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Carbon dioxide sequestration: how much and when?

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Abstract Carbon dioxide (CO_2) sequestration has been proposed as a key component in technological portfolios for managing anthropogenic climate change, since it may provide a faster and cheaper route to significant reductions in atmospheric CO_2 concentrations than abating CO_2 production. However, CO_2 sequestration is not a perfect substitute for CO_2 abatement because CO_2 may leak back into the atmosphere (thus imposing future climate change impacts) and because CO_2 sequestration requires energy (thus producing more CO_2 and depleting fossil fuel resources earlier). Here we use analytical and numerical models to assess the economic efficiency of CO_2 sequestration and analyze the optimal timing and extent of CO_2 sequestration. The economic efficiency factor of CO_2 sequestration can be expressed as the ratio of the marginal net benefits of sequestering CO_2 and avoiding CO_2 emissions. We derive an analytical solution for this efficiency factor for a simplified case in which we account for CO_2 leakage, discounting, the additional fossil fuel requirement of CO_2 sequestration, and the growth rate of carbon taxes. In this analytical model, the economic efficiency of CO_2 sequestration decreases as the CO_2 tax growth rate, leakage

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rates and energy requirements for CO_2 sequestration increase. Increasing discount rates increases the economic efficiency factor. In this simple model, short-term sequestration methods, such as afforestation, can even have negative economic efficiencies. We use a more realistic integrated-assessment model to additionally account for potentially important effects such as learning-by-doing and socio-economic inertia on optimal strategies. We measure the economic efficiency of CO_2 sequestration by the ratio of the marginal costs of CO_2 sequestration and CO_2 abatement along optimal trajectories. We show that the positive impacts of investments in CO_2 sequestration through the reduction of future marginal CO_2 sequestration costs and the alleviation of future inertia constraints can initially exceed the marginal sequestration costs. As a result, the economic efficiencies of CO_2 sequestration can exceed 100% and an optimal strategy will subsidize CO_2 sequestration that is initially more expensive than CO_2 abatement. The potential economic value of a feasible and acceptable CO_2 sequestration technology is equivalent – in the adopted utilitarian model – to a one-time investment of several percent of present gross world product. It is optimal in the chosen economic framework to sequester substantial CO_2 quantities into reservoirs with small or zero leakage, given published estimates of marginal costs and climate change impacts. The optimal CO_2 trajectories in the case of sequestration from air can approach the pre-industrial level, constituting geoengineering. Our analysis is silent on important questions (e.g., the effects of model and parametric uncertainty, the potential learning about these uncertainties, or ethical dimension of such geoengineering strategies), which need to be addressed before our findings can be translated into policy-relevant recommendations.

1 Introduction

Anthropogenic greenhouse gas emissions are projected to change future climates with potentially nontrivial impacts (Adger et al. 2007; Alley et al. 2007). Efforts to mitigate the greenhouse gas problem have traditionally focused on abating carbon dioxide (CO_2) production by reducing fossil fuel use or switching to less CO_2 intense fossil fuels (typically referred to as “CO_2 abatement”; Nordhaus 1992; Tol 1997). CO_2 abatement, however, requires sizable investments and has to overcome considerable socio-economic inertia (Barker et al. 2007). One alternative to CO_2 abatement is CO_2 capture and storage (Lackner 2003; Marchetti 1977; Rubin et al. 2005; also referred to as “CO_2 sequestration”). CO_2 capture can occur from industrial point sources (e.g., from fossil fuel power plants) or from the atmosphere (e.g., through changes in forestry practices or by absorption of CO_2 from the air). CO_2 sequestration requires additional energy, which, at the current mix of energy sources, depletes fossil fuel resources and increases the amount of produced CO_2. Proposed reservoirs for CO_2 storage include terrestrial biomass, deep oceans, saline aquifers, and minerals. These reservoirs differ considerably in the rates at which the stored CO_2 may leak back to the atmosphere. The characteristic storage times increase from the terrestrial pools (decades to centuries); to the deep oceans (centuries); to geological reservoirs (millennia); to thermodynamically stable minerals (exceeding millennia) (Freund et al. 2005; Lackner 2003).

An optimal portfolio of CO_2 abatement and sequestration has to account for the relative advantages and disadvantages of CO_2 sequestration. Potentially important advantages of CO_2 sequestration compared with CO_2 abatement include (1) large-scale reductions in anthropogenic CO_2 emissions may be cheaper and faster to implement and (2) the marginal CO_2 sequestration costs may be reduced faster through investments than marginal abatement costs (as sequestration is a less mature technology). However, sequestration has some disadvantages compared to CO_2 abatement. For example, CO_2 sequestration may cause future CO_2 leaks and can require additional fossil fuel resources. The inter-temporal tradeoffs due to these differences can occur over several centuries, thus requiring nontrivial long-term projections.

Here we ask five main questions: (1) What are economically efficient choices between CO_2 sequestration and CO_2 abatement? (2) What is the optimal use and timing of CO_2 sequestration? (3) How does CO_2 sequestration change the optimal trajectories of atmospheric CO_2 concentrations, global mean temperature, and marginal CO_2 abatement costs? (4) How do technological inertia, learning-by-doing, and the energy requirement of CO_2 sequestration affect the use of sequestration? and (5) What is the present economic value of a technology that would provide a feasible CO_2 sequestration option in the future? To address these questions, we expand and improve on previous work in two main respects. First, we refine and apply an analytical model (Richards 1997) to estimate the efficiency factor of CO_2 sequestration. Second, we modify an optimal economic growth model (Nordhaus 2007) by adding CO_2 sequestration and learning-by-doing to analyze the optimal use of CO_2 sequestration methods and the effects of optimal carbon dioxide levels.

Previous studies that have addressed CO_2 sequestration have developed elegant analytical expressions for analyzing the question of how much CO_2 sequestration should be counted as a substitute for 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; Riahi et al. 2004; Keith et al. 2006). While breaking important new ground, these studies are silent on important policy questions. For example, the analytical models often neglect the effects of the additional energy required for CO_2 sequestration (Herzog et al. 2003). We expand on the groundbreaking work of Richards (1997) and Herzog et al. (2003) by (1) considering the effects of the energy required for CO_2 sequestration, (2) deriving a closed form solution to the economic efficiency of CO_2 sequestration, and (3) demonstrating with a numerical model that the positive economic impacts of learning-by-doing and the alleviation of future inertia constraints can dominate the negative economic impacts due to leakage. We expand on previous numerical analysis by focusing on sequestration technologies that may allow large reductions in atmospheric CO_2 concentrations and by considering a longer time-horizon. Many numerical models focus on afforestation, which seems unlikely to be a cost effective and feasible strategy for deep cuts in net anthropogenic CO_2 emissions to the atmosphere (Adam 2001; Benitez et al. 2007; Nilsson and Schopehauser 1995; Sohngen and Sedjo 2006). Studies analyzing more powerful sequestration methods, such as deep-aquifer injection or absorption into minerals, either assume negligible marginal costs (Nordhaus 1992), neglect induced technological change (Herzog et al. 2003), or do not analyze the effects of CO_2 leakage (Gerlagh 2006; Keith et al. 2006). Our study additionally contributes to methodological development by demonstrating a reliable and relatively fast method to overcome the convergence problems posed by the potential nonconvexity of the optimal control problem that is arguably simpler than previous approaches (Kverndokk and Rosendah 2007).

We characterize the economic efficiency of CO_2 sequestration by the ratio of the marginal benefits of CO_2 sequestration and CO_2 abatement. We derive an analytical expression for this economic efficiency for an extremely simplified case that accounts for CO_2 leakage, changes in future carbon taxes, the energy requirements of CO_2 sequestration, and discounting. Specifically, we estimate the net present value of sequestered CO_2 in terms of avoided abatement costs required to meet a given climate objective. 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 represent the economic efficiency factor of CO_2 sequestration. The results from our analytical model suggest that afforestation can have negative to slightly positive economic efficiencies, while long-term sequestration possibilities, such as deep aquifer sequestration or ocean injection, would be much more efficient.

