replace costly abatement measures in the present and hence has an economic value. However, leaky CO_2 sequestration imposes future costs. The net savings ($i.e.$, the initial savings minus the future costs) relative to the initial savings represents the efficiency factor of CO_2 sequestration. The results from our analytical model suggest that afforestation is somewhat efficient ($\approx$ 60%), while long-term sequestration possibilities, such as deep aquifer sequestration or ocean injection, could be quite efficient ($\geq$ 90%).

The analytical model provides an intuitive and simple method to account for future leakage of sequestered carbon. The simplicity of the analytical model neglects, however, several potentially important effects such as hyperbolic discounting [*Weitzman*, 1998] or learning-by-doing [*Argote and Epple*, 1990]. We address these shortcomings by analyzing a numerical optimal growth model. Our numerical analysis suggests that the availability of a viable sequestration technology can lower carbon taxes and the optimal atmospheric CO_2 concentrations. In the model, CO_2 sequestration at marginal costs within the range of present estimates is deployed in increasing volume to sequester all the industrial CO_2 emissions by the middle of the next century. Learning-by-doing and technological inertia create an “R & D” market for early sequestration, before it is competitive with abatement technologies. Learning-by-doing allows society to “buy-down” the price of sequestration by employing the technology earlier. Technological inertia requires earlier sequestration to achieve large-scale quantitative goals in the next century. The potential economic benefits derived from sequestration are several percent of present-day gross world product (GWP). The results of our analysis are sensitive to several parameters, such as the rate at which learning-by-doing occurs, the maximum rate at which a new technology can penetrate the market, or the rate of carbon leakage.

2 The efficiency factor of CO_2 sequestration: A simple analytical model

The efficiency factor for CO_2 sequestration is a simple measure to analyze the economic tradeoff between CO_2 abatement and CO_2 sequestration. In an optimal policy, different CO_2 control technologies are used such that their marginal social value (shadow price) are equalized. Thus, in a world in which sequestration has a constant efficiency, η, relative to that of abatement, and an optimal tax (t) is levied on all CO_2 emissions (including those that are sequestered), the optimal “refund” levied for each ton CO_2 sequestered should be equal to the product $\eta \cdot t$. As the relative efficiency of sequestration approaches unity (perfect substitute for abatement), the refund approaches full reimbursement. Conversely, in a credit regime for sequestration, the fraction of a full credit corresponding to the fraction of the social value of abatement, η, should be given for each ton sequestered.

Given its importance, the first goal of our analysis is to derive the efficiency factor of CO_2 sequestration to compare sequestered carbon with avoided carbon emissions. For example, 100 tons of sequestered CO_2 would offset 50 tons of avoided CO_2 emissions at an efficiency factor of 50 %. To illustrate the structure of the problem, we start with a simple analytical model, similar to the one developed by *Richards* [1997]. We expand on the analysis of *Richards* [1997] by estimating relevant parameters and by deriving an analytical expression for the economic efficiency of carbon sequestration considering (i) discounting, (ii) changes in future carbon taxes, (iii) leakage, and (iv) an energy penalty of carbon sequestration. As we illustrate in the subsequent section, many conclusions derived from this simple model are valid in a more realistic numerical model.

The tradeoff between CO_2 abatement and CO_2 sequestration is affected in our analytical model by four factors: (i) the additional energy requirement; (ii) the CO_2 leakage over time; (iii) the changes over time in marginal abatement costs; and (iv) the discount rate. In the following section we develop simple closed form solutions to represent these factors and derive an expression for the efficiency factor of CO_2 sequestration. For analytical convenience, we approximate the problem by an infinite horizon problem.

The first factor accounts for the energy requirement of CO_2 sequestration. The additional energy is derived by burning more fossil fuel and thus imposes an "energy penalty". The relative "energy penalty" (λ) is the consequence of the energy-intensive nature of capturing, transporting, and sequestering CO_2 emissions. λ is defined as the relative increase in fossil fuel use due to CO_2 capture and sequestration. The relative increase in CO_2 emissions that must be sequestered to yield the same amount of energy for end use is:

$$\frac{1}{1-\lambda}. \tag{1}$$

Some fraction of the sequestered CO_2 will leak back to the atmosphere. We approximate the leakage by an exponential decay of the sequestered CO_2 stock. The leakage flux of on ton of CO_2 over time $(l(t))$ is then a function of the decay rate (ζ) and the energy penalty (λ):

$$l(t) = \frac{\zeta}{1-\lambda}\, e^{-\zeta\, t}, \tag{2}$$

where t starts at the time of sequestration.

For the analytical model, we assume an agreed upon atmospheric CO_2 stabilization path. Associated with this stabilization path is a path of allowable CO_2 emissions. The marginal CO_2 abatement costs over time are then a function of the CO_2 reductions over time and the available abatement technologies with their associated marginal costs. If we think about the CO_2 stabilization path as implemented by the application of an emissions tax, this carbon tax would follow the same path as the marginal abatement costs, in this stylized example. For the agreed upon CO_2 stabilization path, any leakage has to be compensated by increased abatement. Because CO_2 abatement is costly, CO_2 leakage imposes additional costs in the future. The additional costs are approximated — in a partial equilibrium sense — by the carbon tax times the leakage flux.

We estimate future carbon taxes by fitting a simple exponential function to results from an optimal growth model. We use the RICE model [*Nordhaus and Yang*, 1996] to estimate carbon taxes that correspond to an optimal emissions path subject to atmospheric concentration stabilization targets. For CO_2 stabilization targets between 450 ppm and 750 ppm, the constraint optimal carbon taxes are well approximated for the next two centuries by exponential functions. The carbon taxes over time (mc) are hence approximated as:

$$mc(t) = \beta_0 \, e^{\beta \, t}, \tag{3}$$

where β_0 is the initial carbon tax in U.S.\$ per ton of C and β is the carbon tax growth rate. Note that the optimal abatement costs at the margin are equal to the optimal carbon tax given the assumed perfect markets. The carbon taxes are projected to increase over time mostly because the positive marginal productivity of capital as well as the free service of the natural carbon sinks favor later abatement measures. The last assumption required for the analytical model is to discount future costs by a discount factor (d),

$$d(t) = e^{-r \, t}, \tag{4}$$

where r is the discount rate.

