Is There an Optimal Timing for Sequestration to Stabilize Future Climate? 1

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We assess the optimal timing of oceanic, geological and biological carbon sequestration to safeguard climate in a stochastic integrated framework with learning about the value of climate sensitivity. We find that, by substituting efforts from more expensive abatement measures to various sequestration measures, total climate policy costs are cut down by up to 35% for the IPCC A1m and A2 scenarios, and the carbon constraint imposed on the energy sector is relaxed. Biological (BCS) and geological or oceanic carbon capture and sequestration (CCS) are complementary to cope with climatic uncertainties: BCS, the most flexible option, is being helpful in the short run (i.e. before the disclosure of information) to prevent a too-fast warming, while CCS in geologic or oceanic reservoirs has its main utility in a longer run to hedge against the risk of overshooting a temperature ceiling. Because of leakage, ocean storage may be of lower utility in case of high emission scenarios and high climate sensitivities: non-leaky geological storage or fossil fuel abatement are then the main solutions to make a +2°C temperature target viable. Therefore, anticipation of long term reference emissions proves essential to the design of sequestration policies. For a specific baseline scenario, the selection order of sequestration potentials and the amount of carbon stored are mainly driven by relative costs, implementation rates and leakage rates of sequestration, suggesting topics on which our knowledge must improve.

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1. INTRODUCTION

In its latest Report, IPCC examines the contribution of Carbon capture and storage options as means to mitigate the climate change associated to Greenhouse Gas (GHG) emissions. These options have received an increasing attention owing to their large potential in reducing climate policy costs through “buying time”: they allow maintaining temporarily intensive fossil energy use while slowing down the bulk of efforts necessary for alternative carbon-free energy sources to penetrate the market. However sequestration techniques raise some concerns with regards to environmental integrity, both locally, with pollution and toxicity risks (such as water acidification or threats to marine ecosystems) and globally, with possible carbon leakage from storage reservoirs, decreasing thereby sequestration efficiency.

In this context, several contributions have examined the implications of carbon sequestration on intertemporal abatement efforts given the eventuality of future leakage, increasing the risk to overshoot climate policy targets and to penalize future generations. Beside Ha Duong and Keith (2003), Keller et al. (2003) and Pacala (2002), who treat carbon sequestration as a generic option, the literature focuses either on the physical or economic efficiency of temporary and permanent sequestration options: be it storage in geological reservoirs (Dooley and Wise, 2002; Hepple and Benson, 2002); in the ocean (Herzog et al., 2003; Haugan and Joos, 2004; Mueller et al., 2004; Jain and Cao, 2005; Orr et al., 2005) or the management of land sinks (Lashof and Hare, 1999).

Here, we assess the optimal timing of a mix of oceanic (OCS), geological (GCS) and biological carbon sequestration (BCS) options, together with fossil emission reduction measures, in a least-cost portfolio policy to safeguard climate. To do so, we use a compact integrated economy/carbon/climate optimal control model with uncertainty and learning about the value of climate sensitivity. This approach has already been used to clarify discussion about the adequate timing of mitigation (see Manne and Richels, 1992; Ha Duong et al., 1997; Nordhaus and Popp, 1997; Ulph and Ulph, 1997) but surprisingly it has been little used so far to quantify the implementation of sequestration activities, characterized by very different duration scales, storage potentials and costs. The questions raised are: how do these sequestration options compare with emissions reductions in terms of amounts of carbon and costs? What are their relative shares along time in least-cost policies? What are their contributions to lowering climate policy costs? Which flexibility do they offer against uncertainty on the magnitude of future climate change?

This paper is organised as follows. The first section is devoted to the description of costs and potentials of mitigation options in our modelling architecture, RESPONSE. The second section illustrates the differences (in terms of atmospheric CO2 and global mean surface temperature impact) across the three carbon sequestration options under consideration. Economic motives are then taken into account in the third section where we determine the optimal mitigation portfolio in the presence of uncertainty about climate sensitivity, which is the major contributor to the uncertainty in global warming projections for a given concentration pathway. In particular, we assess to what extent it is preferable, despite global efficiency concerns and intergenerational issues raised by leakage, to opt for carbon sequestration to alleviate the constraint on the energy sector over the short- and medium terms and ease the transition towards carbon-free societies in a distant future. Finally we analyze the sensitivity of our results to our underlying costs and leakage rates hypotheses to produce robust results in terms of deployment of sequestration options and therefore conclude by highlighting the main features on which our knowledge must progress.