The analytical model provides an intuitive and simple method, but it neglects potentially important effects of learning-by-doing (Argote and Epple 1990), technological inertia (Grübler et al. 1999), and a limited fossil fuel resource base (Herzog et al. 2003). We analyze these effects using a numerical optimal growth model. We adopt a globally aggregated model of optimal economic growth (DICE-07) that represents, in a highly stylized manner, anthropogenic climate change, the associated economic impacts, and strategies to control these impacts (Nordhaus 2007). The choice of this parsimonious model structure is motivated by the need to analyze feedbacks that act over several centuries. Choosing more complex model structures (cf. Schwoon and Tol 2006 or Manne and Barreto 2004) has the potential to provide more detailed insights into the dynamics over the next few decades. Whether increasing the model complexity would actually improve the projection skill over the century-scale time horizon of the problem, is, however, an open question (Craig et al. 2002; Keller et al. 2007). Nonetheless, the simplicity of the model imposes potentially severe caveats. We return to these caveats below. For the numerical analysis, we amend the DICE-07 model with extremely simplistic representations of CO_2 sequestration, technological inertia, and learning-by-doing. We overcome the methodological challenge of a potentially non-convex objective function introduced by learning-by-doing (Arrow 1962; Manne and Barreto 2004) by using an efficient global optimization algorithm (Storn and Price 1997).

One key finding from the numerical analysis is that the positive economic impacts due to learning-by-doing and the mitigation of future inertia constraints can dominate the negative economic impacts due to leakage and the additional energy requirements. As a result, the marginal CO_2 sequestration costs can considerably exceed the marginal CO_2 abatement costs along an optimal path. The economic efficiencies of CO_2 sequestration can hence exceed 100%. In this case, it is a profitable strategy in the adopted optimal growth framework to subsidize ("buy-down") the costs of CO_2 sequestration. In the model, CO_2 sequestration at marginal costs within the range of present estimates is deployed in increasing volume to sequester a large fraction of the anthropogenic CO_2 emissions within this century. The economic value of a feasible CO_2 sequestration technology can be several percent of present-day gross world product (GWP). We explore the sensitivity of our results with respect to parametric assumptions about learning-by-doing, technological inertia, and CO_2 leakage.

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

The efficiency factor of CO_2 sequestration is a simple measure for analyzing the economic efficiency of substituting CO_2 sequestration for CO_2 abatement. A necessary condition for a least-cost strategy is that different CO_2 control technologies are used such that their marginal social values (shadow prices) are equalized. Thus, in a world in which sequestration has a constant efficiency (η) relative to that of abatement, and an optimal tax (τ) is levied on all CO_2 emissions (including those sequestered), the optimal "refund" levied for each ton of CO_2 sequestered should be equal to the product $\eta \cdot \tau$. As the relative efficiency of sequestration approaches unity (perfect substitution 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.

The first goal of our analysis is to derive the economic efficiency factor of CO_2 sequestration to compare CO_2 sequestration and abatement. 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 use a simple analytical model, expanding on the approach discussed by Richards (1997) and refined by Herzog et al (2003).

The economic efficiency of CO_2 sequestration is affected in our analytical model by four factors: (1) the additional energy requirement, (2) the CO_2 leakage over time with associated impacts, (3) the changes over time in marginal abatement costs, and (4) the monetary discount rate. In the following section we develop simple representations of these factors and derive a closed form solution for the efficiency factor of CO_2 sequestration. The first factor accounts for the additional energy required for CO_2 sequestration, which is derived from burning more fossil fuel, and will be referred to as an “energy penalty”. The relative “energy penalty” (λ) is the consequence of the energy-intensive nature of capturing, transporting, and sequestering CO_2 emissions and is defined as the proportion of produced energy required for CO_2 sequestration. (See Appendix 1 for a definition of symbols.) 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 may leak back to the atmosphere. We approximate the leakage by an exponential decay of the sequestered CO_2 stock. For example, the leakage from ocean injection can reasonably be approximated by an exponential decay with half-life times ranging from decades to centuries (cf. Herzog et al. 2003). The leakage flux of one ton of sequestered CO_2 over time (l) is a function of the decay rate (ζ):

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

where t starts at the time of sequestration and the half-life time of the sequestered CO_2 in the reservoir ($T_{1/2}$) is given by $\ln(2)/\zeta$.

For the analytical model, we assume an agreed upon atmospheric CO_2 stabilization path with an associated 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 the adopted simple framework. 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.

Future optimal carbon tax trajectories in economic optimal growth models are reasonably well approximated for the next two centuries by exponential functions over a wide range of climate objectives (Keller et al. 2005; Nordhaus 2007; Yohe et al. 2004). We hence approximate the carbon taxes over time as:

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

where β_0 is the initial carbon tax in U.S.$ per ton of carbon (C) and β is the carbon tax growth rate. As discussed above, we assume that the marginal damages of CO_2 emissions are equal to the carbon tax. The carbon taxes are projected to increase over time, mostly because of the positive marginal productivity of capital and since 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*):

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

where r is the monetary discount rate.

Deriving the efficiency factor of a leaky CO_2 sequestration project is now a matter of calculating the net present value of the project and relating it to the costs of the alternative strategy of abating CO_2 emissions. 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 is therefore

$$\text{net benefit} = \beta_0 - \int_{t=0}^{t=\infty} e^{-rt}\beta_0 e^{\beta t}\frac{\zeta}{1-\lambda}e^{-\zeta t}\,\mathrm{d}t, \tag{5}$$

which can be solved analytically for $r + \zeta - \beta > 0$. If $r + \zeta - \beta < 0$, the costs of leakage grow faster than the rate at which they are discounted and the net impacts (as well as the economic efficiency) are negative. The solution for the net benefits is:

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

The expression in square parentheses reduces the initial project benefits at no leakage (the marginal abatement costs at the time of sequestration) and can be interpreted as the economic 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 as the ratio of the net benefit from a unit of sequestered CO_2 to the net benefit of a unit of avoided CO_2 emissions. Note that this efficiency factor of CO_2 sequestration is equal to the ratio of the marginal benefits (or costs) of CO_2 sequestration to CO_2 abatement along an optimal path. We will return to this ratio in the discussion of the numerical model below.

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 neglect important issues such as the marginal productivity of capital or CO_2 leakage beyond an arbitrarily chosen time horizon (Costa and Wilson 2000; Fearnside et al. 2000). Although this analytical model gives us some insight into the economic efficiency of substituting CO_2 sequestration for CO_2 abatement, it has several shortcomings. First, the partial equilibrium assumption implicit in the fixed carbon tax path is reasonable only for very small-scale use of CO_2 sequestration, because large-scale CO_2 sequestration would affect the carbon tax path. Second, our analytical model neglects the fact that the carbon tax path is affected by the availability of backstop technologies (House et al. 2006; Manne and Richels 1991), technological inertia (Grübler et al. 1999), learning-by-doing (Argote and Epple 1990) and the additional fossil fuel required for sequestration. 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 Dynamic Integrated Model of Climate and the Economy (DICE) as a starting point. This optimal growth model links the global climate and economic system by simple feedbacks. We modify a recent version of this model (DICE-07; Nordhaus 2007) 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 describe our modifications.

3.1 The DICE model

The DICE-07 model (Nordhaus 2007) links climatic relationships between atmospheric CO_2 concentration, radiative forcing, and changes in global mean temperature to economic relationships between consumption and investment in capital. The economic component of the DICE model is a Ramsey type model of economic optimal growth (Ramsey 1928). In the Ramsey model, a social planner chooses an investment (I) path to maximize an objective function (W). In the DICE-07 model, the objective function is the discounted sum of utility

$$W = \sum_{n=0}^{N-1} U[c(t_n), L(t_n)]R(t_n)\,, \tag{8}$$

where U is a flow of utility of consumption, $L(t)$ is the exogenously specified population, $c(t)$ is per-capita consumption, and $R(t)$ is a social time preference discount factor. The N discrete times $t_n = t_0 + \Delta t$ start at an initial time t_0 (the year 2005), are incremented at intervals of Δt=10 years, and extend to a finite time horizon t_{N-1}.The utility of consumption in each period is given by

$$U[c(t), L(t)] = L(t)\left[c(t)^{1-\alpha} - 1\Big/(1-\alpha)\right], \tag{9}$$

where α is the elasticity of marginal utility of consumption, and the discount factor is

$$\mathrm{R(t)} = (1+\rho)^{-(t-t_0)}, \tag{10}$$

where ρ=1.5% per year is the pure rate of social time preference applied to the flow of utility.

Solving this optimization problem numerically requires truncating the infinite horizon problem. We choose a finite numerical time horizon of 590 years. Further extending this horizon has negligible effect on the optimal strategies of the analyzed time window of 2005 to 2150.