Deriving the efficiency factor of a leaky CO_2 sequestration project is now an exercise of calculating the net present value of the project and relating it to the costs of the alternative choice of carbon abatement. Technically, the net benefit of sequestered CO_2 at time zero is the avoided carbon tax (β_0), minus the present value of future costs imposed by the CO_2 leakage. The net benefits per ton of CO_2 sequestered can be expressed by:

$$\text{net benefit} = \beta_0 - \int\limits_{t=0}^{t=\infty} e^{-r \, t} \, \beta_0 \, e^{\beta \, t} \, \frac{\zeta}{1-\lambda} e^{-\zeta \, t} \, dt, \tag{5}$$

which can be solved analytically for $r + \zeta - \beta > 0$. (Otherwise, the costs of leakage grow faster than the rate at which they are discounted and the present value sum of costs will exceed all benefits derived from the ton of sequestered CO_2.) The solution for the net benefit is:

$$\text{net benefit} = \beta_0 \, (1 - \frac{\zeta}{(r + \zeta - \beta) \, (1 - \lambda)}). \tag{6}$$

The expression in parentheses reduces the initial project benefit at no leakage (the marginal abatement costs at the time of sequestration) and can be interpreted as an “efficiency factor of CO_2 sequestration”. We hence rewrite equation (6) as:

$$\eta = \frac{\text{net benefit}}{\text{initial carbon tax}} = (1 - \frac{\zeta}{(r + \zeta - \beta) \, (1 - \lambda)}), \tag{7}$$

where η is the efficiency factor of sequestration calculated by the ratio of net benefit from a CO_2 unit sequestered to the net benefit of a CO_2 unit of avoided emissions. Note that the efficiency factor of sequestration is also equal to the ratio of the marginal benefits of sequestration to the marginal benefits of abatement in the adopted optimal growth framework.

This simple efficiency model is a stylized representation of the complex interactions between sequestration and human welfare. However, such a framework may be preferable to alternative weighting schemes that measure efficiency in terms of carbon that neglect issues such as the marginal productivity of capital or CO_2 leakage beyond an arbitrarily chosen time horizon [*Fearnside et al.*, 2000; *Costa and Wilson*, 2000]. Although this analytical model gives us some insight into the economic tradeoffs involved with CO_2 sequestration, it has several shortcomings. First, the partial equilibrium assumption implicit in the fixed carbon tax path is only reasonable for very small-scale use of CO_2 sequestration. This is because large-scale CO_2 sequestration would affect the carbon tax path which we assume to be unaffected. Second, our analytical model neglects mechanisms such as hyperbolic discounting [*Weitzman*, 1998], backstop technologies [*Manne and Richels*, 1991], or technological inertia [*Grübler et al.*, 1999]. We shall analyze these effects in the more realistic numerical model developed below.

3 The optimal use of CO_2 sequestration: An optimal growth model

We use the Regional Integrated Model of Climate and the Economy (RICE) [*Nordhaus and Yang*, 1996] as a starting point. This optimal growth model links the global climate and economic system by simple feedbacks. The current model version (RICE-01) differs from the original RICE-96 [*Nordhaus and Yang*, 1996] model in two ways. First, we have updated the model parameters to be consistent with recent work *Nordhaus and Boyer* [2000]. Second, we modify the model to account for carbon sequestration, technological inertia, and learning-by-doing. In the following sections we give a brief overview of the model structure and how we incorporate carbon sequestration, technological inertia, and learning-by-doing.

3.1 The RICE model

The RICE model links climatic relationships between atmospheric CO_2 concentration and net global radiative forcing to economic relationships between consumption and investment in capital. The RICE model aims to maximize the discounted sum of utility derived from generalized consumption over a given time horizon.

The economic component of the RICE model is a Ramsey type model of economic optimal growth [*Ramsey*, 1928]. In the Ramsey model, a social planner chooses paths of consumption (C) and investment to maximize an objective function U^*. In the RICE model, the objective function is the weighted sum of the natural logarithm of per-capita consumption with the weighting factors population level (L), a factor accounting for the “pure rate of social time preference” ρ, and the “time-variant Negishi weights” Ψ:

$$U^* \;=\; \sum_{n}^{N}\sum_{t=0}^{t^*} \Psi(n,t)\;\ln(\frac{C(n,t)}{L(n,t)})\;L(n,t)\;(1+\rho)^{-t}. \tag{8}$$

The Negishi weights are an instrument to account for regional disparities in economic development. They equalize the marginal utility of consumption in each region for each period in order to prevent large capital flows between regions. This technique is descriptive rather than prescriptive; although the choice of utility function implies that such capital flows would greatly improve social welfare, without the Negishi weights the problem of climate change would be drowned by the vastly larger problem of underdevelopment. A detailed exposition of Negishi weights is given in *Nordhaus and Yang* [1996] and the references cited therein.

In this equation, the term $\ln(\frac{C(n,t)}{L(n,t)})$ represents the flow of utility at time t for region n and the summation occurs from some starting point $t = 0$ to a finite time horizon t^*. The finite time horizon is required by the numerical solution technique. It is, however, just a numerical approximation to an infinite horizon problem as used in the analytical model (equation 5). The finite time horizon is chosen such that the end point has no significant effect on the policy decision in the analyzed time frame.

Investment (I) in capital is specified in the model as the balance of output (Y) that is not devoted to consumption in a given time period:

$$Y(n,t) = C(n,t) + I(n,t). \tag{9}$$

Investment contributes to the capital stock (K) of the next period, which then depreciates at a constant proportional rate (ς) over time:

$$K(n,t+1) = (1-\varsigma)K(n,t) + I(n,t). \tag{10}$$

At each point in time, the capital stock and labor supply (which is exogenously specified) influence gross world product. In RICE, this relationship is expressed by a modified Cobb-Douglas function:

$$Y(n,t) = \Omega(n,t)A(n,t)K(n,t)^{\gamma}L(n,t)^{1-\gamma}. \tag{11}$$

In the model, gross world output depends on exogenously and endogenously evolving elements. The exogenous elements are the multi-factor productivity (A), the population level, and the constant share of capital (γ) in the economy. The endogenously determined elements are capital and a scaling factor (Ω), which accounts for the costs from investing in carbon mitigation technologies and climate-related damages, as discussed below.

The economic and the natural systems are linked in the model by the anthropogenic CO_2 emissions

(E). The CO_2 emissions depend on the economic output, the exogenously determined energy-intensity of GWP (σ), the CO_2 abatement rate (μ), and the exogenously evolving land-use CO_2 emissions (O) according to:

$$E(n,t) = \sigma(n,t)Y(n,t)[1-\mu(n,t)] + O(n,t). \tag{12}$$

Without carbon mitigation the carbon emissions follow a baseline "business as usual" (BAU) scenario. Increasing relative CO_2 abatement imposes increasing relative abatement costs (B):

$$B(n,t) = b_1(n)\mu(n,t)^{b_2(n)}, \tag{13}$$

with $b_1(n)$ and $b_2(n)$ being model parameters. CO_2 emissions act to increase the atmospheric CO_2 stock (M_{at}). However, increased CO_2 concentrations in the atmosphere drive some proportion into the upper ocean (M_{up}). Eventually most of a given CO_2 pulse emitted into the atmosphere is absorbed by the deep-ocean (M_{lo}) according to a first-order linear model defined by:

$$M_{at}(t+1) = \sum_n E(n,t+1) + b_{11}\ M_{at}(t) + b_{21}\ M_{up}(t), \tag{14}$$

$$M_{up}(t+1) = b_{12}\ M_{at}(t) + b_{22}\ M_{up}(t) + b_{32}\ M_{lo}(t), \tag{15}$$

and

$$M_{lo}(t+1) = b_{23}\ M_{up}(t) + b_{33}\ M_{lo}(t). \tag{16}$$

The variables $b_{i,j}$ are the entries in the carbon cycle model transition matrix [*Nordhaus and Boyer*, 2000].

