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Abstract

This paper addresses the timing of the use of biological carbon sequestration and its capacity to alleviate the carbon constraint on the energy sector. We constructed a stochastic optimal control model balancing the costs of fossil emission abatement, the opportunity costs of lands allocated to afforestation, and the costs of uncertain climate damages. We show that a minor part of the sequestration potential should start immediately as a 'brake', slowing down both the rate of growth of concentrations and the rate of abatement in the energy sector, thus increasing the option value of the emission trajectories. But, most of the potential is put in reserve to be used as a ``safety valve" after the resolution of uncertainty, if a higher and faster decarbonization is required: sequestration cuts off the peaks of costs of fossil abatement and postpones the pivoting of the energy system by up to two decades.

Keywords: biological carbon sequestration, carbon cycle, climate damages, optimal stochastic control, energy sector

Résumé

Cet article traite du tempo de l'utilisation de la séquestration biologique de carbone, et de sa capacité d'alléger la contrainte carbone pesant sur le secteur énergétique. Nous avons construit un modèle de contrôle optimal stochastique, mettant en balance les coûts de réduction des émissions fossiles, les coûts d'opportunité des terres destinées à l'afforestation, et les coûts de dommages climatiques incertains. Nous montrons qu'une petite partie du potentiel de séquestration doit être utilisée immédiatement tel un “frein” à l'augmentation des concentrations de CO_2 et aux efforts de réduction d'émissions dans le secteur énergétique, jouant donc à accroitre la valeur d'option des trajectoires d'émission de court terme. La majeure partie du potentiel de séquestration est réservée à un usage potentiel ultérieur à la résolution des incertitudes climatiques, au cas où une “mauvaise surprise” imposerait des taux de décarbonisation très élevés. Dans ce cas, l'utilisation de la séquestration biologique arase jusqu'à 40% du pic de coût de réduction fossile et permet de différer la date de pivotement du secteur énergétique de jusqu'à deux décades.

Mots-clés : séquestration biologique du carbone, cycle du carbone, dommages climatiques, contrôle optimal stochastique, système énergétique

The timing of biological carbon sequestration and carbon abatement in the energy sector under optimal strategies against climate risks*

Vincent Gitz[1], Jean-Charles Hourcade[2] and Philippe Ciais[3]

Abstract. This paper addresses the timing of the use of biological carbon sequestration and its capacity to alleviate the carbon constraint on the energy sector. We constructed a stochastic optimal control model balancing the costs of fossil emission abatement, the opportunity costs of lands allocated to afforestation, and the costs of uncertain climate damages. We show that a minor part of the sequestration potential should start immediately as a "brake", slowing down both the rate of growth of concentrations and the rate of abatement in the energy sector, thus increasing the option value of the emission trajectories. But, most of the potential is put in reserve to be used as a "safety valve" after the resolution of uncertainty, if a higher and faster decarbonization is required: sequestration cuts off the peaks of costs of fossil abatement and postpones the pivoting of the energy system by up to two decades.

Introduction

Since 1992, debates about biological sequestration of carbon have become an increasingly critical point of contention in climate negotiations[1]. On the last night of the Conference of the Parties in The Hague in 2000 (COP6), delegates met for a final round of negotiations to keep the US on board, but they failed to reach consensus on the amount of sequestered carbon to be allowed to count towards emissions targets under Articles 3.3 and 3.4 of the Kyoto Protocol. This attempt failed for many reasons among which was political tension between two opposing views: some considered sequestration as an attempt to relax the emission constraint on the energy systems. Others considered biological carbon sequestration (BCS) as dangerous loophole, opening the door to excessive delays in energy abatement efforts, while the effect on climate would ultimately be conditioned by the permanence of forests [*Lashof and Hare*, 1999].

This paper adds an economic rationale to this debate by framing it in terms of optimal timing of action under uncertainty. This approach has become conventional since the early nineties [*Nordhaus*, 1994; *Manne and Richels*, 1992] and was used to clarify discussions about the adequacy of various emission targets proposed in Kyoto [*Wigley et al.*, 1996; *Ha-Duong et al.*, 1997]. However, surprisingly, it has been little used so far to clarify carbon sequestration issues[2].

Optimal control models highlight the role of the interplay between inertia and uncertainty in designing climate policies. In the case of heterogeneous capital turnovers, they suggest, for example, that action has to start first in sectors with high inertia or slow turnover, and move on to sectors that have more rapid turnovers, hence less technical inertia [*Lecocq and Hourcade*, 2001]. They also can be used to scrutinize the optimal timing of mobilizing various technical options with different inertia.

Biological carbon sequestration pertains to the category of techniques not hampered by low turnover of capital stock, such as existing electricity plants, transportation infrastructure or buildings. There are many forms of institutional constraints or transaction costs which can slow down the pace of a sequestration pro-

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[1]This debate is politically distinct from the consideration of other land-based strategies like bio-energy which was from the outset understood as normally rewarded by the carbon trading internal to the energy system.

[2]A significant body of literature studies BCS policies, but does not work on a sequential decision making mode; it uses either exogenous carbon prices [*Van't Veld and Plantinga*, 2005; *McCarl and Schneider*, 2001]; or, as in *Sohngen and Mendelsohn* [2003], provides an optimal timing of sequestration without accounting for uncertainty the damage function which, as we will show, matters for short term decisions.

gram. But, in economic terms, the cost of BCS is not solely a matter of investment and operating and maintenance expenditures; it also incorporates the opportunity costs of removing land from other uses[3]. Thus the costs incurred by *a given date* are dependent upon the *cumulative* amount of afforested areas, in turn creating an economic limit to the cumulative amount of carbon that can be stored through this mechanism as a substitute for abatement in the energy sector.

The path dependency of BCS costs immediately raises the question of when to use it:

- should it be used as a brake for net emission growth in the short-term, taking advantage *immediately* of cheap sequestration to gain time to allow for the large scale diffusion of cheaper carbon saving technologies? This was is the only perspective that was discussed at COP6;
- or should it be used as a safety valve, *triggered later* to reduce the costs of accelerating abatement efforts in case of "bad news" regarding the consequences of global warming? This is akin to Dyson's [*1997*] intuition: *"Suppose that with the rising level of CO_2 we run into an acute ecological disaster. Would it then be possible for us to halt or reverse the rise in CO_2 within a few years by means less drastic than the shutdown of industrial civilization?"*.