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

$$Q(t) = C(t) + I(t). \tag{11}$$

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

$$K(t) = I(t-\Delta t) - \delta_K K(t-\Delta t). \tag{12}$$

At each point in time, the endogenous capital stock and exogenous labor supply influence gross world product. In DICE-07, this relationship is expressed by a modified Cobb-Douglas function:

$$Q(t) = \Omega(t)\Lambda(t)A(t)K(t)^{\gamma}L(t)^{1-\gamma}. \tag{13}$$

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

The economic and natural systems are linked in the model by anthropogenic CO_2 emissions (E), consisting of industrial emissions (E_{Ind}) and exogenously evolving land-use emissions (E_{Land}):

$$E(t) = E_{Ind}(t) + E_{Land}(t). \tag{14}$$

Industrial CO_2 emissions depend on the economic output, the exogenously determined carbon-intensity of economic activity (σ), and the CO_2 abatement rate (the decision variable μ), according to:

$$E_{\mathrm{Ind}}(t) = \sigma(t)[1-\mu(t)]A(t)K(t)^{\gamma}L(t)^{1-\gamma}. \tag{15}$$

We limit the total industrial CO_2 emissions to 6,000 Gt C to represent the limited fossil fuel resource base (Rogner 1997). For the hypothetical business as usual (BAU) case, we impose a constraint of zero CO_2 abatement and sequestration until the model year 2200.

CO_2 emissions act to increase the atmospheric CO_2 stock (M_{At}). However, increased CO_2 concentration in the atmosphere drives some proportion into the upper ocean carbon pool (M_{Up}). Eventually, most of a given CO_2 pulse emitted into the atmosphere is absorbed in the model by the deep ocean pool (M_{Lo}) according to a first-order linear three-box model that resolves the carbon pools in the atmosphere (M_{At}), a fast mixing reservoir consisting of the combined terrestrial biosphere and the upper oceans (M_{Up}), and the deep ocean (M_{Lo}):

$$M_{At}(t) = \pi E(t-\Delta t) + \phi_{11}M_{At}(t-\Delta t) + \phi_{21}M_{Up}(t-\Delta t), \tag{16}$$

$$M_{Up}(t) = (1-\pi)E(t-\Delta t) + \phi_{22}M_{Up}(t-\Delta t) + \phi_{32}M_{Lo}(t-\Delta t) + \phi_{12}M_{At}(t-\Delta t), \tag{17}$$

and,

$$M_{Lo}(t) = \phi_{33}M_{Lo}(t-\Delta t) + \phi_{23}M_{Up}(t-\Delta t). \tag{18}$$

This simple model neglects, for example, several nonlinearities of the carbon cycle response (Joos et al. 1999; Schulz and Kasting 1997). In Eq. 16 the parameter π is the fraction of CO_2 emissions that mixes immediately into the atmosphere. The ϕ_{ij} parameters represent transfer rates of CO_2 between reservoirs.

Atmospheric CO_2 levels above the pre-industrial level ($M_{\mathrm{At}}(1750)$) cause a net radiative forcing (F):

$$F(t) = \chi\{\log_2[M_{\mathrm{At}}(t)/M_{\mathrm{At}}(1750)]\} + F_{\mathrm{Ex}}(t), \tag{19}$$

where χ is a proportionality constant linking changes in CO_2 concentrations to the radiative forcing, and F_{Ex} represents exogenously specified radiative forcing from sources such as methane or aerosols.

The anthropogenic climate perturbation is modeled using a simple two-box model (Schneider and Thompson 1981), consisting of a combined atmosphere and surface ocean layer and a deep ocean layer. Increased radiative forcing is translated into global mean surface temperature change (T_{At}):

$$T_{At}(t) = T_{At}(t - \Delta t) + \vartheta_1\{F(t) - \vartheta_2 T_{At}(t - \Delta t) - \vartheta_3[T_{At}(t - \Delta t) - T_{Lo}(t - \Delta t)]\}. \quad (20)$$

In this equation $1/\vartheta_1$ denotes the thermal capacity of the oceanic mixed layer, ϑ_2 is the climate feedback parameter, and ϑ_3 represents the ratio of the heat capacity of the deep ocean to transfer rate from the oceanic mixed layer to the deep ocean. T_{Lo} is the deviation of the deep-ocean temperature from the 1900 level approximated by:

$$T_{Lo}(t) = T_{Lo}(t - \Delta t) + \vartheta_4\{T_{At}(t - \Delta t) - T_{Lo}(t - \Delta t)\}, \quad (21)$$

where $1/\vartheta_4$ is the transfer rate from the upper to lower layers.

In the model, the surface temperature changes are taken as a proxy for anthropogenic climate change, which causes economic damages. The damages are specified in proportion to the gross world product. Climate damages reduce economic output through the scaling factor Ω:

$$\Omega(t) = 1\Big/\left[1 + \psi_1 T_{At}(t) + \psi_2 T_{At}(t)^2\right], \quad (22)$$

which is a function of the change in global mean surface temperature (cf. Eq. 20) and the empirical parameters ψ_1 and ψ_2. Increasing CO_2 abatement imposes increasing abatement costs, which may be expressed as a fraction of world output. The costs of carbon management are subtracted from the gross world product, thereby determining the scaling factor Λ:

$$\Lambda(t) = 1 - b_1(t)\mu(t)^{b_2}. \quad (23)$$

3.2 Representation of CO_2 sequestration from point sources

We add CO_2 sequestration as an additional carbon management option to the standard abatement option considered in the DICE-07 model. We start with the key assumption that CO_2 sequestration is both available and safe in large quantities. At each time, a fraction of industrial emissions (ν) is sequestered and stored in a carbon reservoir. As a result, industrial emissions are reduced, and Eq. 15 becomes

$$E_{Ind}(t) = \sigma(t)[1 - \nu(t)][1 - \mu(t)]A(t)K(t)^{\gamma}L(t)^{1-\gamma}. \quad (24)$$

The amount of CO_2 sequestered at time t from the industrial emissions is:

$$S_0(t) = \nu(t)[1 - \mu(t)]\sigma(t)A(t)K(t)^{\gamma}L(t)^{1-\gamma}. \quad (25)$$

As explained in Section 2, CO_2 sequestration requires additional energy and hence increases CO_2 production. Recalling Eq. 1, CO_2 production is increased by the factor

$$\frac{1}{1-\lambda},$$

where λ is the energy penalty. The relative increase in CO_2 production (κ), is given by

$$1+\kappa=\frac{1}{1-\lambda},$$

so that

$$\kappa=\frac{\lambda}{1-\lambda}.$$

For small energy penalties, $\kappa \approx \lambda$.

CO_2 emissions due to the additional energy required to sequester the amount $S_0(t)$ are

$$E_{\mathrm{Pen},0}(t)=\kappa S_0(t)=\kappa v(t)[1-\mu(t)]\sigma(t)A(t)K(t)^{\gamma}L(t)^{1-\gamma}. \tag{26}$$

We assume that the energy source used for industry is also used for sequestration, so that the fraction $\nu(t)$ is also sequestered from the above additional emissions. This results in an additional sequestration flux

$$S_1(t)=v(t)E_{\mathrm{Pen},0}(t)=\kappa v^2(t)[1-\mu(t)]\sigma(t)A(t)K(t)^{\gamma}L(t)^{1-\gamma}.$$

and an additional energy penalty

$$E_{\mathrm{Pen},1}(t)=\kappa S_1(t)=\kappa^2 v^2(t)[1-\mu(t)]\sigma(t)A(t)K(t)^{\gamma}L(t)^{1-\gamma}. \tag{27}$$

Further sequestration of the additional CO_2 required for sequestration results in a total sequestration flux at time t of

$$S(t)=S_0(t)+S_1(t)+S_2(t)+\ldots=\nu(t)\left[1+\kappa\nu(t)+\kappa^2\nu^2(t)+\ldots\right][1-\mu(t)]\sigma(t)A(t)K(t)^{\gamma}L(t)^{1-\gamma} \tag{28}$$

and an energy penalty of

$$E_{\mathrm{Pen},1}=\lambda[1-v(t)]S(t). \tag{29}$$

Since $0 \leq v \leq 1$, and for small κ, truncation of the series in Eq. 28 at $S_2(t)$ provides a reasonable approximation to the infinite series.