Atmospheric CO_2 levels above the preindustrial level of 590 Gigatons of carbon cause a net radiative greenhouse gas forcing (F):

$$F(t) = 4.1\ \ln[M_{at}(t) - 590]/\ln(2), \tag{17}$$

where the factor of 4.1 is the change in radiative forcing due to a doubling of atmospheric CO_2 concentrations. Note that physical variables, such as the atmospheric CO_2 stock or temperature, are all global in the model. As such, temperature change in the model is really the temporal and spatial average of the change in global surface temperature. Increased radiative forcing is translated into global mean temperature change (T) by a simple climate model:

$$T(t) = T(t-1) + (\sigma_1)[F(t) - \lambda' T(t-1) - (\sigma_2)(T(t-1) - T^*(t-1))]. \tag{18}$$

In this equation $\frac{1}{\sigma_1}$ denotes the thermal capacity of the oceanic mixed layer and λ' is the climate feedback parameter. The climate sensitivity (λ^*) of the model is defined as the equilibrium temperature response to a doubling of atmospheric CO_2. The climate sensitivity is given by $\lambda^* = \frac{\Delta\ F_{2xCO_2}}{\lambda}$, where $\Delta\ F_{2xCO_2}$ is the radiative forcing caused by a doubling of CO_2. The parameter σ_2 represents the ratio of the heat capacity of the deep ocean to transfer rate from the oceanic mixed layer to the deep ocean. T^* is the deviation of the deep-ocean temperature from the preindustrial level approximated by:

$$T^*(t) = T^*(t-1) + (\sigma_3)(T(t-1) - T^*(t-1))]. \tag{19}$$

To complete the circle linking climate to the economy, temperature changes (T, equation 18) cause economic damages (D), which are specified as a fraction of the gross world product:

$$D(n,t) = a_1(n)\,T(t) + a_2(n)\,T(t)^2. \tag{20}$$

The costs of carbon management and the climate damages are subtracted from the gross world product, thereby determining the scaling factor Ω:

$$\Omega(n,t) = 1 - D(n,t) - B(n,t). \tag{21}$$

3.2 Representation of CO_2 Sequestration

We add sequestration as an additional carbon management option to the standard abatement option considered in the original RICE-01 model. The carbon sequestration flux (S) is removed from industrial emissions ($E - O$) and stored in a carbon reservoir (M_{re}) from which it leaks back into the atmosphere following an exponential decay:

$$M_{re}(t+1) = \sum_n S(n,t+1) + b_{44}\ M_{re}(t). \tag{22}$$

All sequestered carbon is presumed in this exercise to enter the same reservoir; this is mathematically equivalent to an arbitrary number of reservoirs for our assumption of a linear rate of decay. The original equation describing the atmospheric CO_2 budget (14) is hence modified as:

$$M_{at}(t+1) = \sum_n [E(n,t+1) - S(n,t+1)] + b_{11}\ M_{at}(t) + b_{21}\ M_{up}(t) + b_{41}\ M_{re}(t). \tag{23}$$

Sequestration is represented as a carbon backstop technology, similar to the representation of non-abatement options in previous economic models ($e.g.$, *Ward* [1979], *Manne et al.* [1995]). A backstop technology implies that the marginal costs of sequestering CO_2 can be approximated as independent of the sequestered quantity. This somewhat crude approximation might be justified because the capacity of carbon sequestration methods (such as injection into deep aquifers, the deep oceans, or CO_2 absorption out of the atmosphere) exceeds the necessary CO_2 emission reductions [*Elliot et al.*, 2001; *Herzog et al.*, 2001; *Ha-Duong and Keith*, 2002]. Note that the CO_2 sequestration method based on CO_2 absorption out of the air [*Lackner*, 2003] is a very close approximation to the type of backstop technology considered here, as the marginal costs are rather insensitive to the fraction of anthropogenic CO_2 emissions being sequestered.

In the model, we subtract the product of the CO_2 sequestration flux and the marginal sequestration costs ($V(t)$) from world output. The original production function (equation 11) is hence modified according to:

$$Y(n,t) = \Omega(n,t)A(n,t)K(n,t)^{\gamma}L(n,t)^{1-\gamma} - S(n,t)V(t). \quad (24)$$

Sequestration becomes an additional choice (besides CO_2 abatement and capital investment) to maximize the objective function. We neglect the possibility that CO_2 sequestration might occur out of the atmosphere. As a result, sequestration fluxes have to be below the industrial emissions.

Present estimates of the marginal costs of CO_2 sequestration vary widely and are primarily based on theoretical calculations. Given the considerable technological and logistical challenges of large scale CO_2 sequestration, the cost estimates have to be taken with a grain of salt. *Williams* [2003], for example, considers an integrated gasification combined cycle power plant using coal. For hydrogen production, the marginal cost of CO_2 sequestration is estimated as roughly 50 U.S.$ per ton C. For electricity production, the estimated marginal costs are around 100 U.S.$ per ton C. For comparison, *Chiesa and Consonni* [2000] analyze natural gas-fired combined cycle power plants and estimates that carbon taxes between roughly 125 to 180 U.S.$ per ton C would render the CO_2 sequestration option competitive. We adopt a marginal cost for large scale carbon sequestration of 100 U.S.$ per ton C as our central estimate and explore the implications of this parameter uncertainty in a sensitivity study (discussed below).

3.3 Representation of Learning-by-Doing

Technological improvements resulting from large-scale manufacture of various technologies have been shown to decrease the costs of those technologies in a phenomenon typically referred to as "learning-by-doing" [*Argote and Epple*, 1990]. Learning-by-doing is especially important for relatively new technologies such as CO_2 sequestration. To represent learning-by-doing for CO_2 sequestration, the cost of sequestering one ton of carbon dioxide (V) decreases in our model as a function of cumulative installed capacity (cc) according to:

$$cc(t+1) = cc(t) + \sum_{n} S(n,t). \quad (25)$$

and

$$V(t) = V_0[\frac{cc(t)}{cc(t_0)}]^{-\nu}. \quad (26)$$

Note that the above equation implies that cumulative capacity is irrespective of the region in which the capacity is installed, meaning that cost-reducing technologies developed in each region are perfectly shared.

The cost curve is characterized by an exponent (ν) that is a function of the “progress ratio” (pr):

$$\nu = -\frac{\ln(pr)}{\ln(2)}. \tag{27}$$

The progress ratio is defined as the relative costs after a doubling of the installed capacity. We assume a progress ratio of 85% to represent technologies between the research and development phase and the commercialization phase [*Grübler et al.*, 1999]. As initial installed capacity, we assume 10 Gt C to represent a relatively immature technology.