This paper will try to clarify the terms of the tradeoff between timing and costs of mitigation options. Howver, to keep the analysis simple and fully targeted to the timing of BCS, we neglect the feedbacks between costs related to the energy system strategies (including energy substitution through bio-energy) and the cost of land available for BCS[4].

In section I, we describe the theoretical determinants of the social monetary value of biological carbon sequestration and outline the main conceptual differences between abatement activities in the energy sector and biological sequestration activities. In section II, we develop an integrated optimal control model in the context of uncertainty and learning about climate damages to examine the pattern of abatement and sequestration activities. In section III, we examine the optimal timing of biological sequestration in view of analyzing how it relaxes the carbon constraint on the energy sector.

[3]For example, *Makundi and Sathaye* [2004] account for plantation costs in tropical countries in a range of 18-500 US$/ha, values within the low to mid-range of the *annual* agricultural land opportunity costs worldwide (see Section 2).

[4]In case of large scale development of bio-energy, this feedback may be significant in the US [*Schneider and McCarl*, 2003] or Europe, but remains uncertain at world level [*Smeets et al.*, 2005]. As we will show in sensitivity tests, its magnitude may change the amount of BCS but not its time profile.

I) Monetary social value of biological carbon sequestration and its dependence upon energy policies

The rationale behind using BCS in long term climate control relies on two premises:

(a) the climate benefit of one ton of *ad-infinitum* sequestered carbon at date t and one ton of non emitted carbon at the same date are roughly equivalent[5].

(b) costs of sequestration are significantly lower than GHGs emissions abatement costs in the energy system.

This section moves beyond these premises by analyzing the time dependance of the costs and benefits of either permanent or temporary BCS.

I-1) Costs of permanent vs. temporary carbon sequestration

Permanent sequestration refers to projects in which, once the forest reaches its maximum sequestration capacity, its carbon stock is maintained constant in the absence of natural hazards or criminal fire. Costs of such large scale sequestration may be by construction dominated by the annual opportunity costs of lands, which span over an infinite time period if land scarcity makes costs for a given hectare grow over time significantly compared with other goods and production factors.

The economic return from a permanent sequestration project is then limited; inexorably a time comes where the net flux of carbon stored through a project vanishes, while opportunity costs are still incurred just in order to keep the carbon stock in place.

This provides arguments in favor of temporary sequestration whereby sequestered carbon may deliberately be released in the future, and afforested lands reallocated to other activities, for example when technological progress allows for decarbonization of the energy systems at a lower cost.

I-2) Monetary social value of permanent and temporary sequestered carbon

The monetary social value of sequestration is the difference between the discounted sum of climate change damages in a climate control scenario based on the sole emissions abatement in the energy sector, and in a scenario in which BCS is also included.

[5]This is not strictly true because sequestered carbon may leak out due to human-induced or natural disturbances, and because the pace of afforestation or deforestation impacts the carbon cycle, implying that carbon from fossil reservoirs contribute less to atmospheric CO_2 increase than the same quantity released via land-use change [*Gitz and Ciais*, 2003, 2004]. These effects are neglected in this paper.

We postulate that damages are directly linked to CO_2 concentration by a yet unknown damage function $C(t) \mapsto D(C(t))$, which is increasing with C. Let us assume, for reasons of tractability but with no significant loss in precision, that the relation linking net sources $e(t)$ of carbon and the excess atmospheric carbon over pre-industrial concentrations $C(t) - C_{\text{preind}}$, is linear and time-homogenous. This assumes the existence of an atmospheric pulse response function $R(t)$[6] such that:

$$C(t) = C_{\text{preind}} + \int_0^t e(u)R(t-u)du \tag{1}$$

Let now $C_r(t)$ be a reference atmospheric concentration trajectory, and $\mathcal{P}(\sigma, t, \tau)$ a project of storing a volume of carbon σ (in tC) in a biological reservoir between t and $t+\tau$. In case of a permanent sequestration $\tau = +\infty$ and the project contributes to climate change mitigation in the same proportion as a fossil abatement of a volume σ done at t. Fig. 1a and 1b respectively display the net gain $\zeta_{\mathcal{P}}(t) = C(t) - C_r(t)$ in concentrations for a permanent project and for a temporary sequestration project which releases the stored tons at date τ.

Let $\boldsymbol{\mathcal{D}}(C_r, \sigma, t, \tau)$ be the total discounted climate damages of the atmospheric trajectory $(s \mapsto C_r(s) + \zeta_{\mathcal{P}}(s))$. By definition:

$$\boldsymbol{\mathcal{D}}(C_r, \sigma, t, \tau) = \int_0^{+\infty} e^{-\rho s} D\big(C_r(s) + \zeta_{\mathcal{P}(\sigma,t,\tau)}(s)\big)ds \tag{2}$$

where ρ is the discount rate. The monetary social value $\mathcal{V}$ of the project is the difference in total atmospheric discounted damages between the trajectory with and without the project:

$$\mathcal{V}(C_r, \sigma, t, \tau) = -\int_0^{+\infty} e^{-\rho s} \Delta D(s)ds \tag{3}$$

where

$$\Delta D(s) = D\big(C_r(s) + \zeta_{\mathcal{P}(\sigma,t,\tau)}(s)\big) - D\big(C_r(s)\big) \tag{4}$$

The first, seemingly trivial consequence is that, if we assume $D'(C) > 0$, the value of permanent sequestration project is unambiguously positive. This is not the case for temporary sequestration, its value being the

[6] $R(t)$ is the Green function which gives the evolution of the atmospheric perturbation caused by a unitary pulse of concentration (or emission) at $t = 0$. $R(t)$ is decreasing with t, since terrestrial and oceanic sinks progressively absorb any pulse of excess carbon in the atmosphere.