2. COSTS AND POTENTIALS OF MITIGATION OPTIONS: AN OUTLINE OF RESPONSE

1.1. The RESPONSE model

As an extension of DIAM (Ha Duong et al., 1997), RESPONSE (Ambrosi et al., 2003) is a simple climate policy optimisation model. It includes a simple description of policy controls (global emission reductions, global afforestation rates, geological storage rates in four different reservoirs, oceanic storage rates through three injection techniques) and their related costs. It describes the chain linking net CO2 emissions to mean surface temperature change through very compact models of the global carbon cycle and of the global climate system. Using abatement and sequestration controls, RESPONSE seeks to minimise the discounted sum of mitigation costs to comply with two climate objectives (Fig. 1):

- a constraint on the maximum allowable magnitude of global warming, set at +2°C (over 1990), which is close to the long-term climate policy goal stated by the European Union (Council of the European Union, 2004).

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a constraint on the decadal rate of warming, set at +0.2°C per decade. Introducing such a constraint allows to account for the fact that some impacts of climate change are rate-sensitive (namely, on ecosystems).

[Figure 1: RESPONSE]

Carbon flows between the atmosphere, the ocean and land reservoirs are described using a linear three-reservoirs box-model from DICE and RICE (Nordhaus and Boyer, 2000). This model has been fitted with biological (see 1.2.2), geological and oceanic carbon storage modules (see 1.2.3).

The evolution of global temperature is described using a two-equation perturbation model (based on Schneider and Thompson, 1981) parameterized using a General Circulation Model warming scenario forced by a 1% per year atmospheric CO2 increase (IPSL CM, data kindly provided by Friedlingstein and Le Treut). CO2 is the only radiative agent considered. Since the main issue is the timing of abatement over the short term (up to 2050), our model describes the thermal disequilibrium between atmosphere and surface ocean in response to anthropogenic greenhouse effect. The long-term climate dynamics is constrained by the climate sensitivity, treated as variable parameter.

To account for uncertainty in global warming projections, climate sensitivity is taken as an uncertain parameter up until a given date (2060). We explore three values \(+2.5°C, +3.5°C, +4.5°C\) with equal probabilities.

1.2. Policy costs and potentials

1.2.1 Fossil fuel emissions and abatement. Our reference scenario is the A1m scenario, from the IPCC-SRES family (Nakicenovic, 2000). In this scenario, emissions increase rapidly up to 11 GtC in 2100 and decline after 2100 due to the effects of “cleaner” technologies in the energy sector. As a sensitivity analysis to the global amount of emissions and trajectory, we performed simulations based on the high emissions A2 scenario. CO2 emissions in A2 rise steadily to reach about 30 GtC/year by 2100 and decline afterwards down to 11 GtC in 2300. Cumulative emissions sum up to 2,077 GtC in the A1m scenario and to 6,189 GtC in the A2 scenario.

Global emissions reduction costs from DIAM have been re-calibrated against IPCC TAR estimates for a 550ppm target (Metz et al., chp VIII). This leads to an initial value of 1,200 US$/tC for the cost of the backstop technology. In our specifications and, as in Ha Duong et al. (1997), costs of emissions reductions at time \(t\) are expressed as a quadratic function of both the degree and time-derivative of abatement, thus taking into account transition costs of changing capital stocks in energy systems. Marginal costs also incorporate an autonomous technical change factor (they decrease at a yearly constant rate of 1% down to a limit of one fourth of their initial value). Discount rate is set at 5%.\(^9\)

1.2.2 Biological sequestration. Significant BCS through large scale afforestation or reforestation of agricultural lands (croplands and pastures) cannot be considered as a zero-cost option, like in MERGE (Mann and Richels, 1999), since one has to account for foregone agricultural revenue as lands are deviated from agriculture. Such opportunity costs are incurred as long as land is dedicated to BCS. To derive a marginal annual opportunity cost curve of agricultural lands suitable to afforestation, we compile data from FAO (2005) for the agricultural areas per country, from GTAP (2001) for the annual net agricultural revenue per country, and used potential land-cover maps from Ramankutty and Foley (1999) to exclude existing agricultural lands not suitable to afforestation. This gives a maximum suitable area for BCS of 1 billion ha (25% of existing agricultural lands) at maximum annual cost of 0.1 TUS$/yr (Fig. 2). Annual afforestation rates are capped at 1.5 Mha/yr in our model. We also suppose a net land carbon gain after afforestation of 0.1 GtC per Mha, obtained linearly after 50 years. This implies a maximum BCS storage potential of 100 GtC (i.e. 5 % of baseline emissions until 2100). BCS appears thus as a rather limited mitigation option. BCS is modeled as a potentially reversible option: afforestation projects may be abandoned and land converted back to agriculture, leading to carbon release, zeroing land opportunity costs. These features of BCS put the stress on using it with appropriate timing with respect to other mitigation options.