CO_2 stored in the reservoir can leak back into the atmosphere following an exponential decay, so the total carbon in the reservoir (M_{Res}) follows the relationship

$$M_{\mathrm{Res}}(t)=S(t)+\phi_{44}M_{\mathrm{Res}}(t-\Delta t), \tag{30}$$

where ϕ_{44} is the reservoir retention rate (per decade). CO_2 emissions due to reservoir leakage are:

$$l(t)=(1-\phi_{44})M_{\mathrm{Res}}(t-\Delta t). \tag{31}$$

Eq. 14 is modified to include CO_2 leakage emissions as well as the additional CO_2 emissions due to the additional energy requirement of CO_2 sequestration (E_{Pen}):

$$E(t)=E_{Ind}(t)+E_{Land}(t)+l(t)+E_{Pen}(t). \tag{32}$$

These emissions are subsequently used in Eq. 16.

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; Elliott et al. 2001; Keith et al. 2006). A backstop technology implies that the marginal cost of sequestering CO_2 is independent of the sequestered quantity.

In the model, we subtract the product of the CO_2 sequestration flux and the marginal sequestration costs (V) from world output. The original production function (Eq. 13) is hence modified according to:

$$Q(t) = \Omega(t)\Lambda(t)\Gamma(t)A(t)K(t)^{\gamma}L(t)^{1-\gamma}, \tag{33}$$

where the sequestration cost scaling factor $\Gamma(t)$ is

$$\Gamma(\mathrm{t}) = 1 - \frac{V(t)S(t)}{A(t)K(t)^{\gamma}L(t)^{1-\gamma}} = 1 - V(t)\sigma(t)v(t)[1-\mu(t)]. \tag{34}$$

Sequestration ($\nu(t)$) becomes an additional decision variable (besides CO_2 abatement and capital investment) for maximizing the objective function.

3.3 Representation of CO_2 sequestration from air

We now consider the possibility that CO_2 sequestration might occur out of the atmosphere to form a thermodynamically stable mineral (Elliott et al. 2001; Lackner et al. 1999). This CO_2 sequestration option has the potential to considerably change the optimal CO_2 and temperature trajectories as it allows CO_2 sequestration fluxes that exceed the industrial emissions and is arguably faster to implement than sequestration from point sources (cf. Keith et al. 2006).

To account for sequestration from air, we modify Eq. 16 as follows:

$$M_{At}(t) = \pi E(t-\Delta t) + \phi_{11}M_{At}(t-\Delta t) + \phi_{21}M_{Up}(t-\Delta t) - S(t-\Delta t), \tag{35}$$

with the additional constraint that M_{At} does not decrease below the pre-industrial level (equivalent to an atmospheric concentration of 280 ppm; cf. Keith et al. 2006).

3.4 Sequestration cost estimates

Present estimates of the marginal costs of CO_2 sequestration vary widely and are subject to deep uncertainties (Gerdemann et al. 2007; Herzog et al. 2005; Keith et al. 2006; Rhodes and Keith 2005). 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. In addition, cost estimates depend on factors affected by the base-line, such as the relative prices of fossil fuel sources (Herzog et al. 2005). The recent report on carbon capture and storage from the Intergovernmental Panel on Climate Change (Herzog et al. 2005) concludes that a carbon price of roughly 100 U.S.$ per ton C would render CO_2 sequestration competitive with other large scale mitigation options. Cost estimates for specific technological approaches vary widely, ranging from tens to more than one thousand U.S.$ per ton C. For example, Chiesa and Consonni (2000) analyze natural gas-fired combined cycle power plants and estimate that carbon taxes between roughly 125 to 180 U.S.$ per ton C would render the CO_2 sequestration option competitive. CO_2 sequestration from power plants to form thermodynamically stable minerals would be considerably more expensive, with cost estimates exceeding 1000 U.S.$ per ton C (Gerdemann et al. 2007). Note that an upper bound of roughly 500 U.S.$ per ton C is estimated by Keith et al. (2006) for a technology that absorbs CO_2 from the air. Given the deep uncertainties surrounding these cost projections, we adopt arguably conservative base-case estimates for the marginal costs of 250 U.S.$ per ton C for large scale CO_2 sequestration from point sources and of 500 U.S.$ per ton C for large scale CO_2 sequestration from point sources. We explore the sensitivity of the results to a range of cost estimates.

3.5 Representation of learning-by-doing

The marginal costs of a wide range of technologies have been shown to decrease as a function of the cumulative installed capacity; a phenomenon typically referred to as "learning-by-doing" (Argote and Epple 1990). One often observed behavior is that the marginal costs decrease by an approximately constant ratio (the "progress ratio", *pr*) for each doubling of the cumulative installed capacity (Argote and Epple 1990; McDonald and Schrattenholzer 2001). Given this observed behavior, learning-by-doing is projected to be 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 the endogenous variable cumulative installed capacity (CC_{Seq}) according to:

$$CC_{\mathrm{Seq}}(t) = CC_{\mathrm{Seq}}(t - \Delta t) + S(t), \tag{36}$$

and

$$V(t) = V_0 \left[\frac{CC(t - \Delta t)}{CC(t_0)}\right]^{-n_{\mathrm{pr}}}. \tag{37}$$

The cost curve is characterized by the exponent (n_{pr}), which is a function of the progress ratio. We assume a progress ratio of 85% to represent technologies between the research and development phase and the commercialization phase (Grübler et al. 1999), and an initial installed capacity of 1 Gt C to represent a relatively immature technology. We also implement learning-by-doing for CO_2 abatement. The cost of abatement decreases from its initial value in DICE-07 according to similar equations to Eqs. 31–33. CO_2 abatement is arguably more mature than CO_2 sequestration. This is because a key approach to avoiding CO_2 emissions is through technologies that increase energy use efficiency. We hence represent the more mature technologies of CO_2 abatement with an initially higher cumulative capacity (than that of CO_2 sequestration) of 10 Gt C. It is important to stress that representing the complex processes driving the marginal costs of technologies by a simple model based on an exponential relationship with only three parameters is a crude approximation (cf. Wing 2006; Nemet 2006, and Clarke et al. 2006).

Learning-by-doing can introduce local maxima into the underlying optimization problem (Manne and Barreto 2004; Messner 1997). A gradient-based optimization method can then be trapped by a local maximum. We solve this problem by applying an evolutionary algorithm (Storn and Price 1997) This approach is conceptually simpler than the method discussed by Kverndokk and Rosendah (2007), but does require nontrivial computational resources. We further reduce the dimension of the optimization problem to decrease the solution time as described in McInerney and Keller (2007). Specifically, we first optimize the control variable of investment in capital stock with BAU CO_2 emissions. We then fix this trajectory of investment in capital stock and optimize the CO_2 control option (i.e., CO_2 abatement and sequestration).

3.6 Representation of technological inertia

Market penetration rates of new technologies are limited by factors such as capital turnover and diffusion of knowledge. The penetration rates of technologies such as natural gas, cars, or oil can be approximated as an exponential increase in the delivered quantity (Grübler et al. 1999). 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 (Grübler et al. 1999). We adopt this value as a simple approximation for technological inertia according to:

$$\upsilon(t) \leq \left(1 + \alpha_{\mathrm{Seq}}\right)^{\Delta t} \upsilon(t - \Delta t), \tag{38}$$

where α_{Seq} is the maximum growth rate of 7.5% per year, and $\upsilon(2005) \leq 0.01$.

For sequestration out of air we consider a higher feasible rate growth rate of α_{Seq}=10% per year, so the inertia constraint is

$$S(t) \leq (1 + \alpha_{\mathrm{Seq}})^{\Delta t} S(t - \Delta t),$$

with $S(2005) \leq 1$ Gt C. We adopt this less stringent inertia constraint for CO_2 sequestration from air because scaling up this technology arguably requires less changes in the energy infrastructure than CO_2 sequestration from point sources.

The inertia constraint for abatement is represented by:

$$\mu(t) \leq \mu(t - \Delta t) + 0.2, \tag{39}$$

with and $\mu(2005) \leq 0.02$.

The model and solution algorithm are available from the authors on request.

4 Results and discussion

4.1 Analytical model

The analytical model (Eq. 7) provides some insights into how changes in CO_2 leakage rate (ζ), energy penalty (λ), and carbon tax growth rate (β) affect the economic efficiency of carbon sequestration given the simplifying assumptions. Recall the analytical solution for the economic efficiency given in Eq. 7:

$$\eta = 1 - \frac{\zeta}{(r + \zeta - \beta)(1 - \lambda)}.$$

The economic efficiency increases as the monetary discount rates increase and the carbon tax growth rate and leakage rates decrease. These sensitivities can be explained by observing that increasing monetary discount rates and decreasing leakage and carbon tax growth rates all reduce the discounted costs of future CO_2 leakage. Reducing the discounted costs of future CO_2 leakage increases the economic efficiencies of CO_2 sequestration in the model. Increasing discount rates increases the efficiency factor by lessening the present-value costs associated with future leakage. Decreasing energy penalties increase the efficiency factor by decreasing the overall CO_2 production and hence future CO_2 leakage flux. Decreasing leakage rates increase the efficiency factor by allowing carbon to escape sequestration later, when the discounted costs due to leakage are lower. Finally, decreasing carbon tax growth rate increases the efficiency by decreasing the cost of cutting emissions to compensate for leaked CO_2.