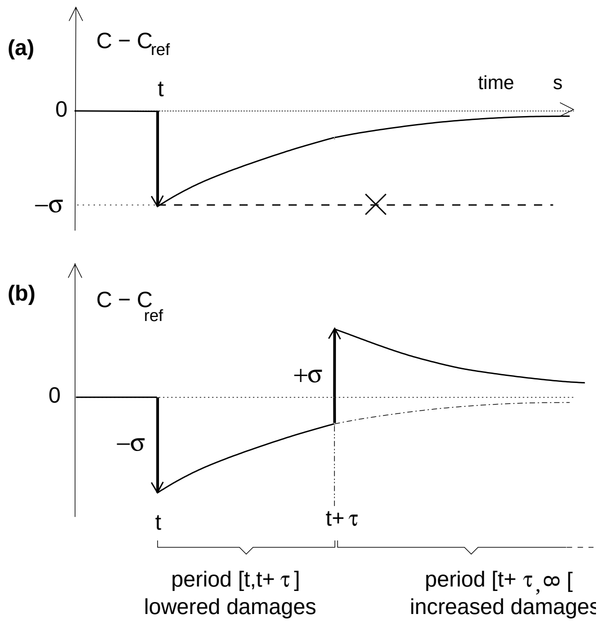


Figure 1. Atmospheric CO_2 defined as the difference between concentration curves in worlds with and without a BCS project. (a) Permanent sequestration project, (b) temporary sequestration project between t and $t+\tau$. With our hypothesis of a linear carbon cycle, the curve in (a) is $s \mapsto -\sigma R(s)$. Note that atmospheric CO_2 excess is different from a stock pollutant (dashed line in (a)): because of this, after release, a temporary BCS project leads to higher atmospheric CO_2 levels than without any project.

sum of a positive term relative to the avoided damages $\Delta D(s) < 0$ during the storage period, and of a negative term accounting for additionnal damages $\Delta D(s) > 0$ after the date of release:

$$\mathcal{V}(C_r, \sigma, t, \tau) = -\int_t^{t+\tau} e^{-\rho s} \Delta D(s) ds - \int_{t+\tau}^{+\infty} e^{-\rho s} \Delta D(s) ds \qquad (5)$$

This gives a critical role both to the time profile of reference concentration trajectory $C_r(t)$ and to the shape of the damage function $D(C)$ in assessing the timeliness of the storage period $[t, t+\tau]$. Indeed, storage is more valuable during periods of high damages, and release has a lower social cost if followed by a period of low damages.

This in turn makes the social value of both forms of sequestration ultimately dependant upon the abatement in the energy sector. This value may be low either because the climate damages are low on a "no policy" scenario; or because energy policies resulted in a low concentration profile and/or low marginal emission abatement costs at the date of release of the sequestered carbon. This explains why the main argument in favor of temporary sequestration was the buying time argument [*Lecocq and Chomitz*, 2001] to launch such projects and possibly reverse them if, given new information, this is proven to be socially desirable.

But the optimal timing of this sequestration-release sequence remains to be determined. It depends upon assumptions about the discount rate[7], the relative dynamics of costs formation in the land use and in the energy sector, climate damages and about the progressive resolution of uncertainty surrounding them.

II) Balancing costs and climate benefits of energy policies and of biological sequestration

Within the limits of the benevolent central planner metaphor, optimal control models have the advantage of treating in a consistent manner energy policies and biological sequestration as command variables to meet a given climate objective.

After having sketched our modeling tool, we focus hereafter on how we treat the difference in nature between costs of biological sequestration and costs of emission abatement in the energy sector.

[7] High discount rates lower the social cost of release, everything else being equal.

II-1) A two controls stochastic optimal control model

Response–sequestration (Response-sq) is an extension of the DIAM[8] [*Ha-Duong et al.*, 1997] model designed to scrutinize the optimal timing of mitigation policies.

First, a "no-climate damage / no mitigation" reference scenario is defined to reproduce the IS92a scenario up to 2100 [*Hoffert et al.*, 1998]. This gives a scenario with (i) an annual GDP growth rate[9] $g = 2.5\%.yr^{-1}$ and (ii) fossil CO_2 emissions $E^{ref}(t)$ increasing up to 20 GtC.yr^{-1} by 2100. It anticipates a progression of the energy efficiency (primary energy power/GDP) of 1%.yr^{-1} from 0.49 W.yr.$\$^{-1}$ to about 0.25 W.yr.$\$^{-1}$; and a decrease of carbon intensity in the global energy mix from 0.56 to 0.42 kgC.yr^{-1}.W^{-1}, due to substantial introduction of carbon-free power[10].

Second, climate damages are defined in terms of losses over the reference GDP as a function of the atmospheric CO_2 concentrations, as in [*Dumas and Ha-Duong*, 2004]. Three functional forms are retained (Fig. 2) capturing three beliefs about climate damages $s \in \{L, M, H\}$ (L for low, M for medium, H for high). These damage functions are S-shaped, indiscernible under 500 ppm. This specification presents the advantages, compared with parabolic damage curves, to test high damages hypothesis without the inconvenience of unrealistic GDP losses for high concentrations, and to allow for the elicitation of views about "critical CO_2 thresholds" [*Ambrosi et al.*, 2003].

Climate control scenarios are computed sequentially: at dates up to t_{info}, the value of damages is unknown and the "benevolent planner" selects a unique control trajectory using a subjective distribution of probabilities $p(s)$ about climate damages. At t_{info}, information about the correct value of damages is revealed and the program adjusts the trajectory accordingly. Response-sq maximizes (Fig. 3) the expected value J of the discounted sum of utility flows $\mathcal{U}(s,t)$ using two command variables, the carbon abatement level $x(s,t) \in [0,1]$ in the energy sector relative to fossil emissions baseline $E^{ref}(t)$, and the annual increment $a(s,t)$ of lands diverted from other uses to sequester carbon[11].

[8] DIAM: a model of the dynamics of inertia and adaptability for integrated assessment of climate change mitigation.

[9] This growth pathway is assumed to maximize a logarithmic utility of consumption and the pure time preference coefficient is calibrated accordingly.

[10] In IS92a, renewables and nuclear produce 20TW of the 46TW primary energy needed by 2100, compared with current production of 1.3 TW of renewables and nuclear out of 11 TW of primary energy. The share of coal in fossil fuels now at about 40% rises to 85% by 2100. In terms of carbon intensity, the increase from coal is more than compensated for by the decrease from renewables.

[11] Negative values of $a(t)$ are allowed, accounting for voluntary biological carbon release.