Introducing learning-by-doing can introduce local maxima into the underlying optimization problem [*Messner*, 1997]. Basically, the technologies can be trapped in a local basin of attraction if the existing mature technology is cheaper than the new (but initially more expensive) technology. The local maxima can severely limit the applied local search algorithm implemented in GAMS/MINOS [*Brooke et al.*, 1998]. We test whether the solution is a local (as opposed to a global) solution by starting the model simulations at different initial conditions for abatement and sequestrations for the base case. The fact that all model simulations converge to basically the same result argues strongly against the existence of relevant local maxima in the objective function. The model is formulated in GAMS [*Brooke et al.*, 1998] and is available from the authors.

3.4 Representation of Technological Inertia

Market penetration rates of new technologies are limited by factors such as capital turnover or diffusion of knowledge. The penetration rates of technologies such as natural gas, cars, or oil can be approximated as an exponential increase of delivered quantity [*Grübler et al.*, 1999]. Thus a constant maximum allowable growth rate seems an appropriate constraint to prevent the obviously unrealistic strategy of an instantaneous scale-up of sequestration. An instantaneous scale-up would imply infinite penetration rates, inconsistent with the observations.

Historical rates of market penetration can be quite high. For example, the growth rate of the energy supplied by gas has been around 7.5 % per year in the U.S. over the last 150 years (see *Grübler et al.* [1999]). However, because of the extensive infrastructure necessary for large-scale carbon sequestration, it seems more appropriate to compare it to other infrastructure-intensive technologies (such as railroads), which require more time to penetrate the market. For this reason we choose a growth constraint of 5 % per year for carbon sequestration in our model. The increase in CO_2 sequestration over time is hence constrained by a maximum allowable growth rate (α):

$$S(n, t+1) \leqslant (1+\alpha) S(n, t). \tag{28}$$

The growth constraint for CO_2 sequestration given above is region-specific. Thus, while cost reductions from technological advances can be shared between regions, the increases in capacity to sequester emissions can not: each region must invest time and resources into the necessary infrastructure to sequester CO_2.

4 Results and Discussion

4.1 Analytical Model

We first examine results derived from the analytical model (equation 7) to illustrate some general properties of the problem. As an instructive example, consider the efficiency factor of afforestation. We choose economic parameter values which approximate the optimal policy in the RICE model, resulting in a discount rate of 5 % year^{-1} and a carbon tax growth rate of 1.5 % year^{-1} (consistent with concentration stabilization at 650 ppm). We further assume a half-life time of carbon in newly planted forests of 40 years, and an energy penalty of 10%. This yields an efficiency factor of 61%. For comparison, deep aquifer sequestration (assuming a half-life time of 1000 years and an energy penalty of 15%) would have an efficiency factor of more than 95%.

This simple model suggests four main conclusions. First, a higher discount rate increases the efficiency factor by lessening the present-value costs associated with future leakage. Second, a higher energy penalty decreases the efficiency factor by an increase in overall energy production. Third, smaller reservoir half-life times (equivalent to larger leakage rates) decrease the efficiency factor by allowing carbon to escape sequestration earlier (Figure 1). And fourth, a higher carbon tax growth rate decreases the efficiency factor by increasing the cost of cutting emissions to compensate for leaked CO_2.

4.2 Optimal Economic Growth Model

The analytical model is useful to express the tradeoff between sequestered and abated CO_2 emissions in a closed form solution. The simplicity of the analytical model comes, however, at the price that the system has to be extremely simplified. For example, the analytical model neglects the effects of (i) learning-by-doing, (ii) hyperbolic discounting, (iii) technological inertia, and (iv) the availability of the carbon backstop technology on optimal carbon taxes. We use the numerical model to analyze these effects.

The first question we address with the numerical model is how the availability of the CO_2 sequestration technology affects optimal carbon taxes. To isolate this effect, we use exponential discounting, neglect the technological inertia constraints and learning-by-doing. CO_2 sequestration is available at a constant marginal cost of 100 U.S.$ per ton C and a reservoir half-life time of 200 a. The optimal carbon taxes for this simulation in the case without sequestration, with perfect sequestration and with a “leaky” sequestration are shown in Figure 2.

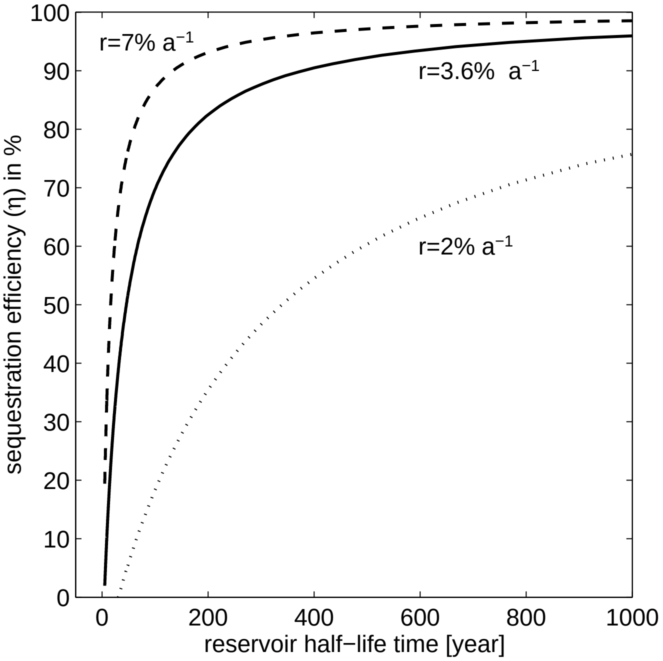

Figure 1: Relationship between the reservoir half-life time of a sequestration project and its efficiency factor (η) (equation 7 in the text) for different discount rates (r).

In this example, the optimal carbon tax increases in all three cases in the next 150 years and approaches the marginal costs of carbon sequestration. If carbon sequestration is not available, the carbon tax continues to rise. If a perfect backstop technology such as non-leaking carbon sequestration without a technological inertia constraint is available, the carbon taxes are bound by the backstop price (equal to 100 U.S.$ per ton C in this example).