[Figure 2: BCS costs]

1.2.3 Carbon Capture and Storage. CCS costs are based on estimates from Freund (2001), Scott et al. (2004) and IPCC Workshop on CCS (2002)\(^11\). We assume CCS will become available on industrial scale basis after 2020, a time horizon commonly encountered in energy-economics studies (Edmonds et al., 2004; Kurosawa, 2004; Riahi et al., 2004).

\(^9\)http://www.lmd.jussieu.fr/Climat/couplage/ipsl_ccm2/index.html

\(^10\)The technology that would allow to zero carbon emissions globally.

Unit costs of the capture-purification-dehydration-compression stage, the most significant share in CCS costs, are assumed to decrease with time at a 1% per year rate from 185 US$/tC down to 92.5 US$/tC. To account for the increase in energy consumption due to the capture process, we apply an energy penalty, initially amounting to a 20% extra emissions, decreasing down to 13% at a 1% per year rate, because of more efficient capture technologies in the future. Note that technical change only affects this stage of CCS, others being considered to be based on mature technologies. Given current estimates, annual emissions suitable for capture are set to 33% of baseline emissions at most, as in Haugan and Joos (2004). This parameter is however uncertain and will depend on the future structure of the energy system: its influence on optimal policies will be examined through sensitivity analysis. Capture is assumed to be perfect: 100% of emissions are confined through the process.

For CO$_2$ transport from capture location to a disposal site, we consider a mean 300 km distance for GCS, resulting in a mean constant transport cost of 26 US$/tC, and a mean 100 km distance between capture site and seashore for OCS, resulting in a mean constant transport cost of 8.67 US$/tC.

[Figure 3: GCS, OCS costs]

Geologic and oceanic potential and storage dynamics are defined as follows:

- We consider storage in four geological reservoirs of the following capacities: 35 GtC for oil fields (both Enhanced Oil Recovery (EOR) and injection in depleted oil fields), 41 GtC for unminable coal seams, 218 GtC for gas fields (both Enhanced Gas Recovery (EGR) and injection in depleted gas fields) and 1,091 GtC for deep saline aquifers. To date, very few information regarding leakage rates from geological formations are available: like Haugan and Joos (2004) we assume non-leaky geological storage. The global maximum potential of these reservoirs amount to some 1,400 GtC. This represents respectively almost 70% of the fossil emissions in A1m and slightly more than 20% in A2. Initial marginal costs of these GCS options are given in Fig. 3.

- Unlike geological formations, ocean storage capacity is assumed to be unlimited but its interest may be limited by leakage and negative impacts on marine ecosystems (ocean acidification). We have selected three injection-dispersal techniques with varying injection depth and spread of CO$_2$: maximal and rapid diffusion or concentration in a CO$_2$ lake. These techniques are: pipe (800 m), towed pipe (1,300 m) and platform (3,000 m). Leakage rates from oceanic CO$_2$ disposal back to the atmosphere are calibrated against 3D ocean carbon models results: among the models in the GOSAC study (Orr, 2004), we took the median estimate for the global carbon injection efficiency. We find an e-folding time for sequestered CO$_2$ returning back to the atmosphere of of 221 years (resp. 633 years, and 7,109 years) for injection at 800 m (resp. 1,500 m and 3,000 m).

[Figure 4: Physical efficiency]

Fig. 4 displays the efficiency of sequestration, measured as the induced excess of atmospheric CO$_2$ concentration (Fig. 4a), surface temperature (Fig. 4b) and rate of surface temperature change (Fig. 4c). Four sequestration actions taken in the period 2000-2010 are compared: (i) a 10 GtC fossil fuel emissions abatement measure or sequestration in repository with no leakage; (ii) a 50 years temporary storage of 10 GtC in terrestrial ecosystems, where stored carbon is voluntarily released by 2050-2060; and (iii-iv) a 10 GtC storage in the ocean or leaky geological reservoirs with prescribed leakage rates of resp. 1% and 0.1 % per year.