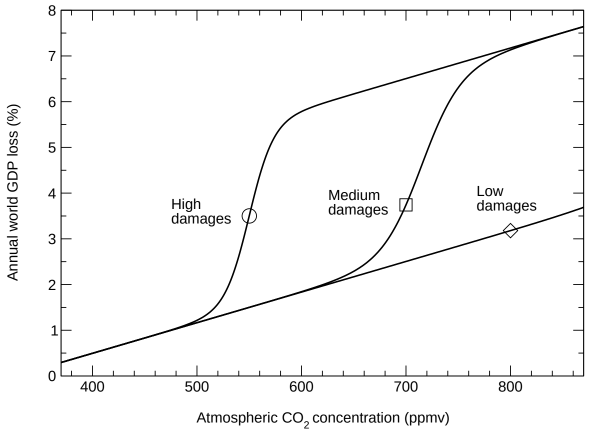


Figure 2. Damage cost functions $D(s, CO_2)$ in Response-sq, after [*Dumas and Ha-Duong*, 2004]. Argument $s = \{H, M, L\}$ relates to different states of the world (circle for H, square for M, and diamond for L), where parameters of the damage function are different (see Table 2 for parameterization). $D(s,t) = D_{\text{lin}}(s,t) + D_{\text{sig}}(s,t)$, with $D_{\text{lin}}(s,t) = \frac{\delta_{\text{lin}}}{(1+\theta)^t} \frac{C(s,t-\tau_D)-C_l^1}{C_l^2-C_l^1}$ and $D_{\text{sig}}(s,t) = \delta_{\text{sig}}\big(1+\exp\{\frac{\hat{C}(s)+\check{C}(s)-2C(s,t-\tau_D)}{\hat{C}(s)-\check{C}(s)}\, log\frac{2-e}{e}\}\big)^{-1}$. θ is an adaptation parameter; $\check{C}$ the concentration level beyond which singularities appear in the damages; $\hat{C}$ the concentration ceiling beyond which damages level off again; and e the steepness of the damage curve beyond $\check{C}$.

$$\max_{x(s,t),a(s,t)} J = \sum_{s=L,M,H} \left[p(s) \sum_{t=0}^{T} \frac{\mathcal{U}(s,t)}{(1+\rho)^t} \right] \quad (6)$$

with

$$\mathcal{U}(s,t) = \log\Big[\big(1 - D(s,t)\big)\Pi^{ref}(t) - Q_f(s,t) - Q_l(s,t)\Big] \quad (7)$$

The evolution of the atmospheric CO_2 is captured by an atmospheric pulse response function[12] $R(t)$, taken from [*Wigley*, 1993]:

$$C(s,t) = C^{ref}(t) - 0.471 \sum_{u=t_0}^{u=t-1} \Bigg[R(t-u) \Big(x(s,u)E^{ref}(u) + \sum_{v=u-\tau-1}^{u} \frac{\kappa}{\tau_F} a(s,v) \Big) \Bigg] \quad (8)$$

Carbon sink per hectare afforested is constant in time and saturates at κ tC/ha after τ_F years. We set $\kappa = 200$ tC/ha and $\tau_F = 50$ yrs as a central hypothesis. The total area of afforested lands follows $A(s,t) = a(s,t) + A(s,t-1)$.

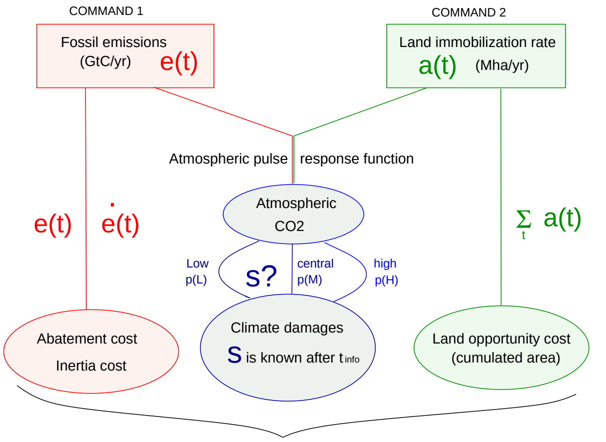
Equation (6) indicates that, given the flow of income Π^{ref} in the reference scenario, the optimal net emissions pathway depends on the abatement costs in the energy sector $Q_f(s,t)$, on the sequestration costs $Q_l(s,t)$ and on climate damages $D(s,t)$.

II-2) Costs of CO_2 abatement and costs of biological sequestration: measurement issues

Abatement expenses in the energy sector depend not only on the cost efficiency of available techniques but also on both the rate and speed of abatement. Whatever the representation of technical change, abatement costs Q_f can be analyzed as composed of both permanent costs and transition costs due to the premature retirement of capital and to the acceleration of the diffusion of semi-matured techniques. Even though an induced technical change specification [*Grübler et al.*, 2002] will intrinsically give more weight to transition costs, we retained in this paper a specification with exogenous technical change:

$$Q_f(s,t) = \frac{c_f\, \Pi_0}{(1+\phi)^t} \frac{E^{ref}(t)}{E_0^{ref}} \Big[x(s,t)^2 + \big(\tau_E \dot{x}(s,t)\big)^2 \Big] \quad (9)$$

[12]The coefficient 0.471 in Eq. 4 converts emissions (in GtC) into units of atmospheric concentration (in ppmv).



$$\max_{e(s,t),a(s,t)} \mathbb{E}\left[\sum_t \frac{\mathcal{U}(s,t)}{(1+\rho)^t}\right]$$

Figure 3. Schematic representation of the Response-sq model. State of the world s is revealed after t_{info}.

where $\dot{x}(s,t) = x(s,t) - x(s,t-1)$ captures the transition costs; ϕ is the rate of exogenous technical change; τ_E the "characteristic time" of energy systems. This parameter encompasses all the factors constraining the pivoting of energy systems (existing equipments, R&D diffusion, formation of human capital); historical experience suggest that it spans between 25 to 50 years [*Grübler*, 1991]. Cost estimates for carbon free technology vary widely [*IPCC*, 1996, 2001] reflecting various assumptions about technical prospects. In this exercise, we chose $\tau_E = 50$ years and coefficient c_f is calibrated so as to reproduce the average of the present discounted cost (4x10^{12}\$) for stabilizing the CO_2 concentrations at 550 ppm, as reviewed by the third assessment report of the *IPCC* [2001], and produced by the Stanford Energy Modeling Forum [*Edmonds et al.*, 2004].