The analytical model (Eq. 7) can also be used to derive illustrative estimates of the economic efficiency of CO_2 sequestration accounting for the approximated effects of the energy penalty, the monetary discount rate, and the future carbon tax growth rate. To this end, we consider a monetary discount rate of 4% per year and a carbon tax growth rate of 1.75% per year to represent typical values from relatively simple economic optimal growth models (Keller et al. 2005; Nordhaus 2007). CO_2 sequestration by afforestation may be approximated using a small energy penalty of 10% and a half-life time of sequestered CO_2 of 30 years, yielding an efficiency factor of approximately 40% (Fig. 1). For comparison, a very approximate representation of deep aquifer sequestration with a half-life time of 1000 years and an energy penalty of 15% (Thambimuthu et al. 2005) would have an efficiency factor exceeding 90%.

4.2 Optimal economic growth model

The analytical model is a useful tool for analyzing the economic efficiency of substituting CO_2 sequestration for CO_2 abatement in a closed form solution. The simple analytical model, however, neglects the effects of (1) learning-by-doing, (2) technological inertia, (3) potential changes in optimal carbon taxes due to the availability of the backstop technology, and (4) potential change in the value of fossil fuel resources due to the additional energy requirements of CO_2 sequestration. We use the numerical model introduced above to analyze these effects.

In the BAU scenario (i.e., without abatement or sequestration) the CO_2 emissions increase from roughly nine Gt C /a in 2015 to around 20 Gt C /a in 2100 (Fig. 2a,c). With CO_2 abatement and sequestration available, CO_2 abatement generally increases slowly with

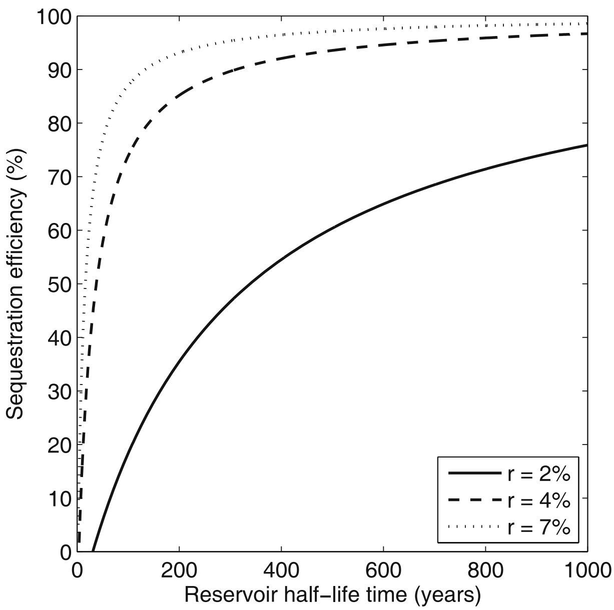

Fig. 1 Relationship between the reservoir half-life time of a sequestration project and its economic efficiency factor (η; Eq. 7 in the text) for a carbon tax growth rate of 1.75% per year, an energy penalty of 10%, and different discount rates (r)

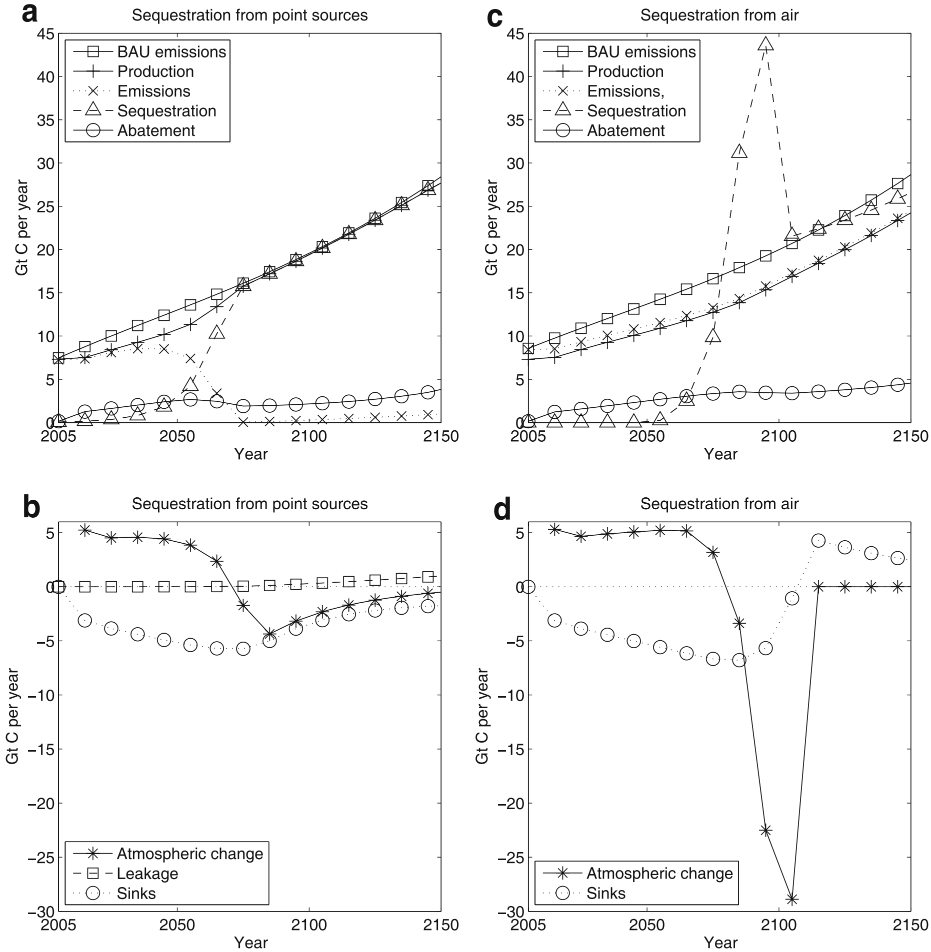

Fig. 2 Optimal carbon fluxes over time for CO_2 sequestration from point sources (**a**, **b**) and from air (**c**, **d**). The simulations for CO_2 sequestration from point sources assume an initial CO_2 sequestration cost of 250 U.S.$ per ton C and a reservoir half-life time of 1000 years. The simulations for CO_2 sequestration from air assume an initial CO_2 sequestration cost of 500 U.S.$ per ton C and no leakage. The emissions in the *upper panels* include the CO_2 emissions due to land-use changes (Eq. 14)

time. The total amount of abatement (e.g., around one and two Gt C /a in 2015 and 2100 for the case of sequestration from point sources) is a relatively small fraction of the BAU emissions. In contrast, CO_2 sequestration expands much faster and captures a large fraction of the BAU emissions. For CO_2 sequestration from point sources, the sequestration flux is limited by the total produced CO_2 flux (Fig. 2a,b). As a result, the net CO_2 emissions due to industrial activities stay roughly constant for the next four decades and then decline to rather small fluxes (mostly driven by CO_2 leakage, cf. Fig. 2a) in the second half of this century. In contrast, when CO_2 sequestration from air is used (Fig. 2c,d), CO_2 emissions continue to grow over the considered time horizon. However, since the amount of sequestered CO_2 is not constrained to that of emissions, the optimal CO_2 sequestration fluxes from air can be considerably larger than the optimal CO_2 sequestration fluxes from point sources.