Fig. 4a illustrates the fact that a sequestration project, while lowering atmospheric CO$_2$ in the short term, may lead to an excess of CO$_2$ concentration later on. If leakage rates are low (0.1%/yr), the efficiency of sequestration is very close to the one of an abatement measure. If leakage rates are higher (e.g. 1%/yr), atmospheric CO$_2$ concentration (resp. Surf. Temp.) will rise above the reference level in about 110 years (resp. 140 years) and the additional rate of warming reaches a maximum of $+0.0045 \degree$C/dec/GtC.

3. LEAKAGE AND EFFICIENCY OF CARBON SEQUESTRATION: A PHYSICAL APPRAISAL

Because carbon stored in different reservoirs can leak out to the atmosphere, sequestration strategies may have long term impacts on atmospheric CO$_2$ and climate. Such long term consequences are of particular importance in a cost-efficiency framework: carbon leakage in the future will call for additional abatement efforts in the long run to stabilise CO$_2$ concentration or temperature. When designing economically-sound policies (section 4), these additional future efforts will have to be considered together with the short term benefits from alleviating the carbon constraints in the energy sector at the early stage of sequestration implementation.

In this section, we use the compact carbon cycle and climate module of RESPONSE to assess the consequences (on atmospheric CO$_2$ and mean surface temperature) of different carbon sequestration options with different leakage rates.

12 Also because we consider a 100% efficient capture process.
stored) about 30-40 years after injection. These results fall within the range of published estimates of critical leakage rates compatible with environmental targets13. The main feature of a temporary sequestration option (such as in our case, afforestation) is the sharp temperature increase when carbon gets released back (Fig. 4b,c).

As a consequence, if temperature stabilisation targets become binding in the future, initial leaky sequestration implementation may require additional longer term countermeasures (sequestration or abatement) to compensate for leakage. In the next section, we explore the implications of this property of sequestration (short term benefits, longer term inconvenients) on the deployment of a least-cost mitigation portfolio.

4. WHICH OPTIMAL PORTFOLIO DEPLOYMENT UNDER UNCERTAINTY?

4.1. Simulations for the A1m scenario

We use the integrated economy-carbon-climate model RESPONSE to compute fossil fuel emissions abatement, BCS, OCS and GCS least-cost trajectories within a cost-effectiveness framework, under prescribed external constraints on global warming amplitude and its rate (as shown on Fig. 1). In this paragraph, we set as baseline the A1m reference scenario.

To study the optimal implementation of sequestration options, it is relevant to compare those with a simulation where fossil fuel abatement is the only option allowed (Sfos simulation). In a second step, we made a set of 3 simulations where each sequestration option (biological, geological and oceanic sequestration, resp.) is implemented one at a time together with fossil fuel abatement (Sbcs, Sgcs, Socs, resp.). Finally, we perform a simulation where abatement and all sequestration options compete (Sall).

Fig. 5a (resp. Fig. 5g) shows the optimal fossil fuel burning (FFB) trajectories (resp. fossil fuel abatement expenditures as a share of the world gross domestic product (GDP)) for the Sfos and Sall simulations. Storage and leakage fluxes in the different reservoirs are shown in Fig. 5b-e. Fig. 5h shows the atmospheric CO2 trajectories, and Fig. 5i the excess surface temperature over 2000 levels. The cumulated carbon budgets and cumulated discounted policy costs are given in Table 1 for all simulations, for two periods: a near-future 1990-2069 period where climate sensitivity remains uncertain, and a long term 2070-2300 period where climate sensitivity is known, with three possible values (see section 2).

4.1.1 Sfos case. If fossil emissions reduction is the only possible option (Sfos), the optimal policy is to reduce emissions in the near future from 848 to 493 GtC in cumulated total (Table 1). A striking feature of the Sfos case is what happens after revelation of the value of climate sensitivity. In case of “good news” (low or medium climate sensitivity), it is possible to progressively relax abatement efforts (Fig. 5a and Tab. 1) and fossil emissions can increase again. On the contrary, if climate sensitivity is found to be high, one must significantly intensify abatement efforts, leading to a peak in abatement expenditures (Fig. 5g), amounting to 0.6% of the annual GDP in 2080, short after the ‘bad’ news are known. The total discounted climate policy costs base on a fossil only action for A1m amounts to 5,55T$ (Tab. 1).