Assessing social costs of biological sequestration represents a totally different challenge. As noticed by *Sohngen and Mendelsohn* [2003], literature does not provide robust assessment of the drivers of the opportunity costs of land $Q_l(A(t))$ worldwide in a general equilibrium framework, neither at present nor in the future. This is the reason why many studies set opportunity cost of land to zero, making afforestation a "manna from heaven" [*Manne and Richels*, 1999], similar to a no-cost abatement potential in energy sectors. Consolidated data are provided only for the US either based on agricultural and forestry sectoral models [*Adams et al.*, 1996, 1993; *McCarl and Schneider*, 2000, 2001], or on econometric analyses [*Newell and Stavins*, 2000; *Stavins*, 1999]. Very fragmented data exist for tropical regions derived from bottom-up studies [*Makundi and Sathaye*, 2004; *Kauppi et al.*, 2001].

To circumvent these limitations and construct a rough

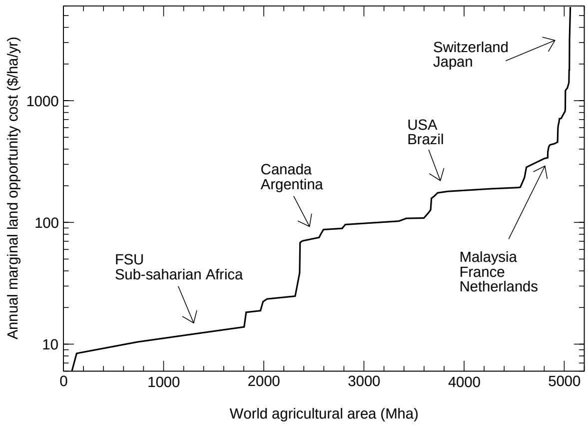


Figure 4. Marginal opportunity cost of agricultural lands in 1997 based on FAO data for areas and GTAP data per country (logarithmic scale), with indication of the position of particular countries.

but reasonable estimate of the current and future opportunity costs curves of the world's agricultural area suitable for afforestation, we compiled per country data from the FAO for cropland and pastures areas [*FAO*, 2005], and from the GTAP database for the agricultural net revenue in 1997 [*GTAP*, 2001]. This allows to rank (Fig. 4) the world agricultural areas, country by country, by increasing average net revenue per hectare. In the lower bound of the curve (revenue per hectare inferior to 100 US\$ $ha^{-1}yr^{-1}$), we unsurprisingly find African countries (Botswana, Mozambique, Zambia with low productive agriculture), and countries with very extensive agricultural practices (Australia, New Zealand, Argentina). US and Brazil show a net revenue of 189 and 193 US\$ $ha^{-1}yr^{-1}$ respectively, relatively low due to extensive cattle ranching. Revenues are higher in rice producing countries (Malaysia 667 US\$ $ha^{-1}yr^{-1}$) and in Europe, and reach their maximum in countries with very intensive or highly subsidized agriculture (Netherlands 1783 US\$ $ha^{-1}yr^{-1}$, Switzerland 3180 US\$ $ha^{-1}yr^{-1}$ or Japan 4913 US\$ $ha^{-1}yr^{-1}$).

To account for geo-climatic constraints we excluded in a second step agricultural land non suitable for afforestation, using the maps of potential and existing vegetation from *Ramankutty and Foley* [1999]. Typically, part of the agricultural areas of African countries with the lower opportunity cost are in great majority unsuitable for afforestation and are taken out of calculation. After these corrections, the real afforestation potential is globally 986 Mha, Fig. 5 shows the resulting curve $Q_l(A(t))$ of total annual opportunity cost of agricultural lands suitable to afforestation in 1997.

From this benchmark, future land costs are conditional upon future land productivity, future needs for

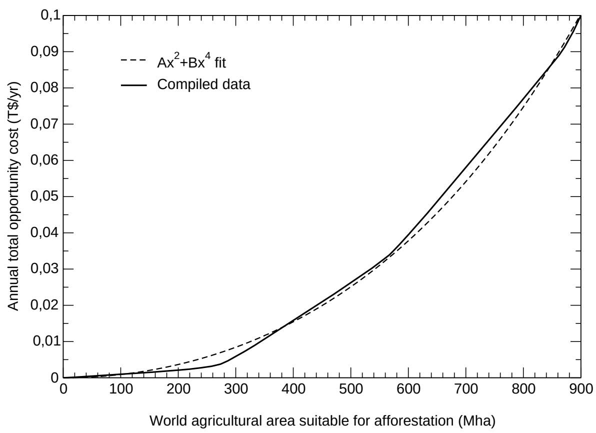


Figure 5. Total annual opportunity cost $Q_l(A)$ of agricultural lands suitable to afforestation in 1997. The model is run using a fitted function (dashed line) $Q_l(A)\big|_{1997} = 8.98517 \times 10^{-8}A^2 + 4.21002 \times 10^{-14}A^4$ of the compiled data (solid curve; see text). For subsequent years, $Q_l(A,t) = f(t)Q_l(A)\big|_{1997}$, where $f(t)$ is a scalar whose value is 1 for $t = 1997$ and increasing at a rate of of 2.25% yr^{-1} (resp 1.25% yr^{-1}, 0.25% yr^{-1}) within the 21st (resp. 22nd, 23rd) century.

food that result from demographic dynamics, households enrichment and alimentary diet diversification [*Colomb*, 1999]; and upon elements not directly linked to agriculture like the need for urban or peri-urban space. The function Q_l in Fig. 5 changes in the future under the assumption that marginal opportunity costs rises uniformly at a rate of 2.25% yr^{-1} over the 21st century (a value equal to the best-fit growth rate of world agricultural output between 1961 and 2003 [*FAO*, 2005]). This rate is supposed to decrease linearly by 1 point/century after 2100, an hypothesis also adopted for the growth rate of the economy. This correlation between the opportunity cost of land and its agricultural output can be changed only in case of substantial technological innovation in food and feed production which could make more agricultural land available for other uses, and if these innovations do not confront acceptability barriers due to a mix of economic and cultural reasons.

Land opportunity costs could be in part offset by the economic co-benefits of afforestation like cleaner water, reduced erosion, effects on biodiversity, increased recreational land. *Elbakidze and McCarl* [2004] show that such co-benefits might represent 50 to 78% of the cost of sequestration for the USA. However, since there is no credible comprehensive study of these side effects at a world level, we decided not to account for them in our best-guess estimate, and to capture them at first approximation in our sensitivity tests through lower bounds of opportunity cost of land.