Sequestration acts here as a backstop technology by forcing the marginal cost of abatement to remain below a flat price. In the case where CO_2 sequestration is the perfect substitute for abatement ($i.e.$, no leakage), society is indifferent between the two technologies as soon as the marginal costs of abatement and sequestration are equal ($i.e.$, at the intersection of the abatement costs curve with the flat sequestration cost curve at 100 U.S.$ per ton C shown in Figure 2). In the case where CO_2 sequestration results in future CO_2 leaks, it is not a perfect substitute for abatement. As a result, leaky CO_2 sequestration is only used at a higher carbon tax than the marginal cost of the technology. Since CO_2 sequestration is *not* a perfect substitute for abatement, it is worth less in the optimal growth framework, and the price at which carbon sequestration is used exceeds the marginal costs of $100 per ton. In fact, the ratio of the marginal cost of sequestration to the marginal cost of abatement when both are used represents the efficiency factor of sequestration introduced before. Reassuringly, the estimated sequestration efficiencies agree quite well between the analytical and the numerical model. (The values are 78 to 86% in the numerical model compared to 84% in the analytical model using the same model parameters.) This implies that the optimal choice between CO_2 sequestration and CO_2 abatement in this simplified example is well approximated by the analytical efficiency factor derived in equation (7).

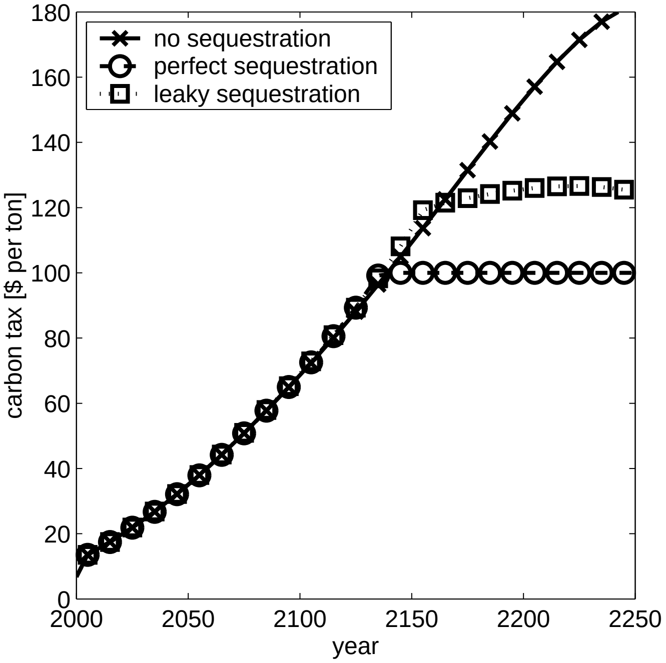

Figure 2: The effect of CO_2 sequestration (with and without CO_2 leakage) on optimal carbon taxes. See text for details.

We now analyze the effects of hyperbolic discounting, learning curves, and technological inertia. Our model suggests that technological inertia, hyperbolic discounting and learning-by-doing all act to increase the optimal use of carbon sequestration in the near future (Figure 3).

In this simulation, two phenomena are driving earlier use of sequestration. First, employing the relatively new technology of CO_2 sequestration, reduces the future marginal costs. This effect is more important for relatively new technologies. Second, sequestering carbon in small amounts early on allows the scale up in time to achieve sequestration of all industrial emissions early in the next century (Figure 3).

The introduction of sequestration technologies can dramatically reduce the optimal atmospheric concentration of CO_2, depending on the marginal cost of CO_2 sequestration (Figure 4).

With a relatively expensive CO_2 sequestration technology (for example 150 U.S.$ per ton C) CO_2 sequestration is not used and the atmospheric CO_2 concentrations exceed 750 ppmV in 2250. For a CO_2 sequestration cost of 100 U.S.$ per ton C (the central estimate), CO_2 sequestration is used and the peak of the optimal CO_2 trajectory decreases to less than 550 ppmV (Figure 4). The secondary increase in CO_2 concentration in the long run (Figure 4A) is due to the relatively early leakage of sequestered CO_2 at the 200 year reservoir half-life time. For a 2000 year reservoir half-life time, the optimal CO_2 concentrations do not show this secondary increase (Figure 4B). Note that the optimal CO_2 paths for arguably realistic assumptions about present CO_2 sequestration costs can be considerably lower than previous optimal growth analyses ($e.g.$, *Tol* [1997] or *Nordhaus and Boyer* [2000]).

Cheaper climate control strategies can improve the weighted sum of present and future welfares (equation 8) by reducing the marginal control costs. In an optimal growth framework, reduced marginal control

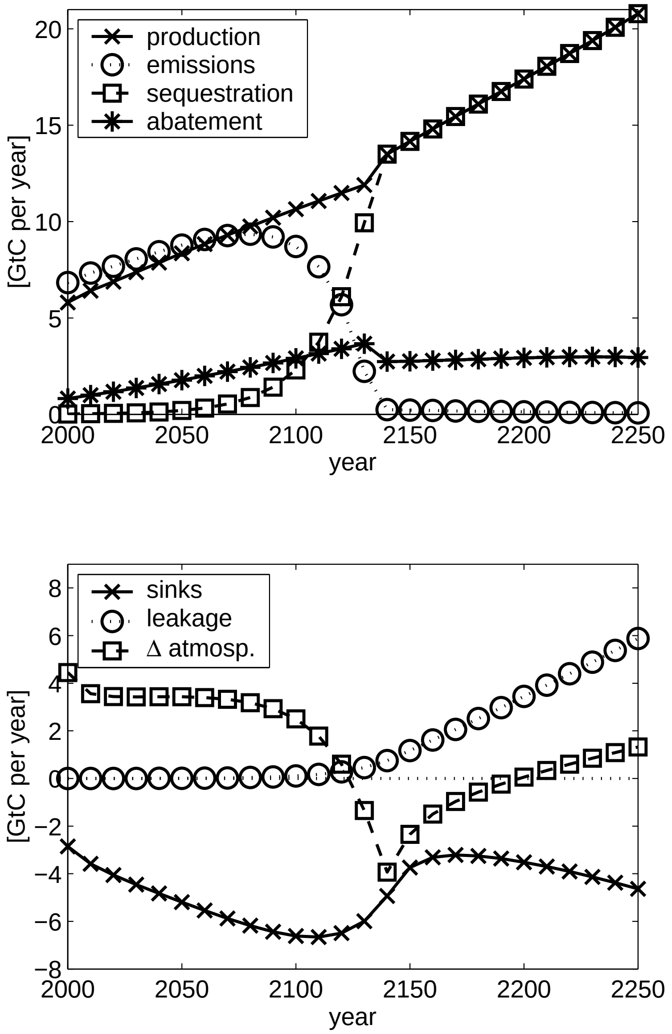

Figure 3: Optimal carbon fluxes over time for the base case. The simulations assume (i) hyperbolic discounting, (ii) a technological inertia constraint, (iii) learning-by-doing, (iv) an initial CO_2 sequestration cost of 100 U.S.$ per ton C, and (v) a reservoir half-life time of 200 years. The emissions in the upper panel include the CO_2 emissions due to land-use changes (equation 12). See text for details.

costs result in reduced global warming (Figure 5a) and, in turn, in reduced climatic damages.