[Figure 5: Optimal emissions trajectories]

[Table 1: Costs and carbon budget across simulations]

4.1.2 Sbcs case. If biological sequestration is added to the portfolio, together with fossil carbon abatement (Sbcs case), the allowable FFB increases by +57 GtC in the short term, representing a 15% (355 GtC) reduction in the fossil abatement effort over 1990-2069 (Tab. 1). This translates into a significant 38% decrease in short term discounted abatement costs14. However, after 2070, the abatement efforts in the Sbcs case are 3 to 8% higher than in the Sfos case because one must compensate release of carbon stored in the biomass. Indeed the bulk of BCS (57 GtC cumulated storage on short term) is only used as a temporary storage. This is to avoid placing a permanent burden of land opportunity costs, constantly incurred even when net carbon storage per ha is decreasing. BCS thus acts mainly as a temporary solution (a “brake” on emission reductions) for postponing fossil abatement to a later period (as technical change and economic growth make this option less expensive), assuming it will be sufficient to absorb the extra-source of CO2 when biospheric stocks are unlocked.

4.1.3 Sgcs case. Let us now consider the case where geological sequestration comes into play (Sgcs). The allowable cumulative fossil fuel burning budget increases in the near future by about 42 GtC (about 11% reduction in abatement efforts) compared to a situation with abatement only. This

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13Hepple and Benson (2002) consider that average leakage rates about 0.01% per year (resp. 0.1% per year) are consistent with stabilisation up to 350ppm (resp. 650 ppm). Due to the heterogeneity among reservoirs, assuming an increasing storage in the less leaky ones, Pacala (2002) estimates that even a 1% per year seepage rate is still compatible with stringent environmental targets.

14Carbon gains lead to more than proportional fossil abatement cost savings because the latter are (i) quadratic in function of abatement and (ii) proportional to the time-derivative of abatement. BCS helps to alleviate both factors.
corresponds to a 19% decrease in short term fossil abatement costs and a 8% decrease in total short term policy costs (Tab. 1). But the main benefits of geological sequestration are especially felt on the long term. In the worst case, up to 213 GtC are stored in geologic reservoirs after 2070 (37% of the FFB over the same period), allowing to cut down by 70% the peak in abatement expenses very efficiently.

4.1.4 Socs case. Similar results are obtained in the Socs case. The main difference is that, as compared to the Sges case, higher efforts (-21 GtC cumulated FFB) are required on the long term to compensate for oceanic carbon leakage, in the high climate sensitivity case.

4.1.5 Sall case. Yet, we found that the most efficient policy is obtained with a diversified mitigation portfolio (Sall). In this case, and if climate sensitivity appears to be high, total discounted climate policy costs (including sequestration costs) amount only to 66% of those in the Sfoss case. Such an impressive gain is the result of (i) a short term alleviation of efforts (+7.5 GtC cumulated FFB up until 2069) mainly due to BCS, and (ii) an important role of sequestration in the long term to relax efforts on emissions in case of a bad climate surprise. In other words, geological sequestration and ocean injection act as a “safety valve”, were more stringent emission targets required in case of bad news about the value of climate sensitivity.

BCS deploys at the maximum of the allowable afforestation rate until 2030 but does not saturate the whole potential; in the high climate sensitivity case, CCS deploys at the maximum of the CO₂ capture rate between 2080 and 2140 but does not saturate the whole geological and oceanic storage potential (Fig. 5b). Hence, technical constraints on the rate of penetration of these options prove binding.

In Figure 5h-i, we show the atmospheric CO₂ trajectories and warming for the Sfoss and Sall scenarios. Since climatic constraints are binding, sequestration actions work together as a substitute to abatement efforts (see Fig. 5h): atmospheric CO₂ trajectories and warming are almost identical in the Sfoss and Sall scenarios. Given the climate targets under consideration and the uncertainty about climate sensitivity (partly magnified by the late learning assumption), the net GHG emissions envelope is almost totally prescribed following carbon cycle and climate dynamics: rate constraint (linked to the increment in atmospheric CO₂) is binding on short-term and magnitude constraint (linked to the amount of atmospheric CO₂ on the long-run (Fig. 5i).