III) Sequestration: brake and/or safety valve?

The relevant benchmark to study the role of sequestration is the profile of optimal fossil abatement pathway when no sequestration option is permitted. Many such optimal expenditures profiles may be envisaged, that derive from different fossil abatement costs functions and from the share of adjustment costs within total abatement costs. Solid curves in Fig. 6 report optimal policies without BCS. The striking feature of Fig. 6c is a systematic peak in the chronogram of total expenditures after the resolution of uncertainty: this peak is low and gently sloped in case of good news suggesting that damages will be ultimately moderate, but it is very high and steeply sloped in the pessimistic case. This is due to the fact that “bad news” forces an accelerated turnover of capital stocks.

Whatever the value judgment whether a peak of 1.3% of total GDP devoted to abatement expenditures is a high or low value[13], or whether costs curves used in this exercise are understated or overstated, the policy insight is clear about possible economic and social shocks entailed by such accelerated abatement policies.

This raises the question of to what extent the bulk of the sequestration options should be used only after the resolution of uncertainty as a safety device apt to plane down these possible peaks of abatement expenditures.

III-1) Lessons from a central case with best-guess cost estimates of the opportunity cost of land

Response-sq suggests that before t_{info}=2040, annual sequestration rates should reach about the current rate of deforestation (10 Mha yr^{-1}, Fig. 6, dashed curves). These sequestration rates are higher in the first years of this period because costless lands are used immediately. In total, by 2040, 69.2 Mha have been afforested, 7% of the 986 Mha potential. The abatement rate in the energy sector is reduced by 18%, and cumulative emissions for the energy sector increases by 1.6 GtC by 2040. But overall BCS more than compensates: only 23% of the early storage is pure substitute to fossil emissions and alleviates the carbon constraint on the energy sector; the remaining 77% serves to increasing the option value in 2040. Atmospheric CO_2 is indeed 3.0 ppm lower with BCS than in a fossil-only policy, which represents an 18 months delay in the apparition of damages.

Even through the use of sequestration before the resolution of the uncertainty is significant (69 Mha are equivalent to about 30 years of Amazonian deforesta-

[13] An aggregation bias in such macroeconomic figures often masks their real implications: assuming a 20% share of the investments on total GDP, among which 40% devoted to construction, 1.3% of GDP represents 10.8% of total investment in other infrastructures, industry and services.

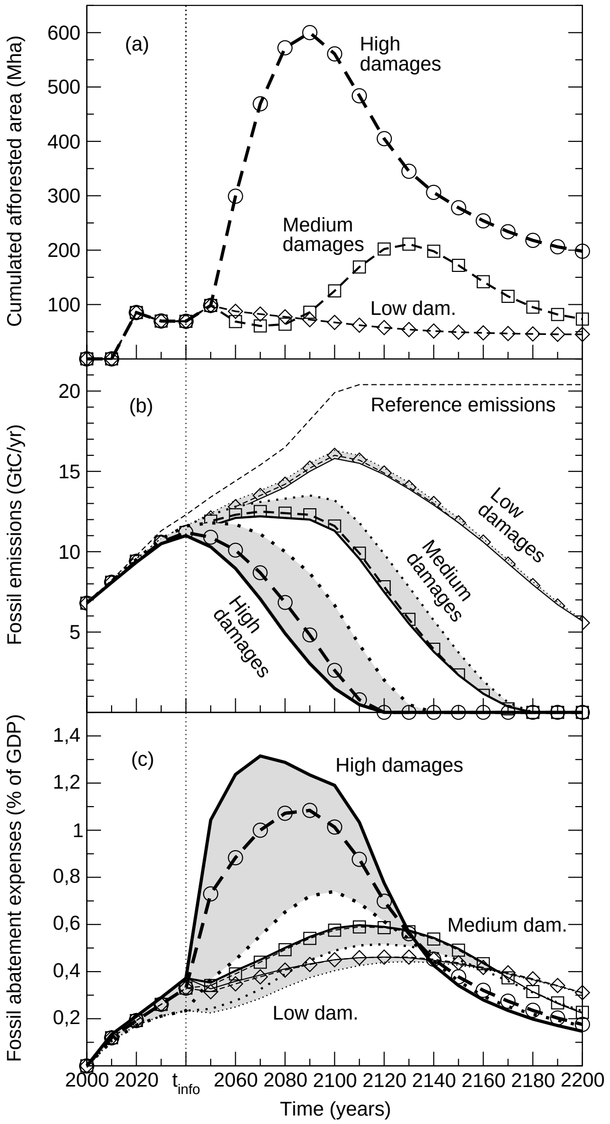


Figure 6. Optimal trajectories of Response-sq for the best-guess simulation and the sensitivity tests. Solid curves: no-sequestration scenarios. Dashed curves: sequestration scenarios using the best-guess estimate of opportunity cost of land and carbon storage per ha. Shaded areas: sequestration scenarios over range of trajectories according to the sensitivity tests described in Table 1. (a) Areas afforested in the best-guess simulation; (b) Fossil emissions trajectories; (c) Fossil abatement cost profiles. After t_{info}, damage function is revealed. Best-guess sequestration scenarios (dashed curves) are identified with circles for high damages, squares for medium damages, diamonds for low damages.

tion at current rates), the bulk of the available potential is being reserved for an eventual later use. After the resolution of uncertainty about damages, afforestation depends on the revealed damage function. For high and medium damage cases, the peak of afforestation is time-correlated with the peak of abatement expenses in the energy sector. The higher the damage function, the higher and sooner the peak of abatement expenses (in share of GDP, Fig. 6c), the higher the social value of sequestration, and the larger the areas afforested (Fig. 6a).

- If damages are low, the hedging strategy has generated an "overcautious" trajectory (with respect to a case where low damages would be known from the outset), and the carbon stored in excess during the first periods is progressively released in the long run.
- If damages are high, a large scale sequestration program is triggered, mobilizing more than one tenth of the existing agricultural lands (an area equivalent to twice the present forested lands in the US), and reaches a peak of 600 Mha afforested (200 Mha in case of medium damages). This near order-of-magnitude surge in sequestration from around 69 Mha to 600 Mha approaches the size of the "*carbon banks*" of *Dyson* [1977].