The availability of sequestration options can dramatically reduce the optimal atmospheric concentration of CO_2, depending, for example, on the marginal cost and the leakage rate of CO_2 sequestration, and whether CO_2 sequestration occurs from point sources or from air (Fig. 3). CO_2 sequestration has relatively small effects on the optimal atmospheric CO_2 concentrations within this century when CO_2 sequestration technology is relatively expensive and the reservoir half-life times are short. For example, the atmospheric CO_2 concentrations rise to approximately 600 ppm by 2100 in the case of marginal sequestration costs of 1000 U.S.$ per ton C and a half-life time of 30 years (Fig. 3a). Increasing reservoir half-life times and decreasing sequestration costs result in decreasing optimal CO_2 concentrations within the 21st century. For example, for a CO_2 sequestration cost of 250 U.S.$ per ton C and a reservoir half-life time of 250 years, the optimal CO_2 trajectory peaks at approximately 500 ppm (Fig. 3b). The secondary increase in CO_2 concentration in the long run for the reservoir half-life times of 30 and 250 years (Fig. 3a,b) is due to the relatively early leakage of sequestered CO_2. For a millennium

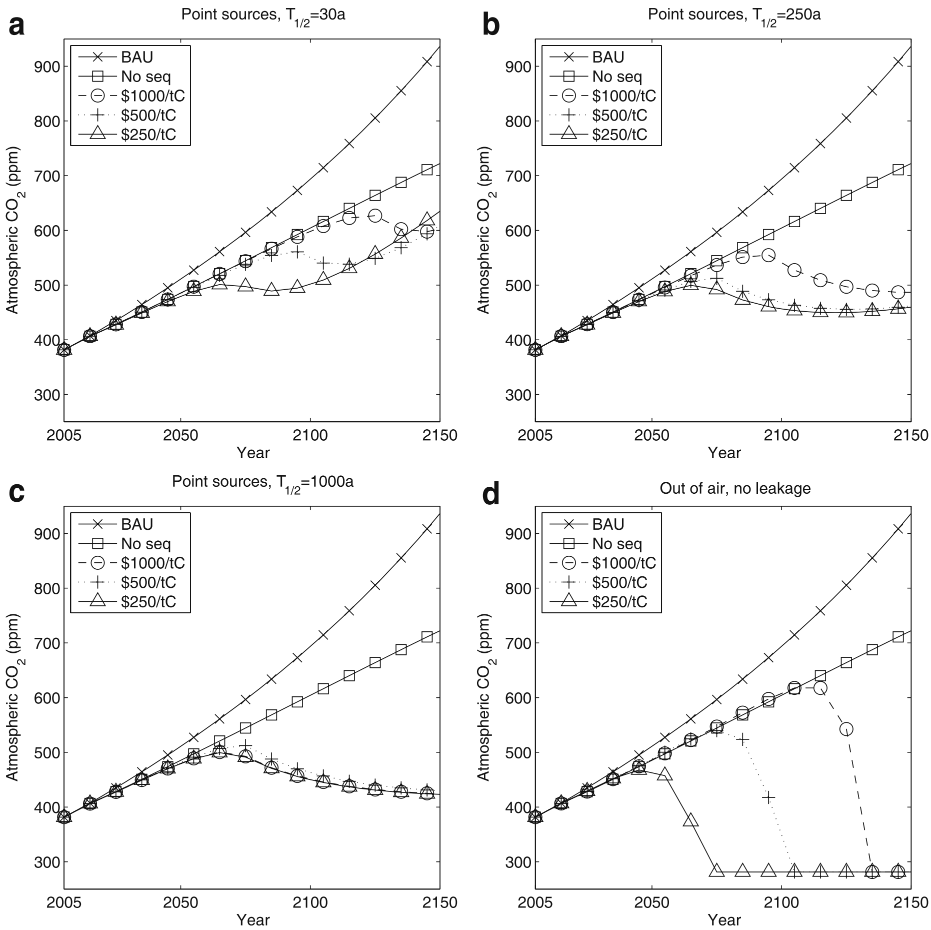

Fig. 3 Effect of initial CO_2 sequestration costs on optimal CO_2 trajectories. Shown are simulations for CO_2 sequestration from point sources and reservoir half-live times ($T_{1/2}$) of 30, 1,000, and 5,000 years, respectively (**a**, **b**, and **c**). The simulations in (**d**) are for CO_2 sequestration from air without leakage

reservoir half-life time, the optimal CO_2 concentration does not show this secondary increase in the considered time horizon (Fig. 3c).

For CO_2 sequestration from point sources (Fig. 3a–c), the optimal CO_2 trajectories stay above 400 ppm in the considered time horizon, even though the CO_2 emissions to the atmosphere are substantially reduced to less than 2 Gt C /a (Fig. 2a). This persistence of the anthropogenic CO_2 perturbation in the atmosphere is due, in the model, to the long atmospheric residence time of CO_2, the CO_2 leakage fluxes, and the constraint that the CO_2 sequestration flux cannot exceed the CO_2 production flux. In contrast, for CO_2 sequestration from air without leakage (Fig. 3d) the optimal CO_2 trajectories return to the pre-industrial level within the considered time horizon. The key differences between the simulations with sequestration from point sources (Figs. 3a–c) and sequestration from air (Fig. 3d) are the ability to enhance the CO_2 sequestration flux beyond the CO_2 production flux and the absence of leakage. The reduction of the optimal CO_2 concentrations to pre-industrial levels in the case of sequestration from air is driven by the adopted damage function. Such an intentional "dialing in" of atmospheric CO_2 concentrations arguably constitutes geo-engineering (Keith 2000), which opens up many questions that our current analysis framework does not address. (We return to this point in the section on caveats and research needs).

The optimal CO_2 paths, for arguably realistic assumptions about present CO_2 sequestration costs, can be considerably lower than in previous optimal growth analyses (e.g., Tol 1997; and Nordhaus 2007). Reducing the atmospheric CO_2 concentrations (Fig. 3) reduces global mean surface temperature changes (Fig. 4). For the BAU case (without any reductions in CO_2 emissions) the global mean temperature increases by roughly 4°C by 2150. The optimal use of CO_2 abatement alone reduces the temperature in 2150 to approximately 3.5°C. The optimal use of CO_2 abatement and a CO_2 sequestration option (either from point sources or from air) at initial marginal costs at or below 500 U.S.$ /tC and a half life times of 1000 years or more reduces this temperature change to less than 2°C in 2150 (Fig. 4). The optimal temperature trajectories for sequestration from point sources and from air differ considerably. The optimal temperature trajectory for all considered cases of CO_2 sequestration from point sources stay above 1.5°C in the considered time horizon. In contrast, the optimal temperature trajectories for the considered cases of CO_2 sequestration from air fall below 1.5°C.

The availability of a CO_2 sequestration option can reduce global warming (Fig. 4), and therefore reduce climate change damages and improve the weighted sum of present and future welfare (Eq. 8). A technology that would provide a feasible CO_2 sequestration option can hence have an economic value. We use our model to derive order of magnitude estimates for the economic value of sequestration over a wide range of initial marginal costs and reservoir half-life times (Fig. 5). The value of the CO_2 sequestration technology is estimated by the maximum amount a social planner would have been willing to pay in 2005 for such a CO_2 sequestration option. The value of a CO_2 sequestration technology is high when sequestration is relatively cheap and the reservoir half-life times are large. For example, the economic value of a CO_2 sequestration technology with costs of 100 U.S.$ per ton C and a millennium reservoir half-life time is on the order of ten percent of present-day GWP. In other words, an investment equivalent to several percent of present GWP (as a one-time investment) that would have delivered such a CO_2 sequestration technology would have passed a cost-benefit test in our model.

The benefits of CO_2 sequestration can justify a subsidy for this technology in the optimal economic growth model. This is illustrated by the optimal marginal abatement and sequestration costs for the case of sequestration from point sources (Fig. 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 optimal in the model because learning-by-doing considerably reduces the unit costs for the relatively new technology.