In the A1m “low-emission” scenario, OCS can penetrate (308 GtC) in spite of substantial long term leakage (up to 211 GtC in the high climate sensitivity case) since the carbon-climate system can “absorb” this leakage in the long run so as to respect the prescribed targets (Fig 4h-i).

4.2. Competitive shares of GCS and OCS

A specificity of the Sall simulation is that oceanic and geologic sequestrations compete with each other. Their implementation depends on relative assumptions on storage costs and leakage rates. The hypotheses we have adopted for OCS and deep saline aquifer (DSA) storage costs (Fig. 3) make them similar to backstop technologies, albeit only applicable to the fraction of the FFB that can be captured. The technology that will likely be implemented in the A1m scenario proves to be the less expensive one, namely OCS in our parameterization.

In fact, leakage introduces a penalty against OCS: even with OCS “backstop” lower than DSA “backstop”, a certain amount of GCS will penetrate within the CCS portfolio. To investigate to what extent hypotheses about leakage rate and relative costs of OCS and GCS influence the structure of the CCS portfolio, we have run a set of simulations where one unique OCS technique (unit cost from 52.4 US$/tCO₂ to 62.4 US$/tCO₂ and leakage rate from 0.1 to 1% per year) competes with the four GCS techniques previously described. Fig. 6 shows the GCS share within the CCS portfolio: it is very low (7.7 %) for low OCS costs and low ocean leakage; and tends to increase (up to 100%) with increasing leakage rate, all the more rapidly as OCS costs gets close to GCS ones.

[Figure 6: share of GCS within CCS in the A1m scenario]

4.3. Sequestration policies in the high emission scenario, A2

More carbon intensive scenarios than A1m, such as A2 (6189 GtC cumulated emissions between 1990 and 2300), may require continued abatement efforts. In this case, climate constraints might be binding even in the long run, emphasizing the problem of oceanic leakage (all the more as CCS volumes are expected to be higher). We made an additional set of simulations based on the A2 scenario. Results are shown in Table 2. The need for CCS is higher in this scenario: 1476 GtC stored through CCS in the Sall simulation.

However, in contrast to scenario A1m, the use of OCS in A2 decreases substantially with increasing

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15 This value is the difference in FFB in the long term for a 4.5°C climate sensitivity value between the Socs and Sges simulations in Tab. 1.

16 It is never zero because of the existence of very low-cost GCS opportunities such as EORs and EGRs.
climate sensitivity (Tab. 2), in order to limit ocean leakage: in the S\textsubscript{all} simulation, allowed cumulated ocean leakage in A2 is 557 GtC for a 2.5°C climate sensitivity, but only 406 GtC for 4.5°C. In the A2-S\textsubscript{all} simulation, this translates into more GCS and additional fossil fuel abatement for higher climate sensitivities (Tab. 2). In the A2-S\textsubscript{soc} simulation, where only fossil fuel limitation is allowed together with OCS, this effect is even more pregnant, since drastic FFB reductions are required in the long term in case of a bad surprise regarding climate sensitivity (Tab. 2): if OCS were to be used instead of FFB reductions, the induced leakage would then not make a +2°C climate stabilization target viable. In other words, OCS may not be compatible with high emission scenarios and high climate sensitivities. If such conditions are encountered, FFB reductions, and non-leaky GCS, if allowed, are the only viable long-term options.

This effect is not present in the “low-emissions” A1m scenario (in which the use of OCS increases with increasing climate sensitivity), because lower injected volumes and lower induced ocean leakage are less likely to put pressure on the stabilization constraints of the climate system (see Fig. 5i).

| Table 2: Costs and carbon budget across simulations for A2 |

4.4. Role of the energy penalty and of the structure of the energy system.

Another factor that influences the substitution of emissions inside the carbon budget is the energy penalty which also automatically induces additional fossil resource extraction, additional storage, and, as a consequence, additional oceanic leakage, likely to favour GCS. A 50% increase in the value of the energy penalty induces a shift of a cumulated 27 GtC (resp. 768 GtC) from OCS to GCS in the A1m (resp. A2) scenario.