In all situations much of the afforestation can be reversed after transition. In the high and medium damage cases, 2/3rds of the maximum afforested area is converted back to other uses once the energy system transitions.

Unsurprisingly, this safety valve erodes the peak of abatement expenses in the energy sector, since it adds new mitigation options to those existing in the energy system. This reduction is nearly 19% in the high damages case (after 2040, the dashed line in Fig. 6c), which is all the more significant as this percent applies to very high energy costs. Another non trivial result is the time gained for coming to very low carbon intensive energy profiles. A good index is the period allowed to return to 1997 emissions. This date is 2070 in the no-sequestration strategy and 2079 in case of optimal use of sequestration. These nine years are not negligible since, for a t_{info} at 2040, this expands by 1/3 the transition period for pivoting the energy system.

III-2) Sensitivity tests

We carried out a very wide range of sensitivity tests, assuming that the cost of land may be four times lower to four times higher than our "best guess" estimate (reflecting uncertainties among which the value of side-benefits and the feedbacks of bio-energy on the cost of land). In addition we tested hypothesis in terms of carbon stored per ha (including wood products and soil carbon) ranging from 40 to 360 tC/ha. Results displayed as shaded areas in Fig. 6, and in Table. 1, shows the robustness of the conclusions concerning the effect of BCS on energy policies:

- before t_{info}, most of the sequestered carbon serves to buy environmental option value. In the most favorable case, it only allows for additional 5.4 GtC cumulated emissions before t_{info} above emissions of a carbon control policy without BCS.
- the peak of abatement costs in case of high damages is cut down by 7% to 32% under hypothesis of cost of lands from +100% to -50% the best guess, and carbon stored per ha varying ±40% around the central estimate.
- the gain of time for coming back to the 1997 fossil emissions level, which was 9 years in the best guess case, can range from no gain to a gain of 28 years across the scenarios considered.

These sensitivity tests show how the contribution of BCS to the alleviation of the burden on the energy sector vary in function of assumptions about the opportunity cost of land. If substantial co-benefits exist, offsetting worldwide up to 3/4 of the land costs, as estimated for the US by *Elbakidze and McCarl* [2004], the BCS program is launched sooner (up to 277 Mha afforested by 2040), but the "safety valve" has also a greater contribution: the whole potential is used and allows for cutting by 29% fossil abatement peak expenses. This confirms that time profiles of sequestration are robust to assumptions about the net cost of land, with the major part of the potential always used as a safety valve after t_{info}.

Finally, since it is unlikely that climate policy will try and directly modify the cost of land, the productivity of the afforestation is a critical factor to relax the constraints impinging on the energy sector. An 80% gain in productivity from our central estimate relaxes the abatement rate in the energy sector at t_{info} from 8.9% to 7.3%, and gives 9 additional years to pivot the energy system back to 1997 emissions.

Land cost (multiplier to central case)	Carbon stored per ha afforested (tC/ha) 40	120	200	280	360
(i) Afforested area at t_{info} (Mha)					
1/4	40.7	154.0	277.0	391.0	493.0
1/2	19.4	76.2	144.0	211.0	276.0
1	9.3	35.6	**69.2**	105.0	141.0
2	4.5	16.3	32.0	49.7	68.0
4	2.2	7.5	14.5	22.7	31.6
(ii) Fossil emission abatement at t_{info} (in % of ref.)					
no-seq			11.00		
1/4	9.76	8.94	7.32	6.50	5.69
1/2	10.57	8.94	8.13	7.32	6.50
1	10.57	9.76	**8.94**	8.13	7.32
2	10.57	9.76	8.94	8.94	8.13
4	10.57	10.57	9.76	8.94	8.94
(iii) Peak fossil expenditure reduction (in % of no seq. peak value, high damage case)					
1/4	6	19	29	38	44
1/2	4	14	23	32	39
1	2	10	**18**	24	31
2	1	7	12	18	23
4	1	4	9	13	17
(iv) Time gained to return to 1997 emissions due to sequestration (years, high damage case)					
1/4	2	9	16	22	28
1/2	1	6	12	18	24
1	0	4	**9**	13	18
2	0	2	6	9	13
4	0	1	3	6	8
(v) Additional 2040-2149 cumulative fossil emissions due to sequestration (GtC, high damage case)					
no-seq			472.51 GtC		
1/4	20	91	167	238	310
1/2	11	65	126	190	255
1	6.9	42	**87**	135	185
2	3.1	26	58	92	128
4	1.5	14	35	59	84

Table 1. Sensitivity tests: (i) Afforested area by $t_{\text{info}} = 2040$. (ii) Fossil emission abatement at $t_{\text{info}} = 2040$. (iii) Fossil expenditure reductions due to sequestration at the peak of fossil cost, in percent of the no-sequestration cost, in case of high damages. (iv) Time gained, over the no-sequestration case, to return to 1997 emissions, in case of high damages. (v) Additional cumulative fossil emissions allowed due to sequestration, between $t_{\text{info}} = 2040$ and 2149, in case of high damages. Best-guess estimate of cost and carbon productivity of afforestation is in bold. Land-cost multipliers of 1/4 and 1/2 accounts for situations with side-benefits to BCS (see text).

IV) Discussion

The present exercise finds a significant impact of sequestration on optimal fossil abatement policies, whereas *Sohngen and Mendelsohn* [2003] find a negligible feedback in their study that captures a feedback loop between sequestration and mitigation policies in order to assess the pace of biological sequestration policies worlwide. Since we use a similar sequestration potential, this can be explained by the fact that (i) they compute sequestration trajectories up to 2100 only, (ii) they use the very flat damage curve of DICE. The result is that the pace of the sequestration control barely impacts marginal damages, and fossil abatement is modified by less than 1% by the BCS policy. Our study works on a longer term sequential decision making mode, and accounts for uncertainty in the "shape" of the damage function.

Its original findings about the arbitrage between using BCS as a short-term brake or as a safety valve triggered later, are explained by three main properties specific to costs and benefits of sequestration, by comparison with costs in the energy sector:

1. Opportunity costs of land are incurred annually during the whole time period while the forest is kept in place to ensure effectiveness of carbon storage.
2. The probability of very high decarbonization costs in the future incites to devote only a minor part of the initial potential to near term afforestation, and to use the major part, even expensive areas, when afforestation has its greatest value.
3. Afforestation is a reversible option: a good part of the immobilized lands can be converted back to agriculture when marginal damages come back to an acceptable level, allowing for carbon release.