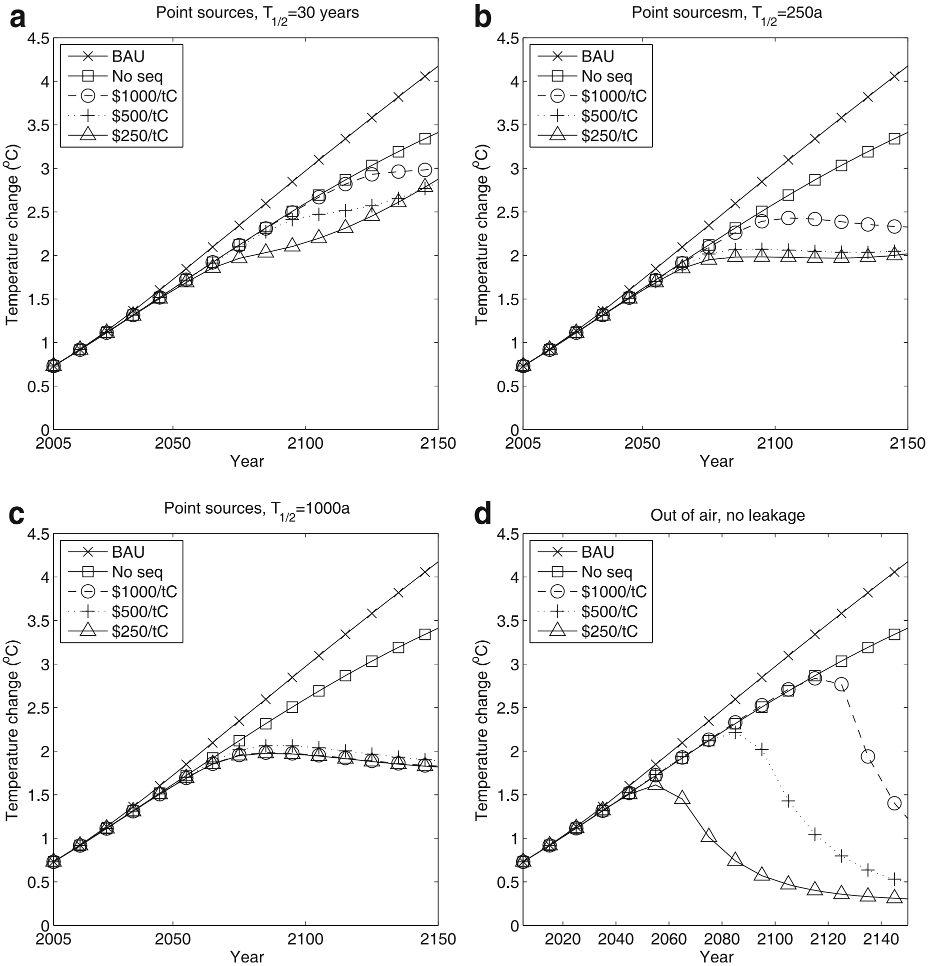

Fig. 4 Effects of different initial CO_2 sequestration costs on optimal temperature changes. The panels are the same as in Fig. 3. Shown are simulations for CO_2 sequestration from point sources and reservoir half-live times ($T_{1/2}$) of 30, 1,000, and 5,000 years, respectively (**a**, **b**, and **c**). The simulations in (**d**) are for CO_2 sequestration from air without leakage

The ratio of the marginal sequestration to abatement costs along an optimal trajectory is the economic efficiency of CO_2 sequestration (Fig. 6c). In the next few decades this economic efficiency is above 100% due to the positive externalities due to the learning-by-doing and the alleviation of future inertia constraints. Early sequestration efforts are quite valuable in this example. In the near term, the marginal sequestration costs are above the marginal abatement costs resulting in an economic efficiency of CO_2 sequestration above 100%. The marginal costs for CO_2 sequestration and abatement decline due to learning-by-doing. Because CO_2 sequestration is a less mature technology than CO_2 abatement, the marginal CO_2 sequestration costs decay faster than the marginal CO_2 abatement costs. In the long run, the marginal costs for optimal CO_2 sequestration fall below the marginal costs for optimal CO_2 abatement because CO_2 sequestration is inefficient (due to leakage) and hence has a lower shadow value than CO_2 abatement (similar to Fig. 2). The effect of the fossil fuel resource constraint is to increase the marginal CO_2 abatement costs along an

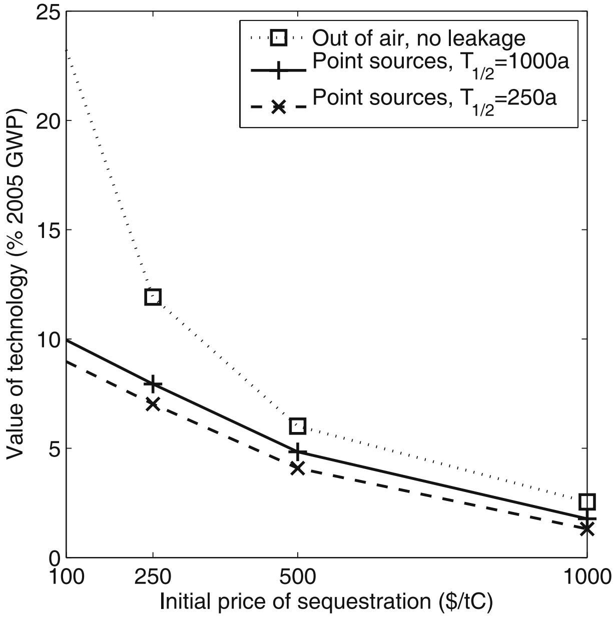

Fig. 5 Effect of different initial CO_2 sequestration costs and reservoir half-life times ($T_{1/2}$) on the economic value of the sequestration technology

optimal trajectory (Fig. 6a,b). This increase in marginal abatement costs is due to the increase in optimal CO_2 abatement that is required to keep the total fossil fuel use below the resource constraint. This increase in marginal CO_2 abatement costs causes a decrease in the CO_2 sequestration efficiency (Fig. 6c).

The optimal strategies are sensitive to structural and parametric assumptions. This is illustrated by the optimal trajectories for CO_2 concentrations and marginal CO_2 abatement costs for different values of (1) the progress ratio of sequestration, (2) the cumulative capacity of CO_2 sequestration in 2005, and (3) the socio-economic inertia constraint for CO_2 sequestration (Fig. 7). This sensitivity analysis suggests that the considered optimal trajectories are relatively insensitive before 2050 with respect to the considered parameter ranges. Beyond the model year 2050, however, the optimal trajectories diverge considerably. The optimal trajectories are most sensitive with respect to the parameter representing socio-economic inertia (Fig. 7e,f). Higher feasible expansion rates allow a higher deployment of CO_2 sequestration and result in lower optimal CO_2 concentrations and marginal CO_2 abatement costs. The trajectories of the optimal CO_2 concentration are basically identical for all considered progress ratios (Fig. 7a). Changing the progress ratio does affect the trajectories of the marginal CO_2 abatement costs (Fig. 7b). Cases with a faster reduction in the marginal CO_2 sequestration cost (i.e., lower progress ratios) show lower marginal CO_2 abatement costs. The availability of CO_2 sequestration decreases the optimal CO_2 trajectories (Fig. 7a) compared to the case without CO_2 sequestration (Fig. 3c) for all considered progress ratios.

5 Caveats and research needs

Our analysis is subject to considerable structural simplifications and uncertainties. We have chosen relatively simple model structures to provide a transparent analysis framework. This simplicity comes at the price of neglecting potentially important effects. For example, the

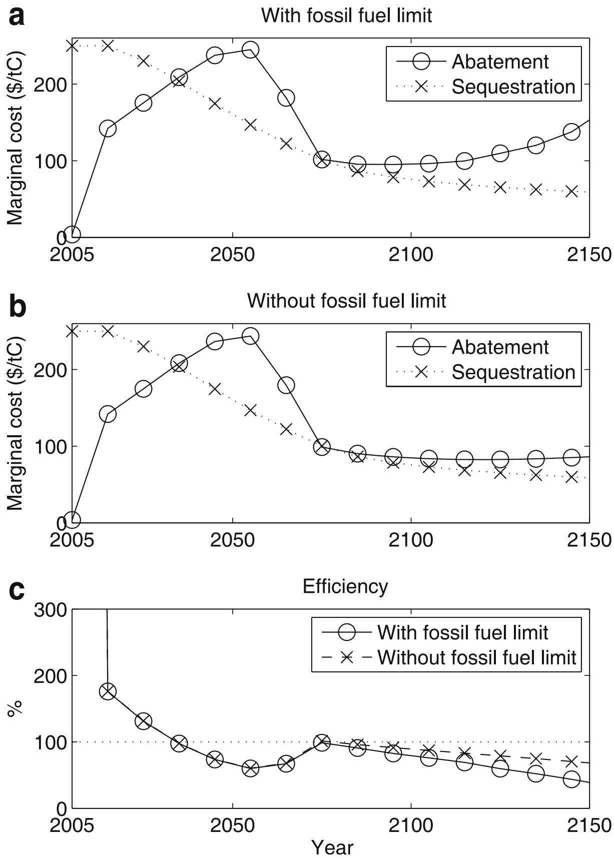

Fig. 6 Marginal costs for CO_2 sequestration and CO_2 abatement along the optimal trajectory with (**a**) and without (**b**) a constraint on the total available fossil fuel resource base. The simulations assume an initial sequestration price of 250 U.S.$ per ton C and a reservoir half-life time of 1,000 years. The ratios of the marginal sequestration to abatement costs for the two cases (which are a measure of the economic efficiency of CO_2 sequestration) are shown in panel **c**

numerical model aggregates all fossil fuels into a single resource and is thus ill-suited for analyzing the effects of potential changes in relative resource prices. Further examples of potential model refinements include representations of the likely increasing marginal costs of CO_2 sequestration with the increasing fraction of anthropogenic CO_2 emissions being sequestered, the consideration of model and parametric uncertainty (and learning about these uncertainties), and the consideration of more refined damage functions. The adopted damage function neglects, for example, adaptation to a warmer climate (in which case returning to pre-industrial levels may not be optimal), and rate dependent damages. We hypothesize that implementing damage functions that incorporate simple descriptions of the effects of adaptation and climate change rates (e.g., Lempert et al. 2000) would likely result in less stringent reductions of optimal CO_2 concentrations in the case of CO_2 sequestration from air (Fig. 3).