In the previous simulations, we assumed that a maximum of one third of annual reference emissions might be captured through CCS. This parameter is however very uncertain, and will depend of the very structure of the energy system (switch to hydrogen for transportation, substitution of liquid fuels towards electricity, etc.), whose precise description goes beyond the scope of this paper. To circumvent this limitation, we made a sensitivity analysis in which this parameter varies between 10 and 90%. Results are depicted in Table 3 for scenarios A1m and A2. An annual CCS ceiling over 50% of the annual reference emissions is never binding in both scenarios. Unsurprisingly, the higher this parameter varies, the higher the volume stored through CCS (up to 33% of cumulated FFB in A1m, up to 72% of cumulated FFB in A2, results obtained with no ceiling and in the high climate sensitivity case).

However, we find an opposite effect, in A1m and A2, of increased CCS ceilings on the penetration of OCS in the mitigation portfolio (Tab. 3): with high CCS ceilings, OCS will be favoured in the low emissions A1m scenario, whereas non-leaky GCS, despite higher costs (Fig. 3), will penetrate in the A2 scenario to avoid consequences of ocean leakage.

| Table 3: Role of the ceiling of annual emissions allowed to be captured |

5. CONCLUDING REMARKS AND PERSPECTIVES

Using an integrated assessment model, RESPONSE, we have investigated the interplay and respective contributions of various carbon sequestration options to hedge against the threat of climate change. Three main conclusions emerge from the analysis.

First, the allocation of efforts (the selection order of sequestration potentials and amount of carbon stored) is mainly driven by considerations of relative costs of available options. In this context, our results confirm the advantage to draw climate policies on a fully diversified portfolio of mitigation option: substitution of efforts (not on a 1-to-1 basis, given the wedge induced by leakage) from abatement measures to various sequestration measures allows to cut down total climate policy costs up to 35% for both A1m and A2 scenario (a reduction equally sensible on short and long term) and relax the constraint on the energy sector on short-term (before learning) or on long-term (where climate sensitivity equals 4.5°C). While the optimal BCS use appears to be robust (~60 GtC stored and subsequently released in all scenarios), the use of CCS is all the more significant in high emissions scenarios: up to 338 GtC cumulated storage in A1m until 2300, and up to 1664 GtC in A2.

Second, a synergy exists between BCS and geological and oceanic sequestration to cope with uncertainty about climate sensitivity: BCS – the most flexible option– is helpful in the short run (i.e. before the disclosure of information) and CCS afterwards. In the decades to come, part of necessary mitigation commitments could be fulfilled through large scale and low cost BCS (at afforestation rates up to 1.5 Mha/yr and sequestration rates up to 1.5 GtC/yr) to prevent a too-fast build-up of atmospheric CO\textsubscript{2}. If a tight constraint on the rate of temperature change has to be respected from now on, early BCS proves helpful in lowering short-term socio-economic transition costs by allowing delaying part of the
fossil abatement measures. Once learning has occurred, BCS projects can be abandoned (because many have reached maturity and they entail opportunity cost because of permanent immobilization of lands) and CCS actions (whose costs have by then decreased) can relay them as a substitute to abatement efforts.

Finally, OCS and GCS compete among CCS options, giving a special importance to relative storage costs and leakage rates. Ocean storage might be affordable and with a quasi-unlimited storage potential; however results may be altered if the environmental costs of ocean storage (i.e. including economic and social costs of coral reefs extinction or other ecosystems through acidification) are internalised. On the other hand, ocean leakage might entail the penetration of OCS in high emission scenarios like A2, the incurred leakage possibly not being compatible with a tight temperature increase ceiling, all the more as climate sensitivity is high.

Anticipation of future trends in the baseline scenario proves thus important when launching sequestration policies, especially in the ocean. Optimal shares and timing of the various forms of carbon sequestration remain also highly dependent on potential implementation rates and costs, leakage rates, and environmental side-consequences. This study, based on the order of magnitude of costs and potentials for CCS available in the literature, and the sensitivity analysis we conducted, suggests that our knowledge must progress before launching large scale CCS projects.

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**Figure 1.** RESPONSE – A stochastic optimal control integrated assessment model, in a cost-effectiveness framework with constraints on global mean temperature change (its magnitude and its rate). Based on reduced-forms calibrated against more elaborated models, RESPONSE captures the main features of the causal chain linking GHG emissions to climate change.
Figure 2. Cumulated annual opportunity costs of lands suitable for afforestation worldwide, in 1997. The model is run using a fitted function (dashed line) \( Q_{1997}(A) = 8.98517 \times 10^{-8} A^2 + 4.21002 \times 10^{-14} A^4 \) of the compiled data from GTAP and FAO databases (solid curve). For subsequent years, \( Q(A,t) = f(t)Q_{1997}(A) \), where \( f(t) \) is a scalar whose value is 1 for \( t = 1997 \) and increasing at a rate of 2.25%/yr (resp 1.25%/yr, 0.25%/yr) within the 21st (resp. 22nd, 23rd) century.