The question of the degree of confidence of our best guess estimate of the costs of land cannot be solved in this paper. However, it should be noted that our simulations suggest pace and levels of afforestation which remain within the range of other studies: in the case of high damages, the amount of immobilized lands is similar to the optimal amount found in [*Sohngen and Mendelsohn*, 2003], twice larger than the 345 Mha lower bound of the bottom-up estimate of *Nilsson and Schopfhauser* [1995], and far below than the amount of degraded lands in the tropics alone (2007 Mha estimated by *Grainger* [1988]).

It should also be noted that our simulations involve some sources of systematic bias:

- Bottom-up engineering studies demonstrate that zero or even negative costs potential may already exist in some places [*Makundi and Sathaye*, 2004], for example in the form of agroforestry practices, or of afforestation of degraded land unsuitable to agriculture. These potentials are not included in our analysis (see Fig. 5); and would add to the amount of immediate sequestration projects. However, their magnitude would not modify our main conclusions.
- For reasons of tractability, this analysis relies on a "constant carbon cycle" neglecting climate-carbon feedbacks [*Friedlingstein et al.*, 2001; *Cox et al.*, 2000], and the reduced natural sink capacity of the terrestrial biosphere with agricultural development [*Gitz and Ciais*, 2004]. Both factors would enhance the role of early (and permanent) sequestration (or forest conservation).

Conclusion

This paper confirms that biological sequestration options constitute a substantial margin of freedom for relaxing the carbon constraint on the energy sector. The main original insight is that BCS is a complement and not a pure substitute to actions in the energy sector:

- First, the social value of BCS ultimately depends upon the net climate damages in future periods, which in turn depends upon both the magnitude of the climate damages in a no climate control scenario and the efficiency of decarbonization policies in the energy sector. If fossil abatement abatement policy is not implemented, it would be economically unsound to use temporary sequestration measures instead, since these would eventually add carbon to the atmosphere in the future, and hence increase climate change damages.
- Second, the most efficient way to exploit the major part of the BCS potential is to trigger it as a safety valve in the case of bad news about climate damages. In that case, delaying afforestation both reduces the incurred opportunity costs of land and increases the social value of that land; This result is based on the use of an economic rationale under uncertainty. It refines the statement by *Kirschbaum* [2003], based on a pure physical analysis of impacts, that sequestration should be used *"closer to the time when the most severe impacts are to be expected"*.
- Third, an interesting robust conclusion across the range of damage assumptions is that about two thirds of the afforested lands are converted back to other uses by the end of the 21th century, after decarbonization. This confirms BCS as a flexible and reversible solution to allow for a delayed transitional period in the energy system of up to two decades.
- Finally, the part of BCS launched before resolution of uncertainty about climate change damages alleviates but does not cancel the necessity of precautionary abatement measures in the energy sector. Indeed, "early" sequestration acts mainly as a "brake" by limiting the rise (and rate of change) in atmospheric CO_2. The sequestration of carbon through early afforestation does not displace early emission mitigation on one to one basis, but only the basis of four to one.

These conclusions hopefully clarify the role that BCS could play in designing "optimal" policies to address the risk of climate change: while BCS has utility in the short run, its major role is that of a "safety valve" to be triggered in the case of impending catastrophe. How to translate this message into practical terms requires further investigation to overcome the limits of this aggregate analysis. Ambitious climate policies may critically impact emerging developing countries, especially those rich in coal like China or India. These countries are likely to use their coal reserves over the short and medium term; in case of technical, environmental and economic limits to geological sequestration, BCS could allow significant flexibility to develop their energy systems while respecting climate change limits or constraints on "acceptable" emissions. However, since developing countries also have stringent land-use constraints, BCS may need to come from less densely populated countries. A useful extension of the anaysis would be to apply the same framework developed to a spatial analysis of BCS potential in order to clarify this new dimension of the "when and where flexibility".

Annex: Parameters of Response-sq

See Table 2.

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	description	unit	value		
ρ	utility discount rate	yr^{-1}	0.01		
g	economic growth rate	% yr^{-1}	2.59 - 1.59 - 0.59		
ϕ	technical progress rate	yr^{-1}	0.01		
θ	adaptation rate	yr^{-1}	0.01		
τ_E	turnover time of energetic capital	years	50		
τ_D	CO_2 – damages delay	years	20		
Π_0	World GDP in 1997	$T\$_{90}$	18		
E_0^{ref}	initial global fossil emissions	GtC yr^{-1}	6.4		
c_f	initial fossil cost coeff.	share of GDP	0.0525		
$Q_l(A)\big\|_{1997}$	total land opportunity cost in 1997	T$	$a_1A^2 + a_2A^4$		
a_1	land opp. cost coeff.	$T\$/Mha^2$	8.98517×10^{-8}		
a_2	land opp. cost coeff.	$T\$/Mha^4$	4.21002×10^{-14}		
δ_{lin}	linear damages at $2{\times}CO_2^{\text{preind}}$	share of GDP	0.01		
δ_{sig}	cap for non linear damages	share of GDP	0.04		
e	stringency of non linear damages	–	0.1		
t_{info}	arrival date of information	years	2040		
T	horizon of problem	years	2400		
κ	C density gained *in fine* per ha afforested	tC/ha	200		
τ_F	time to reach κ after afforestation	years	50		
C_l^1	beginning of linear damages	ppmv	326		
C_l^2	$2{\times}CO_2^{\text{preind}}$	ppmv	550		
			State of the World		
			L	M	H
p	probabilities	–	1/3	1/3	1/3
$\check{C}$	beginning of non linear damages	ppmv	917	660	516
$\hat{C}$	ceiling for non linear damages	ppmv	1100	770	584

Table 2. Variables and parameters of Response-sq for the standard simulation. GDP growth rate is set exogenously to 2.59, 1.59 and 0.59% yr^{-1} in the 21st, 22nd and 23rd centuries respectively. For $t > 1997$, $Q_l(A,t) = f(t)Q_l(A)\big|_{1997}$, where $f(t)$ is a scalar whose value is 1 for $t = 1997$ and increasing at a rate of of 2.25% yr^{-1} (resp 1.25% yr^{-1}, 0.25% yr^{-1}) within the 21st (resp. 22nd, 23rd) century.

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