We explore some effects of parametric uncertainty by a simple scenario analysis. (Note that this approach still assumes perfect knowledge within each scenario). The high sensitivity of the optimal trajectories (Fig. 7) with respect to the representation of socio-economic inertia suggests that developing a more refined representation of this effect (cf. Schwoon and Tol 2006) may be a promising avenue for model refinements.

It is important to stress that our models are nothing more than thinking tools for analyzing the coupled natural-human system in an extremely simplified, but transparent and consistent way. Finally, it is important to recall two of our main assumptions: (1) CO_2

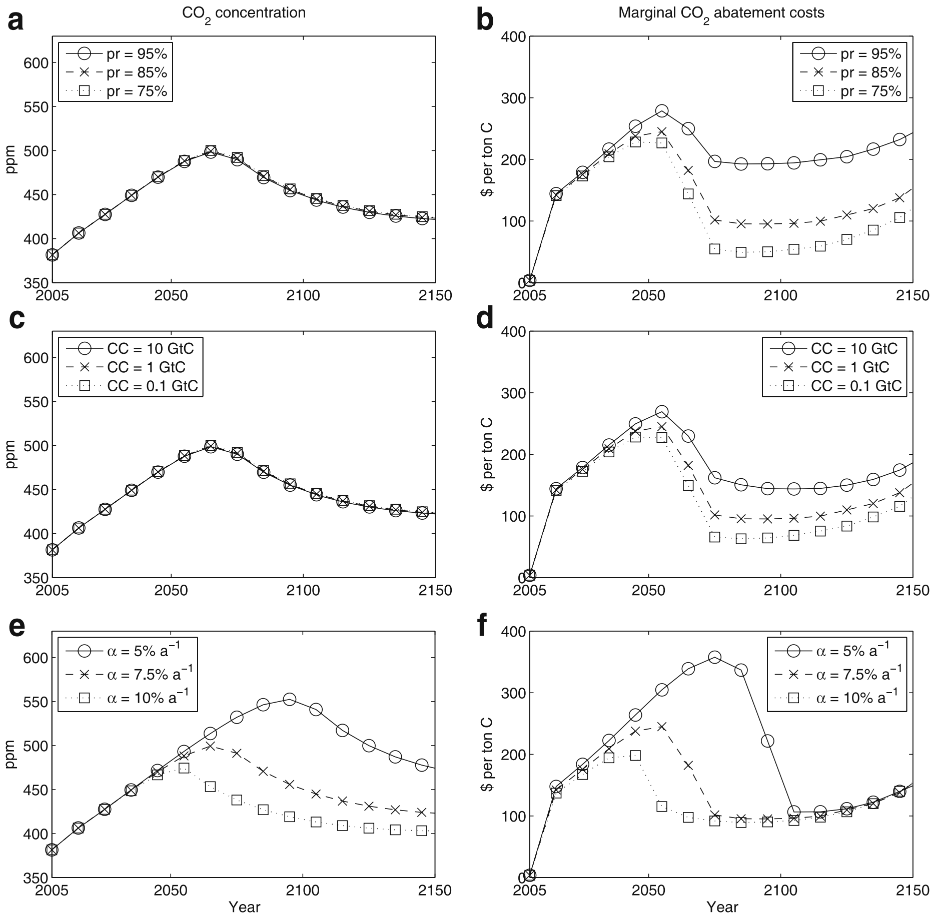

Fig. 7 Sensitivity study with respect to the representation of the sequestration progress ratio (**a** and **b**, parameter *pr*), the initial installed cumulative base of CO_2 sequestration (**c** and **d**, parameter CC_{Seq}, as defined in Eq. 32), and the technological inertia (**e** and **f**, parameter α_{Seq}, as defined in Eq. 34) for the case of CO_2 sequestration from point sources. Each sensitivity study compares the base case with a high and low value for the parameter in question. All simulations assume an initial sequestration price of 250 U.S.$ per ton C and a reservoir half-life time of 1,000 years

sequestration is both available and safe in large quantities; (2) Decisions are based on a discounted utilitarian framework.

6 Conclusions

We define an efficiency factor of CO_2 sequestration as the ratio of net benefit from a unit of sequestered CO_2 to the net benefit of a unit of avoided CO_2 emissions. This efficiency factor provides a consistent economic framework for analyzing the effects of leakage, discounting, learning-by-doing, socio-economic inertia, and energy requirements of CO_2 sequestration. We use a simple integrated assessment model of climate change to show that the positive economic impacts of CO_2 sequestration due to the reduction in future marginal sequestration costs and the alleviation of future inertia constraints can dominate over the negative economic impacts due to leakage and the additional fossil fuel requirements. As a result, a subsidy for the initially noncompetitive technology of CO_2 sequestration can be a sound economic policy. Our model suggests that capturing CO_2 (either from point sources or from the atmosphere) and sequestering it into reservoirs with millennium and longer residence times can be a welfare maximizing investment at current marginal costs.

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Appendix 1: List of symbols and their definitions

α	elasticity of marginal utility of consumption
α_{Seq}	maximum growth rate of CO_2 sequestration
A	total-factor productivity
β_0	initial carbon tax
β	carbon tax growth rate
b_i	parameters in the abatement cost equation
γ	constant share of capital in the economy
C	consumption
CC_{Seq}	cumulative installed capacity for CO_2 sequestration
c	per capita consumption
d	discount factor
δ_k	capital depreciation rate
E	anthropogenic CO_2 emissions
E_{Ind}	industrial CO_2 emissions
E_{Land}	land-use change driven CO_2 emissions
E_{Pen}	CO_2 emissions due to the additional fossil fuel requirement of CO_2 sequestration
Γ	sequestration cost scaling factor
ζ	CO_2 leakage rate
F	total radiative forcing
F_{Ex}	radiative forcing by non-CO_2 greenhouse gases
ϑ_1	inverse of the thermal capacity of the ocean mixed layer
ϑ_2	climate feedback parameter
ϑ_3	ratio of the heat capacity of the deep ocean to transfer rate from the oceanic mixed layer to the deep ocean
ϑ_4	inverse of the heat transfer rate from the upper to lower oceanic layers
η	efficiency factor of CO_2 sequestration
M_{At}	size of the atmospheric CO_2 pool
M_{Lo}	size of the lower ocean carbon pool
M_{Up}	size of the upper ocean carbon pool
M_{Res}	size of the sequestered carbon pool
κ	relative increase in CO_2 production due to sequestration
λ	relative energy penalty
l	leakage flux

I	investment
L	population size
Λ	output scaling factor accounting for mitigation costs
v	fraction of industrial emissions that is sequestered
n_{pr}	exponent in the learning-by-doing cost curve
π	fraction of CO_2 emissions that mixes immediately into the atmosphere
ρ	social rate of time preference
r	monetary discount rate
pr	progress ratio characterizing learning-by-doing
R	social rate of time preference discount factor
σ	carbon-intensity of economic activity
S	CO_2 sequestration flux
τ	tax
t	time
Δt	time-step size
t_0	initial time
T_{At}	global mean surface temperature change
T_{Lo}	deviation of the deep-ocean temperature from the 1900 level
$T_{1/2}$	CO_2 half-life time in the sequestration reservoir
μ	CO_2 emissions abatement rate
V	marginal cost of CO_2 sequestration
W	objective function
Q	output
ϕ_{ij}	CO_2 pools transfer rate parameters
χ	scaling parameter in the radiative forcing equation
ψ_i	parameters in the climate damage equation
Ω	output scaling factor accounting for climate damages

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