CO_2 sequestration can hence be a valuable technology. We use the optimal growth framework to estimate the economic value of the sequestration option as a function of initial price and reservoir half-life time (Figure 5b). The value of the CO_2 sequestration technology is estimated by the amount a social planner would be willing to pay today for a sequestration technology. The value of a CO_2 sequestration technology is high when sequestration is relatively cheap, nearly 6 % of present-day GWP at $50 U.S.$ per ton C and a reservoir half life time of 200 years. In other words, a budget of 6 % of present GWP (as a one time investment) to successfully develop a CO_2 sequestration technology at a marginal cost of $ 50 U.S.$ per ton C and a reservoir half life time of 200 years would pass a cost-benefit test in our model. The value of CO_2 sequestration technologies increases with cheaper options and with longer reservoir half life times.

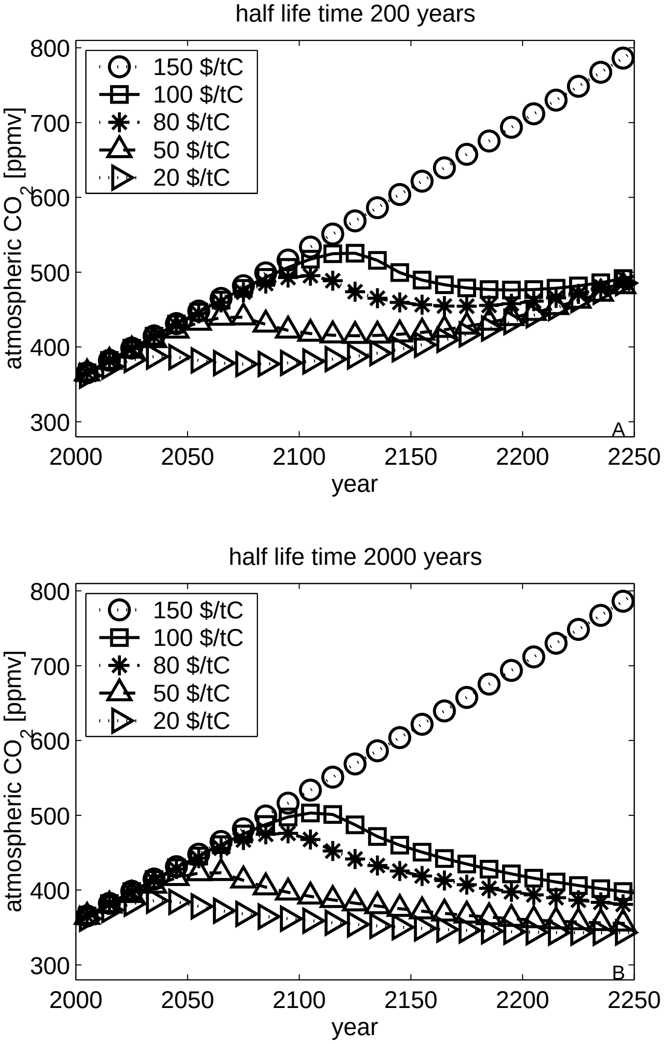

Figure 4: Optimal CO_2 trajectories as a function of initial CO_2 sequestration costs and reservoir half-life time. The upper panel (A) assumes a reservoir half-life time of 200 years. The lower panel (B) assumes a half-life time of 2000 years.

The benefits of CO_2 sequestration would justify a subsidy for this technology in the optimal economic growth model. This is illustrated in the marginal CO_2 abatement costs for CO_2 sequestration and abatement along an optimal path (Figure 6).

In this example, CO_2 sequestration is used even if it is (initially) more expensive than CO_2 abatement. The use of the more expensive CO_2 sequestration option is justified because the learning-by-doing reduces the unit costs for the relatively new technology. In this example, it is optimal to subsidize early CO_2 sequestration.

In Figure 6, sequestration is used early on, even though it is initially more expensive than abatement. Such use drives down the cost of future CO_2 sequestration while capacity ramps up by the maximum rate at which new technologies can penetrate the market (equation 28). Around the year 2150, the capacity for CO_2 sequestration is large enough that essentially all industrial emissions can be sequestered. By then

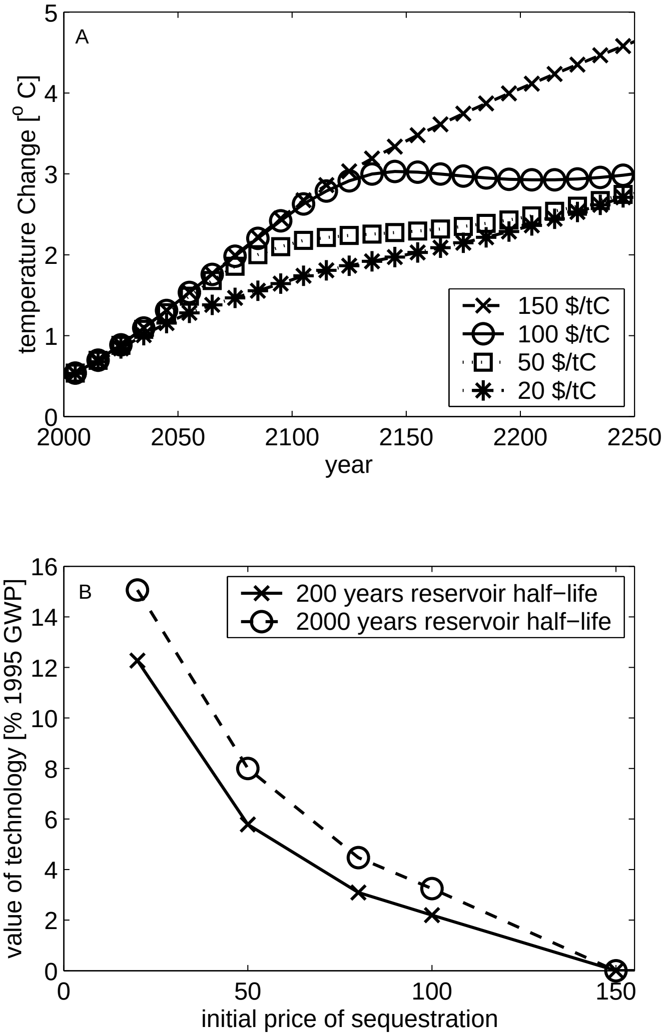

Figure 5: Effect of different initial CO_2 sequestration costs on optimal temperature changes and the value of the sequestration technology. Shown are the optimal temperature changes for half-life time of 200 years (upper panel, A). The lower panel (B) gives the value of CO_2 sequestration technologies as a function of initial price and reservoir half-life time.

sequestration technologies have matured in the model to the point that cost reductions from increased cumulative capacity are small, and we get the relationship that we would expect between the price of sequestration and the price of abatement as derived in our analytical model and illustrated in Figure 2. The ratio of these marginal costs is the marginal economic efficiency of sequestration relative to abatement. Clearly, early sequestration efforts are quite valuable in this example. In the near term, the marginal sequestration costs are above the marginal abatement costs as specified by the initial conditions in the model. In the optimal policy, the marginal costs for the optimal use of CO_2 decline due to learning-by-doing. In the long run, the marginal costs for optimal CO_2 sequestration fall below the marginal costs for optimal CO_2 abatement because leaky CO_2 sequestration is inefficient (due to leakage) and hence has a lower shadow value than CO_2 abatement (similar to Figure 2).