Figure 3. Initial marginal costs for capture and storage of CO\(_2\) in geologic formations and in the ocean. Storage capacities are the following: 130 GtCO\(_2\) for oil fields, 150 GtCO\(_2\) for unminable coal seams, 800 GtCO\(_2\) for gas and 4000 GtCO\(_2\) for deep saline aquifers. Ocean storage capacity is assumed to be non-limitative.
Figure 4. Effect of unitary sequestration projects on future climate trajectories, for 4 projects: *plain curve*: fossil fuel abatement of 1 GtC/yr over the 2000-2010 period; *dashed curve with circles*: temporary sequestration project of 1GtC/yr during 2000-2010, followed by total release by 2050; *dashed curve (resp. dotted curve)*: sequestration in oceanic or geologic reservoir with leakage rate of 1% (resp 0.1%). (a) Excess Atmospheric CO₂ over the reference trajectory without project; (b) Excess mean surface temperature over the A1m reference trajectory; (c) Excess rate of surface temperature increase over the A1m reference trajectory.
Figure 5. (a) Fossil fuel burning in the A1m reference scenario, in the abatement only mitigation hedging scenario ($S_{\text{f0}}$, white labels), and in the scenario with all sequestration types also allowed ($S_{\text{all}}$, black labels). Information about the value of the climate sensitivity (2.5°C, 3.5°C or 4.5°C case) is revealed in 2060; (b) Oceanic and geological carbon storage along these optimal trajectories, and maximum CCS storage rate (marked +); (c) Ocean leakage; (d) Oceanic storage; (e) Geological storage; (f) Net biological storage flux; (g) Fossil fuel abatement costs in share of the world gross domestic product; (h) Atmospheric CO$_2$; (i) surface temperature rise in reference scenarios (A1m 2.5°C, A1m 3.5°C, A1m 4.5°C) with no climate policy, and in optimal scenarios with and without sequestration. In (i), prescribed climatic targets ($T_{\text{max}} = +2^\circ$C and $dT/dt_{\text{max}} = +0.2^\circ$C/decade after 2010) are also displayed.
Figure 6. GCS share within a CCS portfolio for various leakage rates from oceanic injection and different OCS costs, in the A1m scenario, S_all simulation, high climate sensitivity case. Ocean sequestration costs are chosen between 52.4 US$/tCO₂ (this assumes zero ocean injection costs) and 62.4 US$/tCO₂ (this assumes 10$ tCO₂ ocean injection cost). Costs of OCS in the standard version of RESPONSE (section 2) are also displayed.
<table>
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<tr>
<th>A1m scenario</th>
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Table 1. (Left) Fossil Fuel Burning and sequestered fluxes into different reservoirs in the reference case (A1m Ref) and in the five policy scenarios. Abatement effort (in GtC) is the difference in Fossil Fuel Burning between the reference case and the simulation cases. (Right) Discounted climate policy costs (abatement, BCS, GCS and OCS costs in T$) in the different mitigation scenarios, over the short term period (ST, 1990-2069) and in the longer term period (LT, 2070-2300), for the three climate sensitivity cases. Reference scenario is IPCC A1m.
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Table 2. (Left) Fossil Fuel Burning and sequestered fluxes into different reservoirs in the reference case (A2 Ref) and in the five policy scenarios. Abatement effort (in GtC) is the difference in Fossil Fuel Burning between the reference case and the simulation cases. (Right) Discounted climate policy costs (abatement, BCS, GCS and OCS costs in TS) in the different mitigation scenarios, over the short term period (ST, 1990-2069) and in the longer term period (LT, 2070-2300), for the three climate sensitivity cases. Reference scenario is IPCC A2.
Table 3. Effect of the annual CCS limit (CL, first column, in % of annual ref. emissions) on optimal policies for the A1m and the A2 reference scenarios, in the different climate sensitivity cases. Information about climate sensitivity is revealed in 2060. Climatic constraints remain as in the text.