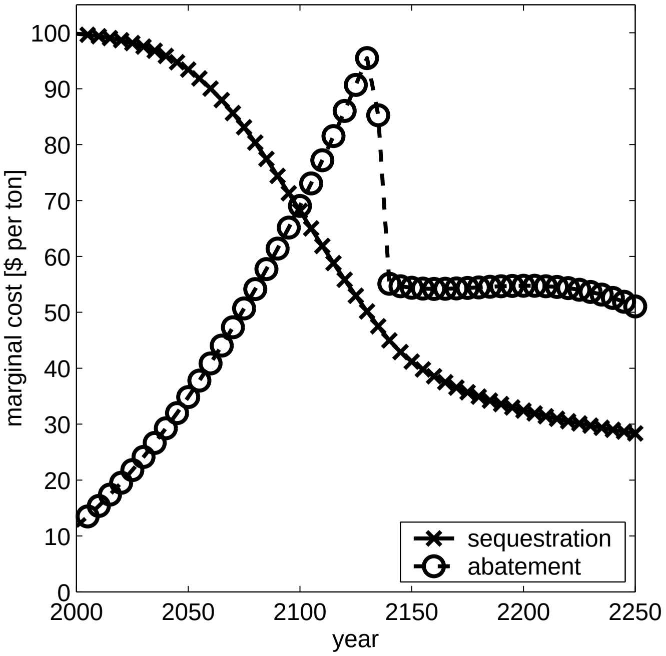

Figure 6: Marginal costs for CO_2 sequestration (stars) and CO_2 abatement (circles) for an initial sequestration price of 100 U.S.$ per ton C.

5 Caveats

Our analysis is subject to considerable parameter uncertainty and the results are — of course — sensitive to the chosen parameters. We explore some effects of parameter uncertainty by a simple scenario analysis. (Note that this approach still assumes perfect knowledge within each scenario). We examine the sensitivity of the optimal CO_2 trajectories with respect to the technological inertia, the progress ratio, and the present experience in CO_2 sequestration. This sensitivity analysis suggests that the model conclusions are very sensitive to the constraint on technological inertia and the progress ratio, but are less sensitive to the present experience in CO_2 sequestration (Figure 7). It is somewhat reassuring that the alternative choices of model parameters shown in Figure 7 do not considerably affect the optimal trajectories of CO_2 and carbon taxes over the next few decades.

Our models as nothing more than thinking tools to analyze the interactions of the social and natural system in a consistent way. Important limitations of our analysis include the limited treatment of uncertainty and the crude approximations of the natural and economic system. Finally, it is important to recall two of our main assumptions. (i) CO_2 sequestration is both available and safe in large quantities; (ii) Decisions are based on a discounted utilitarian framework.

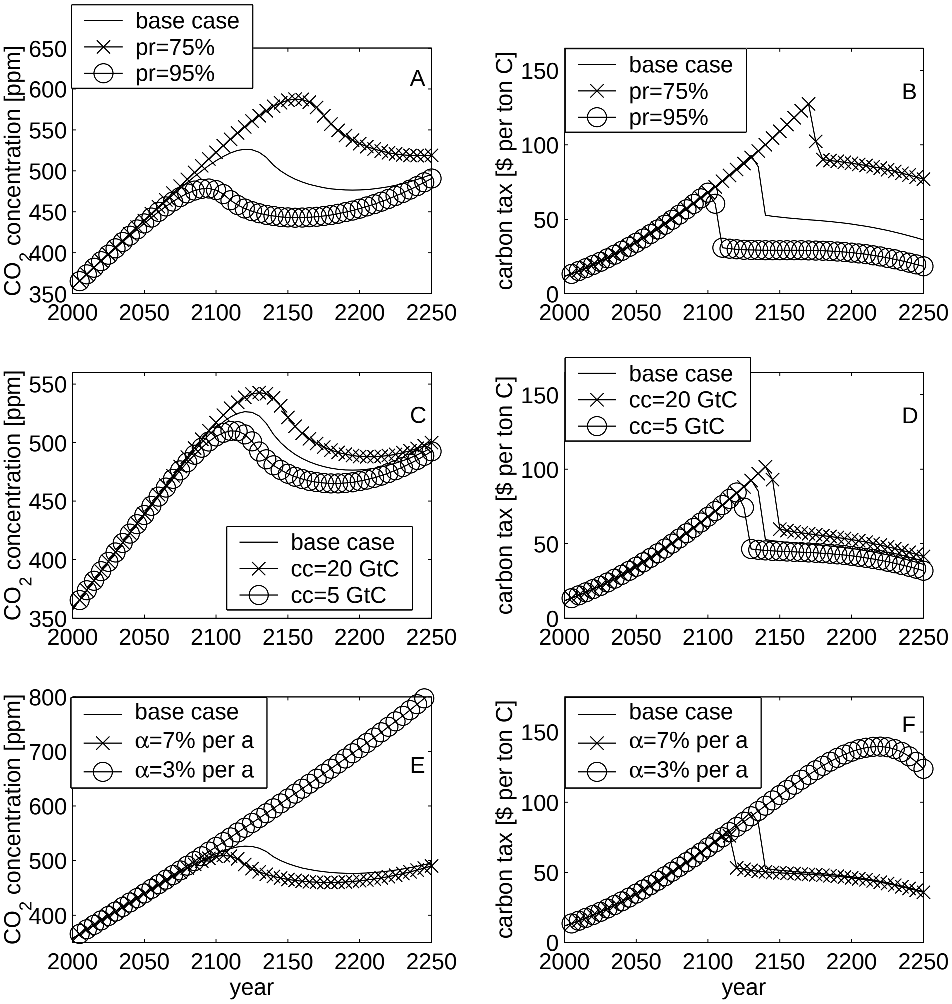

Figure 7: Sensitivity study with respect to the representation of the progress ratio (panels A and B, parameter *pr*, as defined in equation 27), the initial installed cumulative base of CO_2 sequestration (panels C and D, parameter *cc*, as defined in equation 25), and the technological inertia (panels E and F, parameter α, as defined in equation 28). Each sensitivity study compares the base case with a high and low value for the parameter in question.

6 Conclusions

Our analysis suggests three main conclusions. First, the analysis of the net present value of CO_2 sequestration yields an expression for the efficiency factor which seems preferable to previous carbon accounting methods. Second, a subsidy for the initially noncompetitive technology of CO_2 sequestration can be a sound economic policy. Subsidies for CO_2 sequestration can help to overcome technological inertia, to reduce marginal costs via learning-by-doing, and to increase per capita consumption. Third, and finally, CO_2 sequestration presents a potential low-cost solution to the greenhouse gas problem. CO_2 sequestration could reduce mitigation costs and climate damages considerably.

Acknowledgments Financial support from the Carbon Mitigation Initiative at Princeton University and the Environmental Consortium at Penn State is gratefully acknowledged. We are grateful to S. Pacala, M. Oppenheimer, R. Socolow, and B. Williams for helpful discussions. Any remaining mistakes are solely the responsibility of the authors.

References

Adam, D., Royal society disputes value of carbon sinks, *Nature, 412*, 108, 2001.

Argote, L., and D. Epple, Learning curves in manufacturing, *Science*, *247*, 920–924, 1990.

Biggs, S., H. Herzog, J. Reilly, and H. Jacoby, Economic modeling of CO_2 capture and sequestration, presented at the Fifth International Conference on Greenhouse Gas Control Technologies, Cairns, Australia, August 13 - August 16, 2000.

Brooke, A., D. Kendrick, A. Meeraus, and R. Raman, Gams a user's guide, 1998.

Chiesa, P., and S. Consonni, Natural gas fired combined cycles with low co_2 emissions, *Journal of Engineering for Gas Turbines and Power-Transactions of the Asme, 122*(3), 429–436, 2000.

Costa, P. M., and C. Wilson, An equivalence factor between CO_2 avoided emissions and sequestration - description and applications in forestry, *Mitigation and Adaptation Strategies for Global Change, 5*, 51–60, 2000.

Elliot, S., K. S. Lackner, M. K. Dubey, H. P. Hanson, and S. Barr, Compensation of atmospheric CO_2 buildup through engineered chemical sinkage, *Geophys. Res. Lett., 28*, 1235–1238, 2001.

Fearnside, P. M., D. A. Lashof, and P. M. Costa, Accounting for time in mitigating global warming through land-use change and forestry, *Mitigation and Adaptation Strategies for Global Change, 5*, 239–270, 2000.

Grübler, A., N. Nakicenovic, and D. G. Victor, Dynamics of energy technologies and global change, *Energy Policy, 27*, 247–280, 1999.

Ha-Duong, M., and D. Keith, Climate strategy with CO_2 capture from air, in *Energy Policy*, pp. submitted, 2002.

Herzog, H., K. Caldeira, and E. Adams, *Encyclopedia of ocean sciences*, Academic Press, London, UK, 2001.

Herzog, H., K. Caldeira, and J. Reilly, An issue of permanence: Assessing the effectiveness of temporary carbon storage, *Climatic Change*, *59*, 293–310, 2003.

Herzog, H. J., and E. M. Drake, Carbon dioxide recovery and disposal from large energy systems, *Annual Review of Energy and the Environment, 21*, 145–166, 1996.

Hoffert, M. I., K. Caldeira, G. Benford, D. R. Criswell, C. Green, H. Herzog, A. K. Jain, H. S. Kheshgi, K. S. Lackner, J. S. Lewis, H. D. Lightfoot, W. Manheimer, J. C. Mankins, M. E. Mauel, L. J. Perkins,

M. E. Schlesinger, T. Volk, and T. M. L. Wigley, Advanced technology paths to global climate stability: energy for a greenhouse planet, *Science, 298*, 981–987, 2002.

Kaiser, J., Soaking up carbon in forrests and fields, *Science, 290*, 922, 2000.

Lackner, K. S., A guide to CO_2 sequestration, *Science, 300*(5626), 1677–1678, 2003.

Lackner, K. S., C. H. Wendt, D. P. Butt, E. L. Joyce, and D. H. Sharp, Carbon dioxide disposal in carbonate minerals, *Energy, 20*, 1995.

Lecocq, F., and K. Chomitz, Optimal use of sequestration in a global climate mitigation stratgey: Is there a wooden bridge to a clean energy future, World Bank Working Papers – environment, pollution, biodiversity, air quality. Number 2635., 2001.

Manne, A., R. Mendelson, and R. Richels, A model for evaluating regional and global effects of GHG reduction policies, *Energy Policy, 23*, 17–34, 1995.

Manne, A. S., and R. Richels, Buying greenhouse insurance, *Energy Policy, 19*, 543–552, 1991.

Messner, S., Endogenized technological learning in an energy systems model, *Journal of Evolutionary Economics, 7*, 291–313, 1997.

Munasinghe, M., P. Meier, M. Hoel, S. W. Hong, and A. Aaheim, *Climate change 1995, economic and social dimensions of climate change, contribution of working group ii,* Cambridge University Press, 1996.

Nilsson, S., and W. Schopehauser, The carbon-sequestration potential of the global afforestation program, *Climatic Change, 30*, 267–293, 1995.

Nordhaus, W. D., An optimal transition path for controlling greenhouse gases, *Science, 258*, 1315–1319, 1992.

Nordhaus, W. D., and J. Boyer, *Warming the world: Economic models of global warming,* MIT Press, 2000.

Nordhaus, W. D., and Z. L. Yang, A regional dynamic general-equilibrium model of alternative climate-change strategies, *American Economic Review, 86*(4), 741–765, 1996.

Ramsey, F., A mathematical theory of saving, *Economic Journal, 37*, 543–559, 1928.

Richards, K. R., The time value of carbon in bottom-up studies, *Critical Reviews in Environmental Science and Technology, 27*(special), 279–292, 1997.

Swinehart, S. C., 1996, *Afforestation as a method of carbon sequestration: A cost benefit analysis*, Ph. D. thesis, Stanford University.

Tol, R. S. J., On the optimal control of carbon dioxide emissions: An application of FUND, *Environmental Modeling and Assessment, 2*, 151–163, 1997.

van Kooten, G. C., A. Grainger, E. Ley, G. Marland, and B. Solberg, Conceptual issues related to carbon sequestration: uncertainty and time, *Critical Reviews in Environmental Science and Technology, 27*, 65–82, 1997.

Ward, F. A., The net social benefits from a research-induced cost-reduction of an energy backstop technology, *American Journal of Agricultural Economy, 61*, 668–675, 1979.

Weitzman, M. L., Why the far-distant future should be discounted at its lowest possible rate, *Journal of Environmental Economics and Management, 36*, 201–208, 1998.

Weyant, J., O. Davidson, H. Dowlatabadi, J. Edmonds, M. Grubb, E. A. Parson, R. Richels, J. Rotmans, P. R. Shukla, R. S. J. Tol, W. Cline, and S. Fankhauser, *Climate change 1995, economic and social dimensions of climate change*, Cambridge University Press, 1996.

Williams, R. H., Towards zero emissions for transportation using fossil fuel, Presentation at the VIII Biennial Asilomar Conference on Transportration, Energy, and Environmental Policy: Managing Transitions, Asilomar Conference Center, Monterey, CA. K. S. Kurani and D. Sperling (eds.), forthcoming., 